SCOTTISH GOVERNMENT
RURAL AFFAIRS, FOOD AND ENVIRONMENT PORTFOLIO

STRATEGIC RESEARCH PROGRAMME
1 April 2016 to 31 March 2021

Submission

Theme 2 – Productive and Sustainable Land Management and Rural Economies

On behalf of

Scotland's Rural College
James Hutton Institute
Moredun Research Institute
Rowett Institute of Health and Nutrition
Biomathematics and Statistics Scotland
Royal Botanic Garden Edinburgh

Theme 2 Final Version Resubmission February 2016

TENDERER DECLARATION

I the undersigned do hereby agree on the acceptance of the Tender for Grant Funding by the Scottish Ministers, to provide the work detailed in the Specification for the Strategic Research Programme 2016-2021.

This work will be undertaken in accordance with the principles of governance, quality, value for money and I accept that the Scottish Ministers reserves the right to withdraw funding should the outputs not meet the required standards. I confirm that the work will be completed at the prices entered in the Pricing Proposals and in accordance with the Scottish Government Conditions of Grant.

I the undersigned do hereby agree to abide by the requirements that each organisation is to have a structured data management and Intellectual Property plan in place; and to the Joint Code of Practice for Research as detailed in Schedules 2 - Annex D and 4.

*I confirm that the tender as submitted is complete and that all the information contained within this is accurate. I agree to abide by this tender from **Noon on Thursday 30 April 2015** the date fixed for receiving tenders, until the Award of Grant.*

Signature	
Name	PROFESSOR GEOFF SIMM
	(BLOCK CAPITALS)
Designation	VICE PRINCIPAL RESEARCH

Theme 2: Productive and Sustainable Land Management and Rural Economies

Executive Summary

The 2021 vision for the Productive and Sustainable Land Management and Rural Economies Theme (2) is to achieve sustainable production of increased amounts of good food from vibrant rural economies. Theme 2 underpins Scotland's high-performing food and drink industry through innovative, responsive, internationally-recognised research on food security, disease control and climate change in agricultural systems. The Theme proposes a broad spectrum of strategic research and knowledge exchange activities, designed to meet the requirements of many stakeholders in the public and private sectors. In this area there is a recognised need for improved resource use efficiency and increased productivity across primary production sectors to improve the sustainability, resilience and growth of rural economies. Theme 2 delivers this through four work packages, themselves containing a total of 32 research deliverables.

A1: Programme Governance

The overarching vision for the Strategic Research Programme (SRP) is to support the Scottish Government's single purpose of sustainable economic growth by delivering excellent science and translating this into practice to protect our natural assets, promote productive and sustainable land management and rural economies, ensure a supply of safe, nutritious and affordable food, and enhance the health and wellbeing of our people and communities. The SRP involves six Main Research Providers (MRPs), multiple geographical sites, a wide range of scientific disciplines, facilities and equipment, and a significant number of important stakeholders within Scotland and further afield. To manage this complexity, we propose the following governance structure to (a) provide vision and leadership in strategic science excellence, and (b) maintain continual improvement in performance of activities funded and delivered through the SRP and the associated Centres of Expertise (CoEs) and Innovation Platforms.

1. <u>The Strategic Research Programme Board (SRPB)</u> convened by RESAS will oversee all scientific activities and impact from the SRP.
2. <u>The Directors Executive Committee (DEC)</u>, comprising the Directors of each MRP, the KE Director, Programme Advisors, and DEC secretary, will provide top-level management of the SRP and its associated KE, the latter functioning at all levels from RD through to the CKEI.
3. <u>A Strategic Advisory Group (SAG)</u> convened by DEC with wide membership from scientific and stakeholder communities will advise DEC on strategic research and KE activities throughout the life of the SRP. This group will report to DEC and will be chaired by an independent member.

4. The Centre for Knowledge Exchange and Impact (CKEI) consisting of the KE Director, the two Programme Advisors, and five KE Sectorial leads (KESLs) covering the areas of food and drink, livestock, crops/soils, environment, and communities, will coordinate KE activities across the SRP. The role of the KESLs will be to (a) interact with the SRP Themes, CoEs, Innovation Platforms and Underpinning Capacity (UC) services, (b) coordinate engagement with stakeholders, and (c) help implement events and activities through the communications teams at each of the participating organisations. The CKEI will report to the DEC, and a KE Consultative Group will be used to advise on innovative KE approaches to maximise impact locally, regionally, nationally and internationally.
5. Theme Coordinators will coordinate all Theme activities and report to DEC. Management details specific to Theme 2 are given below.
6. Workpackage (WP) Coordinators in each Theme will coordinate Workpackage activities and report to their Theme Coordinator.
7. Research Deliverable (RD) Coordinators will coordinate Research Deliverable activities and report to their WP Coordinator.

Although not formally part of the structure, the CoEs are an important, policy-focused component of the portfolio supported by RESAS, and the SRP will be closely linked with the governance and management of the CoEs through their individual Directors. The structure will facilitate the overall collating, synthesising and dissemination of information between the RDs, WPs, Themes, UC within each MRP, Innovation Platform projects, and the CKEI, to ensure integrated and responsive modes of working. Specific WP and RD coordinators will have a particular responsibility for developing integrative working among the MRPs in new areas of science. Throughout, an ethos of team working and collaboration will be fostered to implement an ambitious and far-reaching strategy for Scottish science and it's KE. Individuals have been identified for each of these roles for the first year of the SRP, although it is anticipated that these may change (subject to DEC approval) as the Programme develops. Rotation of managers may occur where the activities (e.g. at the RD, WP or Theme level) involve multiple major inputs from more than one MRP, or where significant changes have occurred.
Communications within the governance structure will be by a range of routes, including face-to-face meetings, video or teleconferencing, webinars, email and social media. The choice of approach will depend on geographical site, participant number and costs, and will attempt to minimise carbon emissions from travel while maximising communication effectiveness. Meetings at the RD, WP and Theme levels, and with Innovation Platforms (and where requested, CoEs), will focus on the scientific excellence of current work, future opportunities linking with other scientific initiatives (especially within Scotland), and undertaking additional activities to deliver to the SG's purpose of sustainable economic development. The meetings will be an opportunity for some of Scotland's most creative and innovative scientists to design and influence the future agendas for science delivering to the SRP vision. Meetings will also routinely assess delivery of scientific outputs and outcomes from the SRP to account for spend and demonstrate value. The division of time on science excellence/forward look compared to monitoring progress/delivery will be at least 50:50 at all levels and more likely to be 75:25 at the levels of Themes and WPs.

Roles and responsibilities of key individuals in the governance structure:

Members of DEC

1. Each Director, as a member of DEC, will be responsible for ensuring that the high quality of research is maintained and opportunities for more integrated and innovative working are embraced. Each Director will also identify and deliver corrective action in the event that issues affecting delivery have been identified by Theme Coordinators, the KE Director, or SAG.
2. The budgetary implications of issues identified by the Theme Coordinators or the KE Director will also be the responsibility of the relevant Director.

Programme Advisors

1. Assist Theme Coordinators in identifying new opportunities or changes in policy foci, monitoring scientific progress within Themes and at SRP level.
2. Responsible for overall coordination and oversight of the reporting process on behalf of DEC with designated MRP representatives for metrics.
3. Form specific linkages, with KESLs, with RESAS Science Advisors.
4. Stakeholder engagement in liaison with the CKEI Director.
5. Identify cross-Theme opportunities for both research and KE, through attendance at DEC meetings and membership of the CKEI core group.
6. Representation role for SRP at key KE events, liaising with the CKEI Director.

Theme Coordinator:

1. Identify ongoing opportunities to ensure the Theme Vision is realised and delivers to the overall SRP Vision.
2. As the principal point of contact with DEC and RESAS Science Advisors, assume overall responsibility for Theme development and co-ordination.
3. Chair *Theme Management Group* (TMG) meetings, every six months.
4. Responsible for monitoring progress within the Theme against agreed and timetabled activities/deliverables/events, reporting to DEC and RESAS Science Advisors to provide information when objectives are achieved and impact is realised.
5. Where necessary, report on problems with delivery of Theme to DEC and provide advice on contingency plans to address such issues.
6. As empowered by DEC, responsible for implementing changes to Theme delivery/resource allocation.
7. Highlight new opportunities for integration and added value within Theme or across the SRP, both in research and KE activity.
8. Represent Theme activities at key events and to RESAS, as appropriate.

WP Coordinator:

1. Identify ongoing opportunities to ensure the Theme Vision is realised.
2. Responsible for monitoring progress and KE activity of the WP against agreed and timetabled activities/deliverables/events and reporting to the TMG.
3. Organise and chair meetings of the *WP Management Group* (WPMG) consisting of RD leads, Theme Coordinator, and relevant Sectorial KE Leads.
4. Organise WP meetings (all staff working in the WP will be invited), to review research progress and assessment of synergies across the WP portfolio.
5. Coordinate the collation of material and reports in advance of annual reporting according to the reporting processes prescribed by RESAS.
6. Discuss opportunities for, and delivery of, KE at the WP level with the Theme Coordinator and relevant KESLs, and contributing to decision-making on whether this activity might be escalated to either Theme or CKEI levels.
7. Responsible for dealing with issues that have not been resolved at RD level.

RD Coordinator:

1. Identify ongoing opportunities to ensure the Theme Vision is realised.

2. Responsible for monitoring research progress within the RD against agreed and timetabled activities/deliverables/events and reporting to the WPMG.
3. Coordinate the collation of material and reports in advance of annual reporting according to the reporting processes prescribed by RESAS.
4. Responsible for dealing with issues arising at RD level.
5. Responsible for implementation of Data Management and IP Plan, and for dealing with issues arising at RD level.

Specific working arrangements
Theme 2 covers plant and animal health, animal welfare, sustainable improvements to productivity and to the resilience of rural communities in the face of change. The Theme has the following work packages (WPs):

- WP 2.1 – Crop and grassland production and disease control
- WP 2.2 – Livestock production, health, welfare and disease control
- WP 2.3 – Productive and sustainable land management
- WP 2.4 – Rural Industries

The science of each WP is delivered through Research Deliverables (RDs), totalling 32 for the Theme. Theme 2 is the largest of the 3 themes in the SRP. WP2.3 and RD2.3.12 are key integrative elements of Theme 2 that link with the integrative elements of Themes 1 and 3.

A2 Theme 2
This document sets out research proposed by Moredun Research Institute (MRI), Scotland's Rural College (SRUC), James Hutton Institute (JHI), Rowett Institute of Nutrition and Health (RINH), and Biomathematics and Statistics Scotland (BioSS) in response to the RESAS invitation to tender (ITGF) on the Theme (2) of "Productive and Sustainable Management of Rural Economies".

A2.1 Strategic Relevance (Plain English Statement)
The ultimate aim of Theme 2 is to provide the science needed for Scotland to improve the efficiency of production of good food whilst protecting the environment, rural communities and animal welfare. The science is useful to a broad range of end users, from government to businesses, and we will engage with end users to seek opportunities for the science to be put into practice and for Scotland to benefit. By doing so, we aim to strengthen the performance and sustainability of agricultural systems in Scotland. Theme 2 delivers the tools (e.g. disease control, welfare and genetic tools), component science (e.g. microbiology, physiology, behaviour and ecology), integrative concepts and approaches (e.g. systems and socio-economic approaches) and their applications and demonstrations in rural communities and environments that are needed to support the Scottish Government's strategies and policies relating to the productive and sustainable management of rural economies. This helps deliver the Scottish Government's single purpose "sustainable economic growth". The research in Theme 2 provides the evidence base underpinning resource use efficiency and the production of increased amounts of good food from agricultural land (e.g. sustainable intensification) to improve the competitiveness of Scotland's rural economies, and to help Scotland become a "Good Food Nation", including through the activities of Scotland's Food Commission. Disease (amongst others) is a key challenge to resource use efficiency in agricultural production and the depth of research of Theme 2 tackles that challenge at all scales, from understanding host-pathogen interactions to explaining patterns of infection in the

environment to informing disease control strategies. As well as improving efficiency, disease control also delivers 'win wins' associated with human health, animal welfare, profitability, and reductions in green house gas emissions. Significant improvements in resource use efficiency have already been realised (including from MRP research in previous SRPs), for example in breeding and genetics. Theme 2 aims to continue these trajectories, as well as improve rates of return through new innovations and thus improve the competitiveness of Scotland's agricultural production and rural economies.

The Scottish Government's economic strategy (2015) aims to deliver sustainable economic growth through four main priorities: Long-term sustainable **investment**, growth based on **innovation**, an **international** outlook and focus, **inclusive growth** promoting a fair and inclusive jobs market. The proposed research programme takes place during a dynamic period of significant change for agriculture as the Common Agricultural Policy creates a 5 year transition to fully regionalised payments. This once in a generation redistribution of funding may have significant long-term structural effects on the agricultural industry and as such it is one of the key drivers over the research period. The outputs from Theme 2 will help make strategic decisions at local, national and international scale more informed, efficient and equitable. They will contribute to sustainable economic growth through the above priorities and help deliver the key National Performance Framework (NPF) indicators and targets: Wealthier and Fairer, Healthier, Safer and Stronger, Smarter, Greener. Multiple other government (Scottish, UK and EU) policies seek to improve land management and promote rural industries through the development of more efficient and resilient food crops, healthier and more productive animals and improved farming practices. The policies embodied within The Animal Health and Welfare Framework (2015), Recipe for Success - The Scottish Food and Drink Policy (2009), Scottish Plant Health Strategy (2014/5) and proposed Plant Health Centre of Expertise (both in development), and the Scottish Rural Development Programme (2014-2020), amongst others, create the environment in which the targeted and policy-relevant research found within this Theme can make a significant impact. In the broader context policies such as the UK Cross-Government Food Research and Innovation Strategy (2010), the Cross-Council vision for Food, Nutrition and Health research (2015), BBSRC Research in Food, Nutrition and Health 2015-2020, The Food Standards Agency Strategy (2015-20), European Union Animal Health Regulations (due 2016), EU Plant Health Directive 2000/29/EC, EU Statutory Mandate on Integrated Pest Management (IPM) (2014), European Food Safety Authority Science Strategy (2012-16), Tree Health and Plant Biosecurity Action Plan (2011), UK Strategy for Agricultural Technologies (2013), UK Plant Health Risk Register (2014), Plant Biosecurity Strategy for GB (2014), Animal and Plant Health in the UK (2014) and Foresight. The Future of Food and Farming (2011) all address widely accepted international issues for agriculture in the areas of animal and plant health and disease, sustainable agriculture, food production and security. These demonstrate that there are many shared areas of interest in the productive and sustainable use of land that are intimately connected to the research proposed in this Theme and provide ground for additional collaboratively-funded research at a national and international level.

A2.2 Collaboration, Co-ordination and Networking within the Theme
Face-to-face DEC meetings involving the Theme Coordinators and the CKEI Director will be timetabled prior to SAG meetings (2 per annum). The meetings will be scheduled sufficiently in advance for DEC members to be able to assess and react to the information provided by the Theme Coordinators and the CKEI Director, and thereby support SAG in forming a strategic view. DEC will also have scheduled monthly meetings by video conference, which the Theme Coordinators will attend and contribute to, thereby allowing an appropriate oversight and integration of activities within the SRP. At the face-to-face DEC meetings prior to SAG, identification of new challenges, technological advances and opportunities for co-funding will take a central role. The Theme Coordinator will provide DEC with a summary of progress, including identification of problems and potential solutions, but also highlighting opportunities for greater integration within and between Themes. The Programme Advisors, with their pan-SRP role, will also play an important part in identifying opportunities for greater integration across all activities. Information will be provided verbally, supported by audit information arising from WP/RD progress monitoring. Updates on KE at Theme level, incorporating information from WP and RD leads, will be provided by the relevant Sectorial KE leads and by the Theme Coordinators, who will be working closely with the CKEI Director.

Theme 2 has many linkages with the other Themes, CoEs and the wider Scottish Universities (see Appendix A for a list of specific HEI projects linked to Theme 2) and these are evidence of a cohesive programme of research across the Scottish Government spend. Specific linkages are detailed within the RDs and cross-referenced to highlight the flow of information through the SRP and to the CoEs. Overall these linkages represent a net delivery of outputs from Theme 2 to the other Themes and CoEs. Reporting on these interactions will be a fixed agenda item at the biannual Theme meetings (see below). Discussions with other Theme Coordinators will identify specific topic meetings to be held with relevant PIs in the participating Themes. The Theme will be managed by a Theme Management Group, the core of which will comprise the Theme Coordinator, the 4 WP leads, and Sectorial KE leads. The Theme Management Group meetings are likely to include more than one Sectorial Lead due to the breadth of research encompassed in Theme 2 (see below).

Theme 2 Management Group Structure:
- Theme 2 Coordinator (Chair)
- Sectorial KE Leads (where relevant).
- MRP Theme 2 Representatives (where not represented by WP Coordinator)
- Theme 2 WP Coordinators
- Programme Advisor(s) [to provide linkage across WPs and Themes]
- RESAS Science Advisors

The Theme Management Group (TMG) will be responsible for the strategic direction of the work and will be accountable for the delivery of outcomes (including KE), will discuss issues arising within Theme 2, and will be the arbitrator where decisions within or between WPs are required but cannot be reached by other means. Where issues persist, the DEC will be the final arbitrator. The Theme Management Group will meet at least twice annually and have the responsibility to:
1. Build a shared vision within and between the Themes and across the SRP
2. Provide overall co-ordination (financial, administrative, and intellectual);
3. Communicate with, and report to, DEC.

4. Co-ordinate and ensure consistency and excellence in the science, and;
5. Communicate with and to a wider stakeholder community through integration with Sectorial KE Leads and with the CKEI.

WP Management Group structure:

- WP Coordinator (Chair)
- MRP WP Representatives
- RD Coordinators
- Programme Advisors
- RESAS Scientific Advisors
- Sectorial KE leads

WP Coordinators will be expected to be pro-active in ensuring that opportunities for collaboration are exploited. Identifying these opportunities will be a fixed agenda item for the WP meetings with the Principal Investigators (PIs) responsible for Research Deliverables (RDs). In addition there will be an annual workshop for PIs, post-doctoral scientists and post-graduate students, where the emphasis will be on developing innovative approaches arising from trans/interdisciplinary linkages. This will include generation of new ideas for the 'Think Tank' – a mechanism for developing agenda-setting concepts from the RESAS programme (see CKEI tender).

Collaboration, Co-ordination and Networking with CAMERAS and the wider community

The research proposed within Theme 2 aims to promote animal health and welfare, minimise disease impacts on our crops and promote successful, sustainable enterprise that improves our environment and food security. These aims are shared with other external organisations including members of CAMERAS and the wider scientific community in the UK, Europe and beyond. In response to feedback from stakeholders we will create bespoke KE structures, in collaboration with the Sectorial KE Leads, across WPs to simplify engagement and facilitate their interactions with researchers. These structures will produce regular reports of progress and outcomes, host regular KE events as detailed below, and will link closely with the indicative activities within the CKEI. The delivery of these will be refined in consultation with stakeholders throughout the programme.

Interaction with Underpinning Capacity

Individual interactions between the research outlined within Theme 2 and the "Underpinning Capacity" element of the SRP funding are outlined in each of the RD submissions within the Theme. In general, however, the research will involve the use of data, animal, plant and pathogen collections held within the MRPs and make use of facilities such as glass houses, containment facilities and specialised animal accommodation, Balruddery Centre for Sustainable Cropping etc. that are maintained by the MRPs, entities that are supported by the "Services" stream of funding available under Underpinning Capacity. BioSS consultancy Underpinning Capacity will support all of the Theme's research as and where required. "Platform" and "Seedcorn" funding will be used to support and expand the science base of the MRPs, particularly supporting early stage scientists, both pre- and post-doctoral to explore topics that relate to the wider programme or which will exploit new opportunities that arise during the programme either as a direct result of the SRP or because of advances elsewhere. To ensure effective "Support to Policy" key individuals within the Theme will be identified to act as an information conduit from the Theme to policy colleagues within government. This will also involve liaising with the CKEI to ensure that the key messages from the research are disseminated appropriately and as widely as possible.

Management of annual reporting

Annual reporting will be delivered according to the processes and requirements detailed by RESAS at the time, and within the Theme will build on the lessons learned during the current SRP. The production of metrics, as applicable, progress reports and narratives will see the WP and Theme Management Groups working closely with the Programme Advisors. Metrics will be collated by each of the MRPs, and a SRP-wide database of outputs will be developed and held by the CKEI and Programme Advisors. This will ensure that cross-Theme referencing is complete, consistent, and accurate. The progress of activities within each RD will be monitored routinely by the relevant RD and WP Coordinators, with RD Coordinators providing the WP Coordinator with summaries of scientific progress, key outputs and reporting with respect to the proposed schedule. Updates will be provided at meetings of the Theme Management Group. This communication process will begin to identify narratives that are suitable and sufficiently developed to be included in the Theme level reporting. Accordingly, individuals will be identified to draft the details as required at the time of reporting. Final editorial responsibility for narratives and their submission will lie with the Theme Coordinator, acting on behalf of the Theme Management Group, and the relevant Programme Advisor. Progress will be assessed, classified (on schedule, slight delay, significant delay) and reported as described above. Key findings, activities and impacts will be collated into a WP level report for compilation into Theme level reporting. Each MRP will follow a QA system for its contributions to reporting, with the ascending editorial responsibility of RD, WP and then Theme Coordinator. High impact narratives will be identified in the following areas: (i) Policy relevance, (ii) Industry/innovation, (iii) Scientific excellence, (iv) Leveraged external funding, (v) Collaboration and interdisciplinary working

A2.2.5 Risk Management

A common risk management structure will be implemented across the SRP at Theme and WP levels. Theme 2 and its four WPs will establish an iterative risk register. Risk management strategies for the WP will link to and be a component of the Theme level risk management. At Theme and WP Management meetings:

- The status of current risks will be assessed.
- New emerging risks will be identified and added to the register.
- Mitigation strategies will be proposed, taking into account research implications for cross programme links and external collaborations including stakeholders.
- Assessment will be agreed (e.g. tolerate, monitor, take action, escalate).
- WP management committee will send risk register updates to TMG.

A table with currently projected key risks for Theme 2 is provided below based on the following risk assessment structure. In assessing risk status, a system of **Red**, **Amber** or **Green** indicator status is used.

Risk Assessment	Description	Escalation
High	Showstoppers - risks that are extremely likely to occur and would have a very serious impact on delivery.	All red risks must be escalated by the risk owner to Programme Advisors who will immediately consult with risk owner and theme coordinator and report to DEC.
Medium	Risks that could potentially become showstoppers if not effectively managed and monitored.	Responsibility of risk owner to manage and monitor these risks, providing updates to the relevant Management Group through the highlight and exception reports. Immediate escalation to

		Programme Advisors if an amber risk is re-assessed as red.
Low	Low risk that requires minimal management, although monitoring is still required.	Responsibility of project owner to manage and monitor these risks. If reassessed as amber they must be reported to the relevant level Management Group through the highlight and exception report.

Risk Descriptor	Risk Level	Impact	Risk owner	Controls
Significant reduction in budgets	**MEDIUM**	**HIGH**	**DEC**	RD content to be renegotiated with SG, and consequences agreed with partners
Staff turnover or long term absence due to ill-health	**MEDIUM**	**LOW-HIGH**	**RD, WP, Theme Coordinator**	Identify early, discuss with RD/WP Groups – option to cover with existing staff or recruit on temporary or permanent basis
Divergence in stakeholder and research priorities	**LOW**	**LOW**	**WP, Theme, KE Coordinator**	RESAS, DEC, Advisory Group to help clarify interface between the commissioned research programme and stakeholder priorities.
Divergence in priorities between partner MRPs and perspectives on optimal delivery	**LOW**	**MED-HIGH**	**RD, WP, Theme, Coordinator**	Early identification of potential issues through discussion at Theme Management Group. Option to report to DEC for resolution.

Each of the partners recognises that risk control is an integral part of good management and therefore is committed to achieving best practice with audited structures, procedures and protocols in place. Thus, the majority of risks fall to the management of the individual organisations that are all accredited to ISO9001 and ISO14001 standard, or working towards these. The hazards that threaten the success of the proposed work and the proper delivery of Theme 2 have been discussed in the development of the tender. Key risks that have been identified relate to communication failures and external factors affecting delivery. These risks will all be controlled through the described management arrangements and risk ownership will focus on the TMG. The TMG will act impartially to resolve any conflicts and will communicate with both the partner organisations and RESAS on a regular basis to ensure responses to identified risks are proportionate and that any problems are overcome. Any conflict that cannot be resolved through the above mechanisms will be referred to the DEC.

A2.3 Impact and Knowledge Exchange

The MRPs welcome the creation of the CKEI to facilitate a step change in KE activity from the SRP to maximise the impact for a range of beneficiaries with responsibilities for policy, practice, industry and in civic society, particularly in the priority areas of the Scottish Government Economic Strategy of investment, innovation, inclusive growth and internationalisation. KE activities will take place at all levels of the SRP, at RD, WP and Theme, as well as the CoEs and Innovation projects, all being guided by the CKEI, with interactions being facilitated through the sectorial leads. All activities will be complementary to ensure best value for

money and to avoid duplication. Within the RDs KE will be geared towards the timely and successful completion of milestones and deliverables as laid out in RD detailed work plans, whereas at WP level interactions with wider stakeholder groups will take place through a range of dissemination/media tools. Building on existing relationships, with for example livestock and/or arable farmers, growers, levy bodies and policy makers, specific stakeholder events will be run to assist in the development of, and obtain feedback on, identified research outputs. Exemplars of such would be “Cereals in Practice”, “Fruit for the Future” and “Livestock Health Roadshows”; others are detailed in the WP documents. Informal meetings or themed workshops with specific stakeholders will also be a key feature, responding to stakeholder demand and focus (e.g. SG Animal Health & Welfare Board). The CoEs (CXC, CREW and EPIC) synthesise evidence from the SRP and other sources for use by the policy teams within SG. Much of this work is by “call-down” in which information is requested within a specified time frame, typically 3-6 months, but there are also a number of projects designed to address longer term policy questions, typically 1-2 years in duration, and which link to work in the SRP – These are outlined in the relevant WP and RD documents.

The CKEI will provide the overarching KE strategy for the Themes (outlined in the CKEI tender document). Examples of where and how Theme 2 will contribute to the proposed activities are listed below:

	CKEI Indicative Activity	**Example contributions from Theme 2**
2	Visibility, branding and collective identity	Provision of material for the centralised WWW site and CKEI media outlets
3	Launch of CKEI and promotional tour	Identification of suitable topics, staff and provision of material for the launch and tour.
4	Annual campaigns relevant to stakeholders/policy	Annual “In Practice” events and Animal Health Roadshows
5	Annual showcase event	Provision of speakers for plenary sessions and organisation of breakout groups on specified topics.
6	Think tank: science without boundaries	Proposal of Think Tank topics
7	Practitioner workshops and staff training opportunities	Training workshops for SQPs; animal welfare practitioners
8	Leadership programme for early career researchers	Identification of suitable junior staff, and contribution to leadership training activities by senior staff.
9	Work shadowing, secondments, residencies	Identification of staff for all of these in specific policy areas.

KE impact will be trackable and reportable, and will contribute to an accessible and useable legacy of the 2016-2021 Programme. We recognise that impacts can take effect over different time periods, from short-term actions resulting from use of specific products, to adoption and implementation of ideas and knowledge over the longer time. The principal indicators of impact will be evidence of:

- Influence on the aims, content or implementation of public policy, including new policy, changes in policy, or continuation of existing policy
- Changes in practice by stakeholders
- Awareness of Theme research and findings, and uptake of products
- Additionality through funding for complementary areas of research (e.g. EU H2020, UKRC, Innovate UK)

Metrics for monitoring these indicators will be embedded in processes of information capture, and ongoing development of good practice in evaluation.

Name of WP: 2.1: Crop and grassland production and disease control

Overview

Key Scottish Government policy documents (e.g. Scotland Economic Strategy, Recipe for Success, Becoming a Good Food Nation, Scottish Rural Development Programme, CAP) show that crops are sustainable (economic, environment and social) and profitable routes to delivering policy priorities including: “business viability and competitiveness”, “continued economic growth”, “local food”, “adaptations to mitigate climate change” “Secure and resilient food systems” and “Crop diversification (CAP)”. Encouraging innovation and nurturing Scotland’s natural assets are actions at the heart of Scotland’s recently up-dated Economic Strategy (March 2015). For successful delivery of these priorities to the public sector, commercial sector and civil society, a significant and aligned research and translation effort is required at the crop and disease level. The research programme will build on the major discoveries and technical advances achieved during the current Strategic Research Programme, particularly current work packages (CWPs) 5.2, 6.4 and 7.2 and the Food and Drink Strategic Partnerships. We will maintain the current level of high impact and topical publications, targeted and effective knowledge exchange, and delivery of products that are crucial for our ability to leverage external grant income and extend our impact on policymakers, industry and scientific end-users.

The key aims of the Work Package (WP) 2.1 are therefore:

To deliver, against a background of environmental change, to sustainable intensification, food security and improved agricultural practice through:

- The provision of crop cultivars and varieties with improved quality, yield and resource efficiency traits, which are resilient to key biotic and abiotic stresses with a focus on barley, potato and soft fruits.
- Integrated Pest Management systems which translate an understanding of plant-pest interactions, host resistance, epidemiology and new disease threats, supported by the use of monitoring, modelling and diagnostic technologies to improve crop performance.
- Outputs that contribute to more efficient production systems, healthier soils and more sustainable rotations delivered through the uptake of best practice by stakeholders facilitated by close stakeholder interactions and co-ordinated KE strategies.
- Realising the potential of novel and minor crops that could underpin the circular or bio-economy by developing novel methods and approaches to support their integration into existing rotations, practices, processes and supply chains.
- Research that is underpinned by the best use of resources and technologies including germplasm and pest collections, computational analyses, statistical modelling, diagnostics, and metagenomics.

Coordination and Management

Work package structures

This is a broad-ranging interdisciplinary WP that involves a co-ordinated cross-MRP approach. Collaboration and networking across the WP, MRPs and within the SRP will require an effective management structure. Responsibility for co-ordination of WP activities and overall delivery will be under the auspices of the WP Coordinator who will ensure that the WP maintains its position at the leading edge of innovation in crop science. Each of the eight ‘research deliverables’ (RDs) within WP2.1 will have a PI

appointed as RD Coordinator who will manage activity in that RD and be responsible to the WP Coordinator for meeting all objectives. PIs working on objectives within a deliverable will report to their RD Coordinator to ensure that the agreed project direction is adhered to, and will monitor project progress against the timelines shown in RD Gantt charts.
The WP2.1 management team (WPMT) will be chaired by the WP2.1 co-ordinator and will contain the RD Coordinators, at least one KE sectorial lead (e.g. crops/soils) and a BioSS representative who will provide linkage to the relevant BioSS research and consultancy managers. The WPMT will meet on a six-monthly basis, using online collaboration facilities where feasible. RESAS Scientific Advisor and Programme advisors will be invited in order to review progress and provide steering advice. Work Package meetings will partly focus on management issues (monitoring of progress against objectives for all RDs, investigating opportunities for collaboration within and between Themes, resolution of problems, reporting of progress and exceptions to the Theme 2 management group (in accordance with arrangements outlined at Theme Level). However, a greater emphasis of the WP meetings will be on discussing the on-going RD science against the backdrop of developments in crop plant science and the development of WP KE outputs. This may be done through selected scientific presentations or workshops and sessions devoted to the discussion of emerging issues of scientific or policy relevance. Minutes of WP meetings will be communicated to staff in the WP and to other WP co-ordinators to ensure transparency and a vibrant, but not over burdensome, collaborative interchange of ideas and updates within and across the RDs, WPs and Themes. Additionally, there will be an annual workshop to develop innovative approaches arising from trans/interdisciplinary linkages (see Theme level document).

Aside from the day to day interactions of the research partners, collaboration, co-ordination and networking opportunities will be facilitated at the Theme level and through the CKEI via the KE sectorial leads. Contacts for KE in each RD will be identified and will be responsible for identifying major KE events in their areas of work for inclusion in these events. It will be the responsibility of individual PIs, together with the KE sectorial leads, to identify potential KE activities. The interactions of RDs within WP2.1, between work packages and themes are illustrated below.

RD interactions within WP2.1

Informs ↓	Informed by →	RD 2.1.1	RD 2.1.2	RD 2.1.3	RD 2.1.4	RD 2.1.5	RD 2.1.6	RD 2.1.7	RD 2.1.8
	RD2.1.1		■		■			■	■
	RD2.1.2	■		■			■	■	■
	RD2.1.3	■	■		■				
	RD2.1.4			■		■			
	RD2.1.5			■	■				
	RD2.1.6	■	■	■	■	■		■	
	RD2.1.7	■	■						■
	RD2.1.8	■	■						

WP2.1 linkages within and across themes

Theme 2: **Productive & Sustainable Land management**									**Theme 1:** **Natural Assets**		**Theme 3** **Food, Health and Wellbeing**	
WP2.1 **Crop & Grassland production and disease control**	**WP2.2** **Livestock prod., health, welfare, disease ctrl.**	**WP2.3** **Agricultural Systems and Land Management**						**WP2.4** **Rural Industries**	**WP1.1** **Soil**	**WP1.3** **Biodiversity and ecosystems**	**WP3.1** **Improved Food and drink production**	**WP3.2** **Healthy diets & dietary choice**
RD2.1.1 Genetic Diversity of Crops		RD2.3.2 Protecting genetic diversity	RD2.3.3 Disease Threats in the Envt		RD2.3.9 IMS		RD2.3.12 Uptake of best practice			RD1.3.1. Biodiversity & ecosystem function	RD3.1.1 Improving Scottish primary production RD3.1.2 Improving food & drink production	RD3.2.2 Dietary components of healthy diets
RD2.1.2 Crop Genetic Improvement												
RD2.1.3 Plant-Pest interactions	RD2.2.5 Vaccines RD2.2.4 Diagnostics											
RD2.1.4 Plant-Pest Epidemiology											RD3.1.3 Food safety	
RD2.1.5 In-field Detection	RD2.2.4 Novel Diagnostics											
RD2.1.6 IPM				RD2.3.8 Alternative approaches to sust. land mgt.		RD2.3.11 Trade-offs productivity & sust.						
RD2.1.7 Plant-soil-water int.		RD2.3.4 Sust. soil & water mgt.							RD1.1.1 Soil & its ecosys functions		RD3.1.1 Scottish primary production	
RD2.1.8 Novel Crops								RD2.4.3 circular economy				

WP2.1 will benefit from and contribute to Themes and WPs within the Strategic Research Programme as illustrated in the table above. Primary links are with i) WP2.3 – Agricultural Systems and Land Management. Other major links are with ii) WP1.1 – Soil, iii) WP1.3 Biodiversity and Ecosystems iv) WP3.1 Improved Food and Drink production, WP3.2 Healthy Diets & Dietary Choice and v) WP 2.4 Rural Industries. Research within WP2.1 has been co-constructed by the MRPs involved to ensure coordinated research programmes at the RD level and specific routes of delivery to stakeholders by linkages to other relevant WPs. As an example, work in RDs 2.1.1-8 delivers to RD2.1.6 (IPM), which links through to RD2.3.9 (IMS) and RD2.3.12 (uptake of best practice). Close working relationships within and across MRPs, fostered by a collaborative approach to delivering research to answer specific stakeholder needs and underpinned by a focused WP and Theme management strategy will ensure maximum impact of the programme.

Collaboration, co-ordination and networking

Threats from both indigenous and non-indigenous pests/pathogens arising as a consequence of climate change and/or globalisation are of particular relevance to RDs 2.1.1-2.1.6 and will be considered in close partnership with RD2.3.3 and with CAMERAS partners including SASA and the Forestry Commission. This networking will take place as part of existing networks such as the Plant Health Forum and are anticipated to fall within the remit of the proposed Plant Health Centre of Expertise, which will provide a focus for many of the activities of plant disease work within WP2.1 and also linking to Forestry Commission and other relevant organisations. Additionally, delegations of the WPMT will continue the series of meeting between crop scientists involved in CWPs 5.2 and 6.4 and SG policy officials to ensure a two-way communication of findings and new developments.

Particularly relevant to WP2.1 will be interactions with industry leadership organisations: Scottish Whisky Research Institute, Potato Processors Association, Scotland Food and Drink, Food Standards Scotland, the Scottish Government Food and Drink and Rural Communities Division and the AHDB. Engagement with, and cross fertilisation between, the Scottish Government funded programme (WPs, Themes and including the centres and innovation platform projects where appropriate: see below) will utilise the scheduled programme of events identified in the RD work plans and WP management (and those in other WPs and Theme levels descriptions) plans. Senior PIs involved in delivering WP2.1 will continue to sit on external committees such as EPSO, Agritech, BBSRC review panels, IBioIC and Industrial Scientific Advisory Boards in order to influence the crop science research agenda nationally and internationally, to ensure SG interests are at the heart of developments in this arena.

Interaction with underpinning capacity

WP2.1 will have strong interactions with underpinning capacity (UC) activities. The UC plant (barley, soft fruit and potato), pathogen collections and Centre for Sustainable Cropping provide exciting new opportunities for the planned science programme. The interaction with UC will be an important element in the WP2.1 management and interaction plan detailed below. The WP Coordinator and the PIs leading the UC plans are co-located in the same MRP ensuring regular and fruitful collaboration and interaction. Furthermore, there are common staff leading and/or delivering on the planned outputs of WP2.1 RDs and the UC activities thereby further ensuring effective links to those resources will be made, maintained and managed. Funding for BioSS inputs of a collaborative or advisory nature will be provided as described at the Theme level through Underpinning Capacity Function 7, "Provision of Biomathematical & Statistical Consultancy Services". Management inputs will be provided through identification of a BioSS WP Representative, who will be invited to WP level meetings and be involved in the preparation of annual reports and KE activities. Although many interactions between staff in BioSS and the MRPs have a long history and function effectively, the nomination of a BioSS WP Representative will ensure that no scientist contributing to the WP is left without a point of contact in BioSS. In addition, the BioSS WP Contact will be well placed to maintain a watching brief over BioSS-MRP interactions in the WP and to identify gaps in coverage or other mismatches between resource and demand, which will be discussed with the BioSS Theme Representative along with other appropriate managerial staff in BioSS and the MRPs.

WP level structures and the annual reporting cycle

The WP 2.1 management and interaction work plan is shown below:

Programme Year	2016-17				2017-18				2018-19				2019-20				2020-21			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
WP Meetings		■		■		■		■		■		■		■		■		■		■
RD Meetings	■		■		■		■		■		■		■		■		■		■	
Stakeholder Meetings & Workshops				■			■			■				■	■			■	■	
UC and Centres Engagement		■		■		■		■		■		■		■		■		■		■
Update and Progress Reports		■		■		■		■		■		■		■		■		■		■

Additionality

Ability to leverage external funding: RESAS funding has helped to raise >£25M for the Hutton and SRUC crop and pathology based funding over the past 3 years. We fully expect this leverage to be maintained and ideally increased significantly (e.g. Research Council UK [if Hutton eligibility is ensured], Innovate UK, Agriculture and Horticulture Development Board, EU and the agrochemical and breeding industries).

Interdisciplinarity: The WP is innately interdisciplinary and will facilitate successful policy, science and economic delivery. The work will include a range of disciplines including modelling, statistics, cell biology, crop genetics, microbiology, ecology, genomics, bioinformatics and molecular biology.

Collaborative working out-with the MRPs (e.g. with HEIs, NGOs, Industry): numerous non-MRP collaborators (including commercial) in UK, EU and globally. Nationally includes Scotland Food and Drink Ltd, Food Standards Scotland, National Farmers Union Scotland, BOBMA, Scottish Food and Drink Federation, SASA, FERA, AHDB, Department for Environment, Food and Rural Affairs , Higher Education Institutions , East coast Scotland Farm Network; EU includes numerous industries and networks such as DISCO, PURE, ENDURE (IPM) and Euroblight. Globally includes micro to global international industries (e.g. potatoes, barley, oats, fruit, and crop protection) and CGIAR centres (International Maize and Wheat Improvement Center (CIMMYT), International Potato Centre (CIP). There are also links to scientists in institutes such as John Innes, Rothamsted, IBERS, East Malling and NIAB. A number of HEI-collaborative projects will also be funded through the Programme, with the intention of additional future external funding support.

Delivery to Policy: The proposed plan delivers to multiple aspects of policy as outlined in the Theme 2 document and includes: Recipe for Success/Becoming a Good Food Nation, Scottish Rural Development Programme [SRDP] and Common Agricultural Policy [CAP]. There will be close alignment with delivery to the plant health policy division through the Scottish Plant Health Strategy, the Plant Health Centre of Expertise, SASA, Fera and policy workshops and advice. Previous research has directly influenced plant health legislation in Scotland, e.g. *Dickeya*. At a UK level the research delivers to the Tree Health and Plant Biosecurity Action Plan (2011), The UK Strategy for Agricultural Technologies (2013), The UK Plant Health Risk Register (2014), Plant Biosecurity Strategy for GB (2014), Animal and Plant Health in the UK (2014) and plant health as one of four policy priorities in DEFRA. Relevance at the EU level includes European Food Safety Authority [EFSA], EU Plant Health Directive 91/414/EEC (1991) and EU Statutory Mandate on Integrated Pest Management (IPM) (2014). Additional links include groups that inform pesticide policy such as FRAG-UK (informing Chemical regulations Directorate (CRD).

Delivery to Innovation/ commercialisation: The WP has the potential to deliver new IP to the Scottish economy particularly if co-constructed with industry. Numerous innovations including gene markers, crop varieties and associated downstream products, novel diagnostics, precision monitoring tools (pest traps), bio-pesticides, elicitors, resistant cultivars and systems for their development, biotechnology, semio-chemicals and techniques to develop them.

Contribution to 'science agenda-setting' issues: The adoption of an interdisciplinary approach could/should shed light across the food and drink supply chain on drivers of delivering improvements in food and drink production and sustainable health diets. It will also inform issues relating to plant health and sustainable production. This interdisciplinarity will be used to propose projects and, as relevant, contribute expertise to the CKEI Think Tank projects

Contribution to Internationalisation: All the areas identified will deliver to, and are highly relevant for, global and EU food security agendas, and be the efforts will be leveraged internationally for further research and translation. Via the identified scientists and research groups this RESAS funded research will be delivered on international platforms and the principles tools, technologies and approaches exploited therein.

Key risks to delivery and management

The risk management strategy for the WP will be aligned with the Theme level strategy through the establishment of a risk register which will be revised and updated on an annual basis. The WP and Theme level meetings will be used to assess the status of current risks and to identify emerging risks, which will be added to the risk register. In the event of problems arising, the management team and key partners will develop a number of proposed mitigation solutions, taking account of the implications for the research, cross-programme linkages and external collaborations including the implications for stakeholders. From these, a course of action will be agreed (e.g. tolerate, monitor, take action, escalate) and will include consultation with RESAS if appropriate. A number of possible risks and responses are identified below:

Risk Descriptor	Response
Loss of specific staff expertise due to staff movements	Risk Owner: WP team Mapping of staff expertise within and between RDs and WPs. Management by WPMT, escalate to Programme Advisors for report to DEC if amber risk is re-assessed as red. Re-direction of work (DEC in consultation with RESAS) if necessary
Delayed delivery due to dependencies of inter-disciplinary working	Risk Owner: RD and WP teams Regular RD and WP meetings to anticipate issues, review Gantt charts. Escalate to Theme Coordinator if re-assessed as amber.
Budget reductions	Risk Owner: Theme, MRP/DEC Work programmes renegotiated and consequences agreed with SG
Divergence in stakeholder and research priorities	Risk Owner: WP team Identify divergence, consult with Programme Advisors and SG on implications and required changes to programme

Impact and KE

A key function of the WP management team (WPMT) will be to co-ordinate impacts and KE emerging from WP2.1. The WPMT will interact, through the KE sectorial leads, with the CKEI which will oversee the main KE events and orchestrate input from other associated WPs including 1.1, 2.3 and 3.1 and will link to, and be coordinated with, Theme 2 KE activities The WP will also provide contributions to the CKEI Think Tank development of options for cross-strategic programme Horizon Scanning and Agenda Setting projects. In addition to Think Tank, WP2.1 KE will contribute to many of the CKEI indicative activities, in particular activity 5 (annual showcase events. These themed events attract all the relevant industry including Cereals in Practice, Potatoes in Practice, Fruit for the Future (all include growers, agricultural consultants and advisers, propagators, packers, processors, plant health inspectors, SASA, policy, representatives from levy boards, retail groups, trade press, crop and horticultural society members, breeders, producers from overseas, industry-leading companies, and to a lesser extent the public), LEAF Open Farm Sundays (public), and SRUC's annual 'Success Through Knowledge' events comprising regional field open days and winter workshops (the SRUC knowledge transfer programme has audiences comprising growers, agricultural consultants & advisers, representatives from levy boards, farming press, NFUS representatives) in conjunction with AHDB and the Hutton. Our work will also continue to be communicated at high profile grower and public events such as 'Cereals' (as for industry events above), the Royal Highland Show (public, growers, merchants, scientists, agronomists etc.) Crop Protection in Northern Britain and Crop Protection in Southern Britain (merchants, processors, seed breeders and providers, industry-leading companies, agronomists, scientists and government), Dundee Food and Flower Festival and science festivals (public). Field events including the 'Potatoes in Partnership' farms (mainly targeting growers and agronomists) will be held on a yearly basis to showcase our latest research findings. Industry and academia will also be brought together in a series of workshops (initially supported by the Scottish Society for Crop Research) specifically targeted around opportunities for joint funding, e.g. AgriTech, Horizon2020, AHDB, allowing industry priorities and cognate academic capabilities to be identified.

In addition to the larger events as listed above, which consolidate research messages coming from the WP/Programme as a whole, science leaders are actively involved in presenting at events at all levels, from international and national science conferences and workshops to schools, Rotary and Probus Clubs (public), British Science Association (scientists) and Fascination of Plants days. Advice is regularly provided to key industry vehicles such as CEL Recommended List Committees, Scottish Whisky Research Institute, Scottish Society for Crop Research, AHDB, etc., and to policy through groups such as the Scottish Government Agriculture and Climate Change Stakeholder Group and, where appropriate, through direct collaboration with the CAMERAS and other relevant organisations (e.g. SASA, Forestry Commission). A series of peer-reviewed science publications, general media and grower magazines (including Scottish Farmer), as well as contributions to annual updates of guides including the AHDB barley growth guide, FRAG-UK stewardship guidance notes, SRUC technical notes, the AHDB-Potatoes publication 'Grower Gateway', information leaflets and advisory notices, will be produced throughout the WP. Regular meetings between Agriculture and Rural Development Division, CAP Reform & Crop Policy with SRUC staff will be ongoing, providing an opportunity to disseminate relevant information from the research of importance to crop policy. Delegations of the WPMT will continue the series of meetings previously established between crop scientists involved in the 2011-2016 SRP, SG policy officials and SASA to ensure a two-way communication of findings and new developments.

Measures to maximise impact at the WP level will also include meetings with MRP commercial divisions to discuss commercialisation of outputs. The WPMT will ensure that relevant MRP commercialisation managers are aware of potential intellectual property arising from WP2.1 that may be protected either using commercialisation funding or by identifying interested commercial partners who are potential customers of the IP.

Quality Assurance

The MRPs are dedicated to achieving and maintaining the highest possible standards of quality in order to meet the requirements of their work and the needs of their internal and external customers. To achieve this they will:

- Comply with the requirements of the Joint Code of Practice (March 2012) on behalf of quality assurance and the BBSRC Statement on Safeguarding Good Scientific Practice.
- Operate a quality management system that meets the requirements of the ISO 9001:2008 and which is systematically maintained, reviewed and revised to ensure continuous improvement.
- The relevant Quality Management Systems, or equivalents, in each Institute will ensure:
    - Compliance with the requirements of customers and official bodies.− Plan and develop standard work processes by means of Standard Operating Procedures, where required.
    - Monitoring of quality performance through internal and external auditing relating to the pertaining ISO standard.
    - Setting of quality objectives and targets.
    - Assign competent personnel to co-ordinate the quality management system.
- Allocate sufficient resources to achieve quality objectives and targets within budgetary constraints.
- Obtain and act upon feedback from RESAS and key stakeholders.

- Development of competency through provision of training and communication.

Ethical and Regulatory Issues

The proposed work within WP2.1 will involve the use of genetically modified (GM) organisms, imported biological materials and hazardous materials. These activities will be reviewed, approved and regulated in accordance with the relevant legislative and QA procedures.

GM organisms will be used in accordance with the Biological Agents and Modified Organisms (Contained Use) Regulations, the Genetically Modified Organisms (Risk Assessment) (Records and Exemptions) Regulations 1996 and the Genetically Modified Organisms (Deliberate Release and Risk Assessment – Amendment) Regulations 1997, and the Genetically Modified Organisms (Contained Use) Regulations 2014 ('the GMO (CU) Regulations'). Use of licensed plant pathogens and of imported soils and plant materials is governed by the Plant Health (Scotland) Order 2005, regulated by SASA for the Scottish Government. Environmental protection is enacted through the Environmental Protection Act 1990 (and amended Scotland 2001). Should data collection from stakeholders be required, it will only be done with prior approval by the Scottish Government Survey Control Unit.

Contribution to the 3R's (reduction, refinement, replacement)

The use of animals is not required for the research proposed within WP2.1.

Sustainable Development

The MRPs have Environmental Policy Statements which affirm that they are committed to adopting and promoting environmental best practice in the aims and operations of their research activities. They are committed to working practices such that the environment is not compromised, and the relevant principles set out in the links provided under the Scottish Sustainable Procurement Action Plan (Scottish Government, 2009).

To achieve this they monitor relevant aspects of their activities and make such changes as are deemed necessary to achieve a good environmental footprint. The Institute will operate a waste management strategy which attempts to minimise emissions to the environment and ensures that all relevant legislation is either complied with or exceeded.

The policies of the MRPs include:

- Regularly reviewing the environmental impacts of the research and modify processes in light of new opportunities and circumstances.
- Operating transport policies which recognises the need to minimise pollution.
- Minimising waste, promote re-use of materials and maximise recycling.
- Set environmental objectives and target, including CO2 emissions reduction
- Minimise the use of chemicals, radioisotopes and other toxic materials and to adhere to statutory regulations relating to their storage, handling, use and disposal.
- Exploring alternative technologies to improve environmental performance
- Operate an environmental management system which is systematically maintained, reviewed and revised to ensure continuous improvement. Some MRPs currently operate to the ISO 14001 standard.
- Senior management within the MRPs receive advice from Environment Committees or their equivalent.

- Ensure competency through provision of training and communication.
- Ensure that energy consumption is monitored to explore potential for reduction.

Name of RD: 2.1.1 Genetic Diversity of Crops

Research aim and key drivers

The major aim of RD2.1.1 is to develop suitably characterised germplasm resources leading to generation of crops better equipped and adapted to future climatic conditions, taking into account key areas of stakeholder concern that impact on profitability and the sustainability of Scottish crop production**.** It builds on recent developments in crop genomics, requiring expertise in germplasm development, phenotyping/genotyping, and application of crop-specific knowledge to facilitate crop genetic improvement. The specific goals are based on identifying relevant genetic diversity in germplasm and developing new phenotyping methods. This is especially important with crop plant research moving towards 'sustainable intensification' traits, reduced crop waste and resistance to biotic and abiotic threats to primary production. An ongoing challenge is the threat of future widespread unfavourable stress conditions that will cause annual losses in both yield and crop quality. The work will focus on acquisition and phenotypic and genotypic characterisation of diverse germplasm and the development of genetic tools to facilitate its use. Work will be targeted into key areas of science relevant to UK stakeholders/industry that are also important from a more global perspective (climate change, new pathogen threats, water stress, food security). In developing this proposal we have consulted widely with potential end-users. The work outlined will involve collaboration with industry. We have engaged with stakeholders, including growers, breeders, agronomists, processors, and consumer groups, ensuring that the resources developed in the project are relevant to the challenges faced by these groups.

Summary of the proposal:

Objectives and Major Activities

Our overall aim is to exploit genetic diversity in crop plant germplasm enabling production of plant varieties with improved performance, and crop systems which are more resource-use efficient. Specific objectives are to assemble the relevant germplasm, collect phenotypic and genotypic data and develop marker resources for assessing and exploiting diversity. The work will focus on traits such as yield stability and responses to changing environmental conditions, likely to put our key crops at considerable risk. We will use genetic approaches to develop crop genetic resources improved for traits that will provide a delivery vehicle for cultivars suitable for future climate change scenarios and for enhanced food security. Our approach has been shown to work extremely well in previous research programmes for production and other traits. We will develop underpinning new methodologies, such as novel phenotyping methods for abiotic stress traits and field assessment of crops, as well as novel genotyping platforms for the assessment of diversity. For barley, we will focus effort under the common theme of 'adaptation and yield stability'. In potato we will place major emphasis on abiotic and biotic stress resistances that threaten primary production, with a secondary focus on quality traits identified by stakeholders as being critical to profitability and consumer health. In soft fruit focus will be placed on traits affecting crop ripening, quality as well as responses to biotic and abiotic stresses.

Many of the outputs of RD2.1.1 directly underpin the work in RD2.1.2.

The major objectives will be:

O1 Development and acquisition of improved germplasm resources for our major crops.

O1.1 Extended barley collections for studies of adaptation. We will explore the genetic diversity within a worldwide collection of geo-referenced landrace accessions.

A primary aim is to understand the relationship between gene level haplotype structure and eco-geographic and bioclimatic variables.

O1.2 Identifying novel germplasm with stress tolerance in barley. This work will combine field experimentation with controlled environment assays to find germplasm with improved tolerance to abiotic stress. This will support identification of beneficial alleles for crop improvement.

O1.3 Establishment of a potato core collection from a diverse genebank. A working 'core' of The Commonwealth Potato Collection (CPC) will be selected and phenotyped for traits impacting on climate change adaptation, as well as new biotic threats, and traits which impact on storage and crop waste.

O1.4 Development of Backcross Inbred Line (BIL) populations for potato. Newly constructed inbred, self-fertile diploid potato genotypes will be used to construct novel mapping populations, as an aid to trait dissection and introgression.

O1.5 Novel fruit populations. The focus is to generate germplasm for crops of interest, to phenotype this germplasm, and to identify mechanisms of biotic and abiotic tolerance/resistance.

Key Deliverables: Years 1-2 O1.1i Global collection of georeferenced barley landrace accessions; O1.1ii Development of new segregating barley populations; O1.2i Phenotypic data on diverse barley germplasm; O1.2ii Identification of phenotypic plasticity to stress in barley; O1.2iii Section of germplasm and traits for further study ; O1.3i Identification of a CPC core collection (200-250) clones; O1.4i First generation of crossing for at least one donor line to the recurrent M6 genotype; O1.5i Raspberry, blackcurrant, and blackberry populations developed. **Years 3-5** O1.1iii Structure of genetic diversity across ecogeographical clines; O1.2iv Barley phenotyping to extend to combinations of stress in wider testing for resilience; O1.4ii Second generation of crossing for at least one donor line to the recurrent M6 genotype**;** O1.4iii Genotyping of BX1 generation with SNP markers; O1.5ii Soft fruit populations assessed under field conditions.

O2 Phenotyping of diverse germplasm

O2.1 Phenotyping of barley populations for sustainability traits. We will collect phenotypic data from a large 'global' collection of barley landraces with an aim of understanding relationships between genotypic and eco-geographic/climatic variables.

O2.2 Improving resource capture and resilience in barley. We will focus on genetic variation that exists in resource capture and yield resilience, including nutrient uptake and utilization efficiency. Diversity in photosynthetic traits and yield components in relation to resource capture will be studied. We will characterise how crop diversity can be used to improve environmental resilience.

O2.3 Phenotyping for improved ear and grain traits in cereals. Phenotyping approaches optimised for understanding response to stress will be used to support genetic analysis of (i) grain quality characteristics in barley and (ii) quality of seed set in wheat, both of which are crucial for development of new varieties more resilient to climatic stress and more environmentally stable.

O2.4 Phenotyping of CPC core and other populations for abiotic stress and resistance traits. The CPC core and other populations will be phenotyped for abiotic stress traits. We will address key biotic threats (e.g. late blight, PCN). Resistance work will focus on 'recombinant screening' for the purposes of fine mapping.

O2.5 Phenotyping of potato populations for key quality and developmental traits. This work will address traits relevant to stakeholders such as tuber greening and dormancy, skin colour retention and Vitamin C. An association mapping panel will be used for field based phenotyping using 3d-imaging, Infrared thermography and hyperspectral imaging, providing measurements of crop growth.

O2.6 Phenotyping of fruit populations. In raspberry we will use glasshouse treatments to test relationships between above/below ground plant growth characteristics. Data will be compared with field-based remote sensing data to test the utility of canopy monitoring as indicators of root phenotypes, assisting early detection of stress, assessing plant stress responses, and will evaluate the utility of imaging for detecting variability in stress tolerance.

Key Deliverables: Years 1-2 O2.1i Phenotypic data on global landrace populations; O2.1ii Phenotypic data on morphological variant populations; O2.1iii Omics level phenotypic data; O2.2i Quantification of variation in nitrogen uptake traits; O2.2ii Identification of diversity of photosynthetic traits in barley; O2.2iii Strategies for optimising crop diversity for improved resource capture; O2.3i Phenotype barley lines for variation in grain physical integrity; O2.3ii Phenotype wheat lines for differential patterns of seed set; O2.3iii Integrate phenotyping with targets for genetic improvement in barley and wheat; O2.4i Heat stress phenotyping of CPC core and associated material;; O2.4ii Phenotyping of selected stress resistant genotypes for combinations of stresses (e.g. heat and drought); O2.4iii Phenotyping of extended populations for disease traits (e.g. late blight and G. pallida).; O2.5i Phenotyping of 06H1 diploid population for tuber greening and associated traits; O2.5ii Phenotypic assessment of Stenotomum population for tuber dormancy, shape and other characteristics; O2.5iii Phenotypic assessment of POTAPP population for 3d-imaging, IRT and HSI; O2.6i Remote sensing data on raspberry populations; O2.6ii Porometry data on raspberry populations; **Years 3-5** O2.1iv Gene specific haplotypes associated with adaptation to different environments; O2.2iv Crop nitrogen use will focus on understanding uptake and utilisation from soil and fertilizer pools. Characterisation of physiological traits will extend to variation in leaf longevity and sink capacity for yield improvement, whilst grain quality will focus on integration with end user requirements; O2.4iv Extended phenotyping of CPC and derived material for disease traits; O2.5iii Phenotyping of selected individuals for quality and developmental traits; O2.6iii In soft fruit crops assess field plots using imaging technologies.

O3 Development of genomic resources for assessing and managing diversity

O3.1 Barley: genotyping and phenotyping diversity. We will develop low cost SNP genotyping and systems to streamline phenotypic data collection and storage, using transcriptome diversity as a novel source of adaptive variation. We will identify barley genotypes which show extremes of tolerance and susceptibility to temperature and drought conditions and use RNA-seq to identify novel molecular signatures of stress and examine these in wider germplasm.

O3.2 Potato: genotyping resources for assessing diversity. We will develop tools that can be used to assess genic diversity as well as tools for trait mapping. We will deploy these tools to inform future SNP array development as well as for trait mapping. For potato BIL population development we will develop SNP markers for 'dissecting' the genome into ~100 segments.

O3.3 Soft fruit genomic resources: Transcriptome sequencing will be used in raspberry and blackcurrant for genome complexity reduction to allow discovery of novel single nucleotide polymorphisms (SNPs). RNAseq libraries will be generated in the Genome Technology group and sent for Illumina sequencing. Polymorphic SNP markers will be identified from candidate genes for prioritised traits and used to design KASP assays for genetic mapping in selected populations. To maximise the value of the various datasets (including the raspberry and blackcurrant genome sequences, RNA-seq, gene predictions, SNPs, sequence annotation and microarray probes and other derived data) a relational database will be developed to store and link items, and make the data available and searchable for researchers.

Key Deliverables: Years 1-2 O3.1i Develop improved GERMINATE database and associated analysis tools (e.g. Flapjack, CurlyWhirly); O3.1ii Generate RNAseq libraries from RNA-seq time courses to identify genotype- and stress-dependent variation in mRNA diversity and dynamics; O3.2i Design exome-wide capture array for potato; O3.2ii Test exome-wide capture array on potato diversity panel; O3.2iii Develop set of SNP markers for BIL construction; O3.3i Generate transcript sequences in raspberry and blackcurrant; O3.3ii Identify SNP for key traits and design KASP assays. **Years 3-5** O3.1iii A versatile SNP platform for routine analysis of genetic variation in barley; O3.2iv Develop KASP markers for key potato traits; O3.3iii Develop database of soft fruit genomic resources.

Technical Approach

Experimental Approaches

O1 Acquisition and Development of new germplasm resources for trait analysis

O1.1 Extended barley collections for studies of adaptation. We will explore diversity within a worldwide collection of georeferenced landrace accessions in order to study relationships between gene-level haplotype structures and eco-geographic/bioclimatic variables. Using accessions collected from sites exhibiting extremes of climate we will develop genetic materials allowing us to assess adaptation. We will investigate how morphological variation may be used to improve overall yield-stability and quality. Six-row types have limited UK use because of concerns over their ability to meet premium specifications for malting and distilling. However they are used widely elsewhere, and tend to be sturdy, robust plants which may be relevant for sustaining future production. We will use segregating populations incorporating alleles that cause lateral floret fertility and determine the value of pyramiding them in different combinations on grain yield and quality. We will explore the genetics of other morpho-developmental characters such as ‘big-leaf’ and ‘awnless’.

O1.2 Identifying novel germplasm with stress tolerance in barley. Pedigree breeding has resulted in loss of alleles needed for sustainable and resilient production with a narrowing of the genetic base in elite varieties. Work will focus on resource use efficiency at the plant and tissue level, yield and grain quality. We will evaluate genetically diverse landrace populations and wild relatives as a source of phenotypic plasticity, with the presumption that they would be adapted to a wide range of different environments. The work will combine field and controlled environment assays to find beneficial alleles and traits for crop improvement. This will link with RD2.1.2 whereby variation in transcriptional control of stress tolerance will help to identify underlying genetic mechanisms that define the outcome of plant abiotic stresses (M7, y2).

O1.3 Establishment of a potato core collection from a diverse genebank. ‘Legacy’ genotypic data (generated during 2006-11 funding period) will be used in combination with ‘passport’ data (geographical origin, climate information) to identify a diverse working ‘core’ of the CPC comprising ~200 genotypes that will be maintained clonally. Selection of the core will be based on marker genotypes, and use of location (e.g. GIS) and other data. The highly geographically and climatically diverse origins of the species in the CPC should ensure that adequate variation in the target traits exists.

O1.4 Development of BIL populations for potato. Availability of lines carrying genes that suppress self-incompatibility (SI) mechanisms (e.g. Sli) allows creation of virtually isogenic populations where each plant carries a small introgression from a ‘donor’ genotype. We will develop populations using a recurrent genotype, donor parents to be selected from material shown to carry useful traits for climate change adaptation (e.g.

heat/drought stress resistance) identified by phenotypic screens (e.g. a region on chromosome 4 conferring heat stress resistance). This approach will allow better QTL resolution and aid QTL deployment in breeding.

O1.5 Novel soft fruit populations. Raspberry populations will be developed to ensure stakeholder requirements in terms of improved germplasm and markers for key traits are met. Linkage mapping and QTL analysis (with BioSS, Underpinning Capacity 7) will be performed to understand and utilise key traits and their environmental responses. Germplasm available in collections both at Hutton and elsewhere will be characterized to identify material for further assessment.

O2 Phenotyping of diverse germplasm

O2.1 Phenotyping of barley populations for sustainability traits. Populations will be phenotyped for life history traits and tolerance to abiotic stresses. We aim to identify genotypes and genes that influence environmentally stable yield and quality traits (e.g. genes controlling the composition of the plant cell wall). By manipulating inputs we will address pressing issues in nutrient use efficiency (NUE). We will investigate how morphological variation in barley may be used to improve the overall yield-stability and quality of the crop. This will involve developing and phenotyping populations involving morphological variants such as ‘Six-row’, broad leaf, naked or awnless types, which have seen limited use to date. Many of the phenotypes that we monitor are derived from transcriptomic, metabolomic, proteomic or compositional data collected from field or glasshouse material. We will extend our collection of this omics scale data to include transcript abundance and variant data.

O2.2 Improving resource capture and resilience in barley. Further improvement in yield and resource use efficiency lies in increasing grain number and potential grain size. These increases must be sought without significantly increasing the requirement for N fertilizer. Mechanisms into two key aspects of NUE and yield will be explored. Firstly relationships between large grain number formation and high post-anthesis N retention and secondly variation in nitrogen uptake and utilization efficiency as influenced by soil N supply. Yield will be explored further by evaluating genetic diversity in photosynthetic capacity, leaf ontogeny, sink capacity and duration of grain filling. Our understanding of crop resilience and efficiency will be extended by the use of crop diversity to broaden a range of traits for improved carbon assimilation and nitrogen use. This work underpins the development of more resilient cropping strategies through links with RD2.1.3 which deals with biotic stress in barley, and RD2.1.6 on integrated pest management (M1, y1, M5, M8, y2).

O2.3 Phenotyping for improved ear and grain traits in cereals. Collections of barley will be phenotyped for grain quality traits, especially those associated with the grain physical integrity e.g. size, shape and nitrogen content. This work will use UK elite germplasm to detect robustness in ear and grain traits, especially in relation to temperature, light and moisture stress, across a range of genetic backgrounds. This will support more detailed phenotyping and transcriptomic profiling of subsets of phenotypes to facilitate molecular understanding of traits towards the identification of candidate genes. Wheat collections will be evaluated for environmental sensitivity to flowering and set seed. It is known that wheat varieties and breeding lines vary in the number and pattern of florets that set seed and that this aspect of yield creation may be crucial for yield stability in wheat across different environments e.g. varying soil nitrogen levels. Findings will be used to understand how phenotypic expression of grain set is associated with allelic variation that can be identified across breeding lines and varieties. This research will support genetic analyses to identify QTLs underlying differential patterns of seed set (M2, M3, y1).

O2.4 Phenotyping of CPC core and other potato populations for abiotic stress and resistance traits. The CPC core will be subjected to phenotypic screens, with an initial focus on heat stress, identifying species with potentially useful genes for abiotic stress tolerance. These will be used to generate new populations for phenotypic and genotypic analysis. Use of established Hutton potato populations to assess abiotic stress responses will focus on use of combinations of relevant stresses. Previous phenotypic studies of abiotic stress tolerance in potato have used biparental populations to assess response to individual stresses. We will apply combinations of stresses simultaneously on selected lines to reproduce realistic stress scenarios more relevant to anticipated climate changes in Scotland. Included will be genotypes that have been shown to exhibit variation in heat tolerance and water use efficiencies and transgenic lines showing altered responses to abiotic stresses. Stresses (a range of elevated and ambient temperature regimes in combination with water stress) will be applied in replicated controlled environment room trials taking into account at which physiological stage of the potato the stress occurs, such as at tuber initiation or bulking. Scottish potato crops face a wide array of pest and disease threats. During the 2011-16 programme, new sources of resistance to late blight (e.g. *S. okadae, S. verrucosum*), PCN species *G. pallida* (e.g. *S. speggazinii, S. tarijense*), *Pectobacterium* and PVY (*S. phureja*) were partially characterised. During this programme we will improve the phenotypic and genetic characterisation of these resistances. For purposes of fine mapping genetic analyses and further phenotyping will be required. SNPs linked to resistance genes will be used for further mapping and for performing marker based introgression of genes. into adapted potato germplasm (M4, y1, M6, y2)

O2.5 Phenotyping of potato populations for key quality and developmental traits We will phenotype potato populations for tuber greening, feeding into a more molecular approach in RD2.1.2. This work will make use of the well-studied 06H1 population that varies for many commercial traits and will exploit extensive existing genotypic information. Tubers will be sampled at harvest grown in a replicated field trial, and will be analysed for chlorophyll content during a time course of illumination. QTL analysis of the chlorophyll values will then be performed, treating values for each time point, external and internal chlorophyll value as separate variables. The trial will be repeated over two growing seasons to establish the robustness of QTLs. We will also examine a diverse Stenotomum diploid cross and associated association mapping population for variation in key tuber traits, such as tuberisation and dormancy. These populations will be genotyped and a linkage map constructed of the cross. The populations will be grown in the glasshouse and assessed for traits of consumer importance – skin and flesh colour, tuber dormancy, etc. An association mapping population (POTAPP) will be used for phenotypic analysis. Field based phenotyping using 3d-imaging (UAV integrated with panoramic cameras), Infra-red thermography (IRT) and hyperspectral imaging (HSI) will be used to obtain measurements of crop growth and development such as canopy size, senescence, stomatal closure and plant stress canopy, leaf-area index (LAI) etc. Leaf and canopy reflectance results from interactions between biophysical and biochemical characteristics of plants. Data on leaf and tissue structure, leaf pigment content and water content will be collected, utilizing a mobile phenology system at key stages of crop development and linked to commercially important traits (e.g. yield) to understand measures of stress adaptation (links to RDs 2.1.5 and 2.1.7).

O2.6 Phenotyping of fruit populations. Leaf spectral reflectance has been shown to be highly correlated with chemical composition. Using remote sensing techniques, spectral signatures can be linked to chlorophyll and other pigment concentrations, providing information on stress responses. We will use this technique to study changes in crop canopy parameters such as LAI as an indicator of root phenotype and root responses to the soil environment. Focusing on raspberry we will use managed experimental treatments in a controlled glasshouse environment, to test the relationship between above/below ground characteristics. We will link this with remote sensing to test the utility of high throughput phenotyping and crop monitoring approaches using IRT and HSI as potential indirect indicators of root phenotype using above ground crop characteristics. This should assist in the early detection of stress together with monitoring plant responses to abiotic and biotic stresses and will allow us to determine the utility of high throughput imaging for detecting genotypic variability and for understanding plant stress tolerance/resistance. Use of established Hutton soft fruit populations to assess abiotic stress responses will focus on use of combinations of stresses. Existing raspberry (‘Glen Moy x Latham’) populations will be used for imaging. A limited number of genotypes will be assessed for stomatal conductance using conventional porometry, while pigment concentrations (e.g. chlorophyll) will be quantified and leaf area index estimated by sampling. The reproducibility of IRT and hyperspectral imaging data and any variation will be assessed across the mapping population using a Monte Carlo approach to test significance at different times of day and at different development stages of crop production.

O3 Development of genomic resources for assessing and managing diversity

O3.1 Barley: genotyping and phenotyping diversity. We will focus on developing low cost SNP genotyping for barley germplasm analysis. We will devote considerable effort on improving existing GERMINATE database and analysis tools (e.g. Flapjack, CurlyWhirly) to enable storage and visualisation of HTP data. In parallel we will explore modern approaches to streamlining phenotypic data collection in the glasshouse/field using hand held data loggers and real time data uploading. This will require establishment of common ontologies and formats for data recording to simplify incorporation into our expanding data warehouse. This will facilitate data distribution and use within our own research programs, but also wider where it may also act as a necessary link in publications. Recent advances in transcriptome sequencing and annotation of the barley genome now provide a means to assess transcriptome diversity and dynamics during development and in response to stress on a gene and transcript basis. Data from RNA-seq time courses will be used to identify genotype- and stress-dependent variation in mRNA diversity and dynamics. We will incorporate these novel molecular signatures into an accurate barley transcriptome phenotyping system. We will examine variation in genetic material with tolerance and sensitivity to stress conditions (temperature, drought) and populations generated from cold tolerant and cold sensitive genotypes. Association of variation with stress response will identify potential candidate genes for tolerance and will be used for SNP discovery. Polymorphic SNP markers will be identified from candidate genes for prioritised traits.

O3.2 Potato: genotyping resources for assessing diversity. We will develop exome-wide capture and an improved NB-LRR gene-specific array, both of which can be used as tools for SNP discovery and trait analysis. Use of exome capture on diverse germplasm will lead to SNP identification that will inform subsequent development of a ~40K SNP array (e.g. Affymetrix). A commercial partner has indicated using such a platform in their breeding programme. Exome capture can also be used to look at allelic diversity in diverse CPC material spanning extremes of climate/geography and will inform work on abiotic/biotic stress adaptation. For BIL population development we will create markers ‘dissecting’ each chromosome such that ~100 BILs are sufficient to cover the whole genome. These markers are used at

each backcrossing generation to select genotypes with the desired allelic constitution. **O3.3 Soft fruit genomic resources.** We will develop genomic/transcriptomic resources for soft fruit that allow more accurate knowledge based breeding. In blueberry we will develop improved linkage map and will collaborate with partners to develop similar resources to those being developed in raspberry and blackcurrant.
Key linkages, interdisciplinarity & collaboration: The programme presented here is integrated across three MRPs; Hutton, SRUC, and BioSS. Key linkages include: 1) Links to a wide range of other related RESAS 2016-21 RDs particularly work in RD2.1.2 on crop genetic improvement, all objectives O1-O3 feeding directly into RD2.1.2. More specifically work in O1.1 and O1.2 here feeds into RD2.1.2: O1 Novel alleles for adaptation in barley and O2.1 Barley inflorescence development. Likewise for potato O2.4 and O2.5 feed into RD2.1.2: O2.4 Potato tuber dormancy, O5.1 Potato tuber greening and O6.1 Biotic stress in potato. For soft fruit O1.5 here links directly with RD2.1.2: O2.2 Crumbly fruit in raspberry, O2.3 Blackcurrant bud dormancy and O6.2 Phytophthora root rot in raspberry. This RD will link with Plant-pest interaction work in 2.1.3 providing material for mechanistic studies carried in in objective 1 of 2.1.3. Other links include RD2.1.5 on in field detection, RD2.1.7 on Plant-soil-water interactions and RD2.3.12 on Uptake of best practice. The approaches and tools developed will find downstream application in the wider range of traits studied in other parts of the programme, providing added value. These interactions will be facilitated via communication strategies described at the work package level. 2) There will also be strong links to other parts of the RESAS programme funding such as underpinning capacity (UC). Unique germplasm identified in collections of potato, barley and soft fruit will be used widely in the RDs 2.1.1, 2.1.2, 2.1.3 experimental programmes. We aim to continue to use cutting edge science with impact in the RD2.1.1 programme as a vehicle for training staff and PhD students. 3) The work links to a number of the priority issues identified by CAMERAS including: (a) ensuring that Scottish food production responds appropriately to the challenge of climate change; (b) protecting our environmental assets; (c) minimising disease impacts on crops. RD2.1.1 scientists will contribute to WP2.1 annual Exchange Meetings with CAMERAS, RESAS and other stakeholder organisations, to highlight outputs and identify opportunities for wider implementation and impact. 4) The RD2.1.1 research programme will help to provide leverage for external funding, continuing the success which has attracted >£25M for the Hutton and SRUC crop/pathology based groups in past 3 years.
Added Scientific Value: This research is aligned with BBSRC strategic priority areas in agriculture and food security, reducing waste in the food chain and sustainably enhancing agricultural production. These priority areas recognise the need for agriculture to produce more from less cultivated land, with reduced inputs of water, energy and nutrients, while minimising adverse environmental impacts on biodiversity, soil, water or the atmosphere. The work is complementary in placing emphasis on crops of high relevance to Scotland. All areas identified in the proposal will deliver to, and are highly relevant for, global and EU food security agendas and efforts will be leveraged internationally for further research and translation. The scientists in this RESAS funded work will deliver to international platforms. The proposed research is complementary to the priorities of the EU H2020 research programme where scientists involved have leveraged additional funding in projects such as DISCO, BachBerry and training networks. The proposed work also complements international efforts to improve cereal crops where MRP scientists take a leading role in collaborative projects such as the International Barley sequencing consortium and projects based at the International Maize and Wheat Improvement Center (CIMMYT). Other MRP

researchers play leading roles in the 'SOL genomics network' ensuring RESAS funded work has an international profile. Collaborative links with CIP, the International Potato Centre, will ensure that the results of RESAS funded work will find application in potato breeding in the developing world. The adoption of an interdisciplinary approach should shed light across the food and drink supply chain on drivers of delivering improvements in food and drink production and sustainable health diets. It will also inform issues relating to plant health and sustainable production. The previous programme delivered many high IF papers, including Nature and PNAS, and this should continue. RESAS funding has helped to leverage >£25M for the Hutton and SRUC crop and pathology based funding over the past 3 years. We fully expect this leverage to be maintained and ideally increased significantly (e.g. Research Council UK, Innovate UK [RCUK], Agriculture and Horticulture Development Board [AHDB], EU and the agrochemical and breeding industry).
KE: Target audiences include the Agri-Food and Drink industries (e.g. Scotland Food and Drink), CAMERAS; public; networks of excellence (e.g. EU ENDURE IPM), crop protection companies, plant breeders/growers and distributors (including both small local and large international companies). The RD will have a cross MRP approach to delivery (including, via the KE sectorial leads (KESLs), working with objectives of the CKEI including, where relevant, the Think Tank) and integration of KE with themed annual stakeholder events; Potatoes in Practice, Cereals in Practice, Fruit for the Future, SRUC field events, AHDB/SRUC Roadshow Workshops, farmer meetings, Scottish Society for Crop Research meetings and Linking Environment and Farming [LEAF] events. Time-lined and targeted workshops will be required for both dissemination and translation in relation to agri-food & drink and crop protection industries priorities. In addition value at an international/EU level will accrue via integration and interaction with the European Innovation Partnerships [EIPs] and European Technology Partnerships [ETPs]. KE will include press briefings and popular articles – for example in popular press i.e. Scottish Farmer, SRUC Crop Protection Report. RD2.1.2 researchers will have a strong input to KE plans described at the CKEI level feeding into indicative activities particularly 5 and 7. **Audience:** Industrial links include those involved in primary crop production such as plant breeders, seed-suppliers and growers. The food-processing industries including brewers and distillers and manufacturers of potato and soft-fruit-based products are also major audiences. As the work is cognate with SG policy in the areas of Climate Change, Food and economic development (detailed in the Theme level proposal) government policy teams will also have an interest in this work. As the proposed work is at the cutting edge of crop research where many MRP scientists lead internationally, a key audience will be the global scientific community. MRP scientists involved in this work will continue to publish in the most appropriate high impact journals, and contribute to national and international conferences on crop and plant science, ensuring the SG investment in this research is publicised. Scientists involved with this work will also interact with SRP over-arching KE plans and will continue to contribute to public debates, web-TV, etc. In developing the KE plan we have consulted widely with many actors involved in all aspects of the crop product supply chain including SWRI, the potato processors association, the AHDB, and the UK Agritech strategy secretariat. **Impact:** Industries involved in all parts of the crop production chain will benefit from the proposed research including, growers, breeders, agronomists, providers of pest and disease management tools and retailers, the primary route being via plant breeding. Hutton Limited runs potato and soft fruit breeding programmes for many UK producers and so we are well placed to translate the outcomes of this research to industry. The

project will involve co-innovation with industry. We will make use of our links with breeders and growers in Scotland and the wider UK and relevant consumer groups to ensure that the resources developed are relevant, practical, and effective. Ultimately the outcomes of this project will impact on sustainable food production benefiting all members of society. In the UK food self- sufficiency will result in reduced imports and costs to the consumer. In the wider context of a globalised world economy, improved human nutrition will improve overall global security and thereby have a benefit in the UK. The main policy and legislative drivers for the proposed work include Climate Change (Scotland) Act 2009, Farming for a Better Climate Initiative (2009), Land Use Strategy (2011), Recipe for Success: Scotlands National Food and Drink Policy. SG policy officials in these areas will have an interest in the outcomes of this work which may provide evidence for further policy development. By identifying germplasm and tools for appropriate traits the project will help growers address one of the biggest challenges facing the agricultural industry in the near future – how to sustain and increase production if many existing conventional pesticides and fungicides are withdrawn under EU directives 2009/128/EC and 91/414/EEC along side additional challenges of climate change and extreme weather patterns.

RESEARCH DELIVERABLE NUMBER: RD2.1.1

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Extended barley collections for studies of adaptation O1.1i Global collection of georeferenced landrace accessions assembled from across the range of the species						**O1.1i**						
O1.2 Identifying novel germplasm with stress tolerance in barley O1.2i Phenotypic data on diverse barley germplasm						**O1.2i**						
O1.3 Establishment of a potato core collection from a diverse genebank O1.3i Identification of a working CPC core collection						**O1.3i**						
O1.4 Development of Backcross Inbred Line (BIL) populations for potato O1.4i First generation of crossing for at least one donor line to the recurrent M6 genotype				**O1.4i**								
O1.5 Novel fruit populations O1.5i Raspberry, blackcurrant, and blackberry populations will be developed.						**O1.5i**						
O2.1 Phenotyping of barley populations for sustainability traits O2.1i Phenotypic data on global landrace populations								**O2.1i**				
O2.2 Improving resource capture and resilience in barley O2.2i Quantification of variation in nitrogen uptake traits							**M1**					**O2.2i**
O2.3 Phenotyping for improved ear and grain traits in cereals O2.3i Phenotype barley lines for variation in grain physical integrity							**M2**					**O2.3i**
O2.3ii Phenotype wheat lines for differential patterns of seed set							**M3**					**O2.3ii**
O2.4 Phenotyping of CPC core and other populations for abiotic stress and resistance								**M4**				**O2.4i**

traits O2.4i Heat stress phenotyping of CPC core and associated material												
O2.5 Phenotyping of potato populations for key quality and developmental traits O2.5i Phenotyping of 06H1 diploid population for tuber greening and associated traits												**O2.5i**
O2.5ii Phenotypic assessment of Stenotomum population for tuber dormancy, shape and other characteristics												**O2.5ii**
O2.6 Phenotyping of fruit populations O2.6i Remote sensing data on raspberry populations												**O2.6i**
O3.1 Barley: genotyping and phenotyping diversity O3.1i Develop improved GERMINATE database and associated analysis tools (e.g. Flapjack, CurlyWhirly)												**O3.1i**
O3.2 Potato: genotyping resources for assessing diversity O3.2i Design exome-wide capture array for potato				**O3.2i**								
O3.2ii Test exome-wide capture array on potato diversity panel									**O3.2ii**			
O3.3 Soft fruit genomic resources O3.3i Generate transcript sequences in raspberry and blackcurrant									**O3.3i**			
KE Events: Potatoes in Practice					**KE3**							
KE Events: Cereals in Practice				**KE1**								
KE Events: Fruit for the Future				**KE2**								
Annual Report (year 1)												**R1**

RESEARCH DELIVERABLE NUMBER: RD2.1.1

Year 2: 2017/18 Activity	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Extended barley collections for studies of adaptation O1.1ii Development of new segregating populations						**O1.1ii**						
O1.2 Identifying novel germplasm with stress tolerance in barley O1.2ii Identification of phenotypic plasticity to stress in barley								**M7**				**O1.2ii**
O1.2iii Selection of germplasm and traits for further study												**O1.2iii**
O1.3 Establishment of a potato core collection from a diverse genebank O1.3ii Establishment of a set of 200-250 clones representing the core						**O1.3ii**						
O1.4 Development of Backcross Inbred Line (BIL) populations for potato O1.4ii Second generation crossing for at least one donor line to the recurrent M6 genotype						**O1.4ii**						
O1.4iii Genotyping of BX1 generation with SNP markers.												**O1.4iii**
O2.1 Phenotyping of barley populations for sustainability traits O2.1ii Phenotypic data on morphological variant populations								**O2.1ii**				
O2.1iv Omics level phenotypic data												**O2.1ii**
O2.2 Improving resource capture and resilience in barley O2.2ii Identification of diversity of photosynthetic traits in barley							**M5**					**O2.2ii**
O2.2iii Strategies for optimisation of crop diversity for improved resource capture								**M8**				**O2.2iii**
O2.3 Phenotyping for improved ear and grain traits in cereals O2.3iii Integrate phenotyping with targets for genetic improvement in barley and wheat												**O2.3iii**

O2.4 Phenotyping of CPC core and other populations for abiotic stress and resistance traits O2.4ii Phenotyping of selected stress resistant genotypes for combinations of stresses (e.g. heat and drought)							**M6**					**O2.4ii**
O2.4 iii Phenotyping of extended populations for disease traits (e.g. late blight and *G. pallida*)												**O2.4iii**
O2.5 Phenotyping of potato populations for key quality and developmental traits O2.5iii Phenotypic assessment of POTAPP population for 3d-imaging, IRT and HSI												**O2.5iii**
O2.6 Phenotyping of fruit populations O2.6ii Porometry data on raspberry populations												**O2.6ii**
O3.1 Barley: genotyping and phenotyping diversity O3.1ii Generate RNAseq libraries from RNA-seq time courses to identify genotype- and stress-dependent variation in mRNA diversity and dynamics												**O3.1ii**
O3.2 Potato: genotyping resources for assessing diversity O3.2iii Develop set of SNP markers for BIL construction												**O3.2iii**
O3.3 Soft fruit genomic resources O3.3ii Identify SNP for key traits and design KASP assays												**O3.3ii**
KE Events: Potatoes in Practice					KE6							
KE Events: Cereals in practice				KE4								
KE Events: Fruit for the future				KE5								
Annual Report (year 2)												R2

Name of RD: 2.1.2 Crop Genetic Improvement

Research aim and key drivers

New genomic/genetic approaches provide the capability to dissect key traits in crop plants and will be the most important vehicle for delivery of improved cultivars to cope with climate change and improve food security over the next 20-30 years. Agriculture is of considerable direct and indirect importance to the Scottish economy, the prime example here being the barley and wheat industry, where the distilling and brewing sector earns over £5 billion and employs over 50,000 people. The overall aim of this RD is to generate the information necessary to improve our translational pipelines that will enable the production of new crop plant varieties with improved performance in terms of yield, quality and resilience to pests, pathogens and climate change with strong links to RD3.1.1 on nutritional quality. To achieve these goals, we will build on advances in crop genomics achieved in the last SG programme to investigate the genetic architecture of key traits and explore the genomic, transcriptomic, metabolomic and proteomic signatures that have been shaped by the natural processes of mutation, selection and adaptation.

Key outputs will be genetic markers, genes and germplasm that can be exploited by plant breeders to the benefit of Scottish agriculture and its dependent downstream processing industries. The research will support policy decisions by providing tools for sustainable economic growth as well as an understanding of the constraints, timescales and practical realities of genetic improvement. Across all crops, this RD will involve the unique expertise available in the MRPs. In developing this proposal we have consulted widely with stakeholders including growers, breeders, agronomists, processors, providers of pest and disease management tools and consumer groups. This will ensure that the germplasm and tools developed in the project are relevant, practical, affordable, effective and acceptable.

Summary of the proposal:

Objectives and Major Activities

The main activities will focus on barley, wheat, potato and soft fruit, the crops of major importance to the Scottish economy. For each crop, the spectrum of capabilities is linked into translational crop genomics pipelines that ultimately deliver improved cultivars. Underpinning research in all projects will be the continued development of novel technologies and approaches including custom platforms for genomic and functional characterisation of important traits. Improvements in genome sequencing and annotation, high-throughput genotyping and phenotyping capabilities will allow identification of genes and alleles which determine key traits. Data generation, analysis and hypothesis testing will require a significant input from the Hutton Functional Genomics, Imaging and Genome Technology facilities, along with BioSS and Plant Bioinformatics. Together, these will allow us to explore new approaches to genomic and functional characterisation of individual genes and gene networks and consolidation of translational pipelines.

O1 Novel alleles for adaptation in barley

Over 10,000 years of post-domestication adaptation and migration, the barley crop has become increasingly tuned to specific environmental niches. Genome sequence information from diverse barley accessions contains a genetic history of variation that has evolved during the process of domestication and migration into different and challenging environments. Variation associated with adaptation to different environments will be targeted for diagnostic development for introgression in plant breeding. The focus is on traits affected by environmental cues, building on work in RD2.1.1 and CWP5.2.

Key deliverables: Year 1-2 i) Exome sequences of landraces and wild barley; ii) Associated bioclimatic data and population level analyses. **Year 3-5** iii) Variant analysis, correlation with bioclimatic data and functional validation of adaptive genes

O2 Genes controlling morphological and developmental variation

O2.1 Barley inflorescence development

The need to improve grain yield in barley requires approaches aimed at understanding inflorescence development and seed set. We will focus on exploring the dramatic developmental switch from the ancestral two-row form of wild barley to the derived six-row barley inflorescence. This work will build on the genetic resources already established in CWP5.2 and externally funded projects and will specifically characterise a row-type gene on barley chromosome 1H.

Key deliverables: Year 1-2 i) Characterisation of germplasm with known row type alleles; ii) Pyramided gene combinations for grain yield and quality. **Year 3-5:** Identification and validation of a gene affecting row type.

O2.2 Crumbly fruit in raspberry

Crumbly fruit in raspberry has become a serious issue over the last few years both during the testing of high health stocks and subsequently in propagation. It can develop through both conventional propagation and tissue culture giving rise to considerable on-farm losses, up to 100% in extreme cases. Pioneering research in CWP5.2 identified chromosomal regions associated with this condition. We will examine the underlying genetic and environmental control to define why some cultivars are more prone to crumbliness and how environment can impact the condition. This will assist breeding efforts to reduce the likelihood of crumbly fruit.

Key deliverables: Year 1-2 i) Identify germplasm with different susceptibility to crumbly fruit. **Year 3-4** ii) Determine the environmental triggers associated with crumbly fruit, **Year 4-5** iii) Identify stress signals associated with crumbly fruit.

O2.3 Blackcurrant bud dormancy

The effect of warmer winters on blackcurrant growth and development is an area of concern that has implications for other woody species. Work on the effects of changing winter conditions on dormancy and bud-break will assess the impacts of winter temperatures on the expression of key genes. Validation will be sought using diverse *Ribes* germplasm and a mapping population developed jointly with collaborators in New Zealand. These can be assessed under different environments and results used to model future scenarios based on climate projections.

Key deliverables: Year 1-2 i) Diverse germplasm assessed in field conditions during the dormant period; ii) Identify genes that are differentially expressed during dormancy break. **Year 2-4** iii) Correlate field observations and gene expression patterns; **Year 5** (iv) Model future cropping patterns under climate change scenarios.

O2.4 Potato tuber dormancy

Potato production relies on industrial-scale storage to ensure year round availability, for both fresh and processing sectors. Chemical inhibitors of sprouting such as chlorpropham are UK industry standards; yet are under threat from new legislation. In potato tubers, onset and duration of dormancy and rate of subsequent sprout growth are governed by genetic factors, orchestrated by hormone signalling and influenced by

environment during growth and storage. We will build on research in CWP5.2 by deploying genomic and other technologies to discover the underlying mechanisms that impact dormancy-related traits.
Key Deliverables: Year 1-2 i) Candidate tuber dormancy genes functionally assessed; ii) Markers for allelic variants for dormancy-related genes identified and tested. **Year 3-5** iii) Effects of environment on dormancy related traits determined.

O3 Manipulating barley recombination
Crop improvement through conventional plant breeding is based on effectively shuffling genetic variation. This shuffling (meiosis) occurs through the process of recombination or crossing over which generates new and improved combinations of alleles along and between chromosomes. In breeding, better combinations are revealed as superior performing individuals. A key problem in large genome crop plants like barley is the inability to shuffle alleles over large tracts of the genome due to the virtual absence of recombination. We will focus on understanding and exploiting the biological mechanisms that determine the frequency and distribution of recombination in barley to unlock genetic variation and improve production efficiency and yield.
Key Deliverables: Year 1-2 i) Identification and initial characterisation of meiotic mutant lines; ii) Determine environmental effects on recombination (lines, mutants and F1s). **Year 3-5** iii) Optimisation of environmental conditions; iv) Characterisation and exploitation of altered recombination patterns.

O4 Tolerance to future climate and environmental change
Temperature and water stresses often occur together, conspiring to decrease yield and quality. The intensity, frequency, and timing of each stress can result in minimal to complete crop loss. We will elucidate molecular mechanisms and define alleles that can be efficiently applied in breeding to improve the response of cereals (wheat and barley, O4.1, 4.2), potato (O4.3) and soft fruits (O4.4) to stress. New, realistic stress phenotyping approaches will build on RD2.1.1 and RD2.1.3 and enable new strategies in disease resistance and stress breeding
Key deliverables: Year 1-2 i) Candidate genes that condition response to stress; ii) Identification of wheat lines with differential response to environmental stress; iii) Development of hierarchical models for genomic data integration; iv) Functional validation of selected genes using genome editing; v) Understanding environmental triggers of poor seed set in wheat; vi) A web portal collating a wide range of soft fruit genomic information. **Year 3-5** – (vii) Functional validation of selected genes using genome editing; (viii) Markers for validated candidate genes.

O5 Product quality for consumers and producers
O5.1 Potato tuber greening
When potato tubers are exposed to light, a greening reaction occurs due to chlorophyll accumulation, along with a concomitant increase in the amount of glycoalkaloids that causes estimated crop losses of 14-17%. In parallel with RD2.1.1, we aim to reduce this waste in the supply chain by identifying and understanding the molecular mechanisms that underpin variation in tuber greening susceptibility and develop genetic markers for use in breeding.
Key deliverables: Year 1-2 i) Candidate genes/markers for tuber greening identified. **Year 3-4** – Functional analysis of candidate genes, Year 5 – Markers for candidate genes developed and assessed

O6 Biotic stress resistance

O6.1 Biotic stress in potato

Scottish potato crops face a wide array of pest and disease threats that are constantly evolving. In CWP6.4 new sources of resistance to late blight (e.g. *S. okadae*, *S. verrucosum*), Potato Cyst Nematode species *G. pallida* (e.g. *S. speggazinii*, *S. tarijense*), and Potato Virus Y (*S. phureja*) were identified and partially characterised. These genetic approaches to the characterisation of the resistance genes and initiating their introgression into adapted potato breeding material will facilitate breeding of cultivars with resistance to these important biotic threats and complement the mechanistic studies in RDs 2.1.3 and 2.1.4.

Key deliverables: Year 1-2 i) Fine mapping of the *S. verrucosum* R gene against late blight and PVY resistance on chromosome 9; ii) Mapping *S. speggazinii* resistance gene on chromosome 5. **Year 3-5** (iii) Identification of SNPs tightly linked to resistance genes; iv) Marker based introgression of the target genes into diploid or tetraploid adapted potato germplasm

O6.2 *Phytophthora* root rot in raspberry

Phytophthora root rot is causing a rapid decline in soil grown raspberry plantations (>70%) and in raspberries grown in soil and substrate. Plant based resistance is the only way forward and material exists that consistently withstands infection. Transcriptomics offers an opportunity to identify genes that play a significant role in this plant-pathogen interaction, to elucidate the mechanisms of resistance and develop novel combative strategies. Comparative gene expression studies in resistant and susceptible varieties will allow strategies for control to be developed.

Key deliverables: Year 1-2 i) Complete the genome sequence of the resistant raspberry cultivar Latham; **Year 3-4** ii) Identify differences in gene expression between resistant and susceptible germplasm, **Year 4-5** iii) identify mechanisms of resistance.

Technical approach

Experimental Approaches

O1 Novel alleles for adaptation in barley

We will focus on traits that are affected by environmental cues such as temperature and rainfall, which affect germination and flowering time. We will survey variation at known genes and other climatically affected genes in our assembled barley collections under different environments, identifying gene combinations that will be resilient to change (Milestone (M) 2, y1). We will explore exome sequence variation from the geo-referenced barley landrace and wild species materials described in RD2.1.1 to identify candidate genes that have been the targets of environmental selection (M9, y1). Interrogation of this data can, through a combination of gene-centric genetic and geo-spatial analysis, identify genomic variation that has over time become enriched or tended towards fixation in certain environmental niches, implying selective advantage. We will establish validation mechanisms that will allow us to investigate how observed allelic variants functionally impact the observed response. Alleles that functionally correlate with adaptation to prevailing environmental variables will be targeted for diagnostic development and made available for trait introgression in plant breeding (M14, y2).

O2 Genes controlling morphological and developmental variation.

O2.1 Barley inflorescence development

Classical mutation studies have shown that a minimum of 11 different genes are associated with the switch from the ancestral two-row form of wild barley to the derived six-row barley inflorescence that is common in current cultivation. We have previously isolated two of these genes (VRS3 and VRS5) and three others have now been identified. Our major challenge is to understand how these genes act together to induce this developmental switch such that a small number of genes change a sterile floret into a fertile one. Our genetic analyses have identified a gene on barley chromosome 1H that is significantly associated with row-type but does not correspond to the location of any known six-row mutant gene. Using our functional genomics toolkit we propose to characterise this locus and attempt to understand its function and how it interacts with other known six-row genes (M9, y1, M20, y2). We believe there are opportunities to exploit the valuable characteristics of six-row barleys in the UK, especially exploiting their durability when considering future climate scenarios.

O2.2 Crumbly fruit development in raspberry

The proposed work will define the developmental and environmental parameters that are associated with crumbly fruit. A range of genotypes will be grown under different environmental conditions and phenomenological factors will be scored (M7, y1). Correlations between these factors and crumbly fruit development will define the environmental conditions that potentially trigger the condition (M17, y2).

O2.3 Blackcurrant development in changing climatic conditions

The response of blackcurrant to changing winter conditions will be monitored across a range of germplasm including mapping populations developed in the 2011-2016 SG programme (M8, y1), and the expression of key genes will be assessed at various stages of dormancy leading to bud-break using the most appropriate transcriptomic approaches (M12, y2). From this, ways of selecting the most resilient genotypes will be developed. Additionally, implications and synergies will be assessed in other woody species of importance in Scotland.

O2.4 Potato tuber dormancy

Studies of potato dormancy in several different bi-parental populations (link to previous RESAS funded work and RD2.1.1) have identified large-effect QTL that influence dormancy release and sprout growth. Examination of genes underlying these QTL has revealed a number of candidate causative genes. We shall use functional genomic approaches to manipulate the expression levels of these genes and identify genes/alleles that impact tuber storage (M3, y1, M13, y2).

O3 Manipulating barley recombination

Within a barley mutant collection, lines will be identified using genetic markers, SNPs and cytological analysis (3D-super resolution microscopy) in which recombination has been perturbed (M1, y1). Using similar approaches we have shown that in wild type lines environmental conditions may impact the observed outcomes (e.g. changing where recombination occurs). Here we will focus on identifying the underlying genes in these barley mutants using map-based cloning to develop new hypotheses about meiosis and recombination in crop plants. We will similarly explore the possibility that environmental conditions (e.g. temperature) can be manipulated to alter recombination outcomes. We will focus on how to exploit this knowledge to increase the frequency and/or distribution of recombination events that occur in plant breeding, a key to exploiting valuable adaptive variation identified in wild or exotic material (M15, y2).

O4 Tolerance to future climate and environmental change

O4.1 Abiotic stress responses in barley

Preselected material (landraces, wild barley, multi-parent populations and mapping populations), controlled greenhouse experiments, supplemented by field screening, will be used to investigate phenotypic changes to abiotic stress factors at the genomic level (M4, y1). Advances in barley genome sequencing and RNA-seq now allow high resolution assessment of transcriptome diversity and dynamics during development and in response to stress at the gene and transcript levels allowing novel gene networking analyses. Understanding the levels of expression control in addition to transcription could lead to novel strategies for tolerance and forms of marker selection for breeding. Having collected time-course RNA-seq in RD2.1.1, we will develop novel, rapid bioinformatics and computational methods to help understand these molecular phenotypes. Networking analyses will identify key genes ("master regulators") that are centrally involved in conditioning stress responses and resulting in tolerant or sensitive phenotypes (M21, y2). Downstream, we will use state-of-the-art proteomic analysis to move from the transcriptional to protein levels and will utilise strategies such as genome editing that allow us to functionally validate their role in the response. We will link with the work described in O1 to correlate sequence level and eco-geographical variation (links to BioSS and Plant Bioinformatics).

O4.2 Stress tolerance in wheat

Tolerance to stress can be described by changes at the epigenetic and gene expression level. However little is known about how different global gene expression patterns in tolerant and susceptible varieties relate to physiological adaptation. The most important event for a wheat crop is flowering. Stress at critical developmental phases is known to result in the failure of wheat florets to set seed. This work will focus on the growth phases which determine the quality of flowering and seed set. Variation in transcriptional control of stress tolerance at the genomic level will help identify genes key to regulating these physiological responses. This builds on work in RD2.1.1. (M5, y1). Our approaches will determine whether there are particular developmental "tipping points" that make plants more prone to poor seed set and losses in yield (M16, y2). Of particular interest are the processes involved in the transition from vegetative to reproductive growth. By utilizing a multiple time series approach our work opens up the potential for new methods of variety selection to be implemented in breeding programmes and potential critical points for crop management practices, leading to links with RD2.3.9.

O4.3 Abiotic stress responses in potato

To understand regulatory processes underlying the physiological and metabolic responses to stress scenarios in potato, microarray and RNA-seq experiments with developing tubers formed under favourable and stress conditions will be conducted (links to RD2.1.1 and underpinning collections). The role of non-coding (nc) RNA (e.g. microRNA, siRNA and long ncRNA) associated with stress scenarios in sensitive and tolerant genotypes will be specifically investigated. Integration of gene expression, physiological and metabolite data will be performed in collaboration with BioSS using a hierarchical Bayesian network inference approach applied to semantic graphs that are able to encapsulate multiple biomolecule types, relationships and meta-data in principled statistical models (M22, y2). These analyses will allow us to identify the key processes associated with response and resilience in different stress scenarios. We aim to identify master regulator genes and will validate their function using of a suite of functional genomic approaches including new gene editing approaches (e.g.CRISPR/Cas9 gene editing, (M23, y2). This information can be converted to molecular markers and identify candidates for generation of transgenic plants with increased stress tolerance. In the later stages of the project these transgenic plants will be obtained and analysed and the potential for state-of-the-art proteomic analysis to move from the transcriptional to protein levels, will be explored.

O4.4 Abiotic stress responses in soft fruit

To maximise the value of the various phenotypic datasets associated with abiotic stress in raspberry and blueberry (including the raspberry genome sequence, RNA-seq, gene predictions, SNPs, sequence annotation and microarrays etc.) a relational database will be developed to store and link items, and make the data available and searchable for researchers. Development of supporting computational infrastructure and ultimately an open web portal (or portals dependant on number of unique species) will provide access to the underlying database resource(s) (M18, y2).

O5 Quality factors of key importance to processors, end-users and consumers

O5.1 Potato tuber greening

Working in parallel to the QTL study for tuber greening in RD2.1.1, this project will utilise transgenic lines in which we have manipulated the light signalling pathway in potato. Biochemical and molecular analysis of these transgenic lines and other genotypes that exhibit contrasting degrees of greening will complement the RD2.1.1 genetic studies. Selection of candidate genes underlying QTLs will be informed by this molecular physiological analysis and markers for allelic variation in these genes will be developed and tested (M24, y2).

O6 Biotic stress resistance

O6.1 Biotic stress in potato

In a range of Solanum species, we previously identified new sources of resistance to late blight (e.g. *S. okadae*, *S. verrucosum*), PCN species *G. pallida* (e.g. *S. speggazinii*, *S. tarijense*), and PVY which were partially characterised. By selective genotyping and phenotyping of populations, linkage and QTL analysis, fine mapping and candidate gene analysis we will improve the genetic characterisation of these resistance genes. Previous mapping work will be extended by using capture array technology (Renseq or genome-wide exome capture) allied to next generation sequencing on phenotypic bulks of susceptible and resistant plants from various crosses shown to vary for these resistance traits (M10, y1 M25, y2). In some cases further phenotyping will be required (see RD2.1.1) prior to genetic analysis.

O6.2 *Phytophthora* root rot in raspberry

We will utilise the genomic and transcriptomic tools and bioinformatic pipelines to understand the expressed genotypic differences between susceptible and resistant raspberry varieties to *P. rubi*. We aim to determine underlying genes of both plant and pathogen that are involved in the early response to infection. Gene expression in raspberry varieties Latham and Glen Moy will be studied to determine how the differing phenotypes respond to the pathogen to allow strategies for control to be developed. We have a draft reference genome for the susceptible cv. Glen Moy. We will produce a draft reference genome for the resistant cv. Latham (M6) in order to generate transcriptome profiles of Glen Moy and Latham roots challenged with *P. rubi* by RNA-seq (M19, y2).

Key linkages, interdisciplinarity & collaboration

RD2.1.2 is integrated across three MRPs; Hutton, SRUC, and BioSS.

Key linkages include:

1) Cross-theme links to nutritional traits in WP3.1, specifically techniques developed in O1(i) (gene pyramiding) will find application in barley nutritional quality work (RD3.1.1) O3 D3.2 in years 3-5. Work on potato vitamin C content O1 D.1.2. will be informed by work in O4 (iii) “hierarchical models” and potentially O4 (iv) on gene editing approaches in year 3-5 of the programme. Soft fruit nutritional quality work in RD3.1.1. D5.2 and D6.2 will employ advances developed in genomics O6.2 (i) and transcriptomics O6.2 (ii) in years 1-2 on the programme. The links between RD3.1.1. and the socio-economic aspects of RD3.1.2 (O1) will also be supported by these links.

Within WP2 – there will be linkages with RD2.3.2 on management of genetic resources – specifically PIs involved in RD2.1.2 will contribute with insights into crop genetics to

Industry and Stakeholder workshops planned in years 1, 3 and 5 of RD2.3.2. O1. Where applicable, newly identified advanced breeding materials will be assessed for their tolerance towards non-plant specific pathogens that could impact on human health linking with RD2.3.3.
Within WP2.1 there will be strong linkages with RD2.1.1, outlined above. Linkages with plant-pest interactions include mechanistic studies (RD2.1.3 objective 1) which will inform genetic screens conducted in O6.1 in years 1-5. New methods for analysing combined omic datasets O4 (iii) will find application in RD2.1.3. objective 3 aimed at identifying signalling networks under combinations of biotic and abiotic stresses (y2-5). New sources of host resistance will be characterised in O6 and these will inform work on IPM (RD2.1.6) which aims to maximise their beneficial use and will also support links between RD2.1.6 and RD2.3.12 (uptake of best practice).
2) There will be strong links to other parts of the RESAS programme funding such as underpinning capacity. Unique germplasm identified in UC collections of potato, barley and soft fruit will be used widely in the RD2.1.2 experimental programme. Linkage analysis and QTL mapping will be done in collaboration with BioSS, their inputs being supported by BioSS funding for UC Function 7. We will continue to use the cutting edge science with impact in the RD2.1.2 programme as a vehicle for training seedcorn PhDs.
3) The research links to several of the priority issues identified by CAMERAS including: (a) ensuring that Scottish food production responds appropriately to the challenge of climate change; (b) protecting our environmental assets; and (c) minimising disease impacts on crops. RD2.1.2 scientists will contribute to WP2.1 Annual Exchange Meetings with CAMERAS, RESAS and other stakeholder organisations, to highlight outputs and identify opportunities for wider implementation and impact.
4) Linkage outwith MRPs: RD2.1.2 scientists take a leading role in collaborative projects such as the International Barley sequencing consortium and collaborative projects with the International Maize and Wheat Improvement Center (CIMMYT). MRP researchers also play leading roles in the SOL (Solanaceae) genomics network and have collaborative links with the International Potato Centre (CIP) to ensure that the results of RESAS funded work will find application in potato breeding in the developing world. We have numerous collaborations with national organisations such as NIAB, IBERS, JIC and East Malling, as well as with the University sector. We have a unique partnership with the College of Life Sciences at the University of Dundee and are expanding such connections with other Scottish Universities.

Added Scientific Value

National and international impact: All the areas identified in the RD2.1.2 proposal will deliver to food security agendas and efforts will be made internationally to develop further research and translation opportunities. The capabilities of our translational crop genomics pipelines including the principal tools, technologies and approaches will be highlighted in national and international meetings and publications which will support opportunities for international collaboration in funding and advancing crop science. For example, the proposed RD2.1.2 research is complementary to the priorities of the EU H2020 research programme where scientists involved in RD2.1.2 have leveraged additional funding in several projects. The research in RD2.1.2 is aligned with BBSRC strategic priority areas in agriculture and food security, reducing waste in the food chain, and sustainably enhancing agricultural production. The research is complementary in that it places the emphasis on crops of particular relevance to Scotland; barley, soft fruit and potatoes. The RD2.1.2 research programme will help to provide leverage for external funding, continuing the success which has attracted

>£25M for the Hutton and SRUC crop and pathology based funding over the past 3 years. We will explore all avenues of research funding (e.g. Research Council UK, Innovate UK, Agriculture and Horticulture Development Board, EU and the agrochemical and breeding industries).

***Delivery to science agenda setting*:** Added value from the science in the RD will be to inform issues relating to plant health and sustainable production in food and drink production and sustainable healthy diets.

Science and funding impact: The previous SRP delivered many high quality publications (including Nature, Science, PNAS) bringing an international profile to the MRPs and RESAS, and these demonstrations of the highest levels of science excellence will continue.

KE: RD2.1.2 researchers will have a strong input to KE plans described at the CKEI level, particularly feeding into indicative activities 5 and 7. RD2.1.2. will have a cross-MRP approach to delivery and integration of KE, with key themed annual stakeholder focussed events: Potatoes in Practice, Cereals in Practice, Fruit for the Future/Fruit Forum, SRUC field events, Home Grown Cereals Authority [HGCA]/SRUC Roadshow Workshops, farmer meetings, Scottish Society for Crop Research [SSCR] meetings and Linking Environment and Farming [LEAF] events. The annual themes will be selected to highlight RD2.1.2 activities and will take into account stakeholder feedback collected at each event. We shall continue to engage locally with the public via annual "Fascination of Plants" or Family Fun Day events held at the University of Dundee Botanical garden attracting 100s of visitors on the day and around 80,000 visitors per year. Targeted workshops will be required for both dissemination and translation in relation to agri-food & drink and crop protection industries priorities. In addition, value at an international/EU level will be garnered via integration and interaction with the European Innovation Partnerships [EIPs], European Technology Partnerships [ETPs] and through EPSO working groups. KE will include press briefings and popular articles – for example Scottish Farmer, SRUC Crop Protection Report.

Audience: Industry throughout the supply chain is a key target audience and includes industries involved in primary crop production such as plant breeders, seed-suppliers and growers. The food-processing industries including brewers and distillers and manufacturers of potato and soft-fruit-based products are also major audiences for this research. As the work is cognate with SG policy in the areas of Climate Change, Food and economic development (detailed in the Theme level proposal) government policy teams will also have an interest in this work. As the proposed work is at the cutting edge of crop research where many MRP scientists lead internationally, a key audience will be the global scientific community ensuring the SG investment in this research is publicised and appreciated. In developing the KE plan we have consulted widely with many players involved in all aspects of the crop product supply chain including SWRI, the potato processors association, the AHDB and the UK Agri-tech strategy secretariat.

Impact: We have established translational crop genomics pipelines for each of our crops and plant breeding is the route through which almost all genetic advances in crop production reach the market to release their benefits to the wider community. The commercial arm of the Hutton, James Hutton Ltd, runs potato and soft fruit breeding programmes for all the many UK producers and barley research interacts closely with UK and EU breeding companies. Thus, we are well placed to translate the outcomes of this research to industry. Ultimately the outcomes of this project will impact on sustainable food production benefitting all members of society. The main policy and legislative drivers for the proposed work include Climate Change (Scotland) Act 2009, Farming for a Better Climate Initiative (2009), Land Use Strategy (2011), Recipe for

Success: Scotland's National Food and Drink Policy. SG policy officials in these areas will have an interest in the outcomes of this research and the long-term planning and investment required to ensure that Scotland can produce adapted crops to support its economy.

RESEARCH DELIVERABLE NUMBER: RD2.1.2

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1. **Novel alleles for adaptation in barley.** O1.1.i Exome sequencing of landrace and wild barley. Variation at known genes and other climatically affected genes will be surveyed in barley collections under different environments, identifying gene combinations resilient to change				M2		O1.1.i						
O1.1.ii Exome sequence variation from the geo-referenced barley landrace and wild species materials (RD2.1.1) will be explored to identify candidate genes that have been the targets of environmental selection									M9		O1.1.ii	
O2.1 Barley inflorescence development O2.1.i. Characterisation of barley germplasm with known row type alleles. Using a functional genomics toolkit the H1 locus that impacts on row type will be identified										M11		O2.1.i
O2.2 Crumbly fruit development in raspberry. O2.2.i. Identify germplasm with different susceptibility to crumbly fruit							M7		O2.2.i			
O2.3 Blackcurrant development in changing climatic conditions. O2.3.i. Monitor response of blackcurrant to changing winter conditions in a range of germplasm assessed in field conditions during the dormant period								M8		O2.3.i		
O2.4 Potato tuber dormancy. O2.4.i. Studies of potato dormancy in biparental populations have identified large-effect QTL				M3		O2.4.i						

that influence dormancy release and sprout growth. Examination of genes underlying these QTL revealed a number of candidate causative genes. Functional genomic approaches will be used to manipulate gene expression and identify genes/alleles that impact tuber storage.												
O3 Manipulating barley recombination. O3.i. Identification of meiotic mutant lines			**M1**		**O3.i**							
O4 Tolerance to future climate and environmental change **O4.1 Abiotic stress responses in barley.** O4.1.i. Preselected barley varieties and landraces exposed to abiotic stresses to identify abiotic stress responses; material for time-course transcriptomics					**M4**		**O4.1.i**					
O4.2 Stress tolerance in wheat O4.2.i. Variation in transcriptional control of stress tolerance will help identify genes key to regulating physiological responses Wheat lines with differential response to environmental stress will be identified					**M5**		**O4.2.i**					
O6 Biotic stress resistance **O6.1 Biotic stress in potato.**O6.1.i Enhanced mapping resolution of S. verrucosum R gene against late blight and PVY resistance on chromosome 9									**M10**		**O6.1.i**	
O6.2 *Phytophthora* root rot in raspberry O6.2.i Genome sequence of raspberry cultivar Latham complete					**M6**		**O6.2.i**					
KE Events: Potatoes in Practice					**KE3**							
KE Events: Cereals in Practice				**KE2**								

KE Events: Fruit for the future				KE3								
Annual Report (year 1)												R1

RESEARCH DELIVERABLE NUMBER: RD2.1.2

Year 2: 2017/18 Activities	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1. Novel alleles for adaptation in barley. O1.1.ii We will establish validation mechanisms that will allow us to investigate how observed allelic variants correlate with bioclimatic data and functionally impact the						**M14**		**O1.1.ii**				
O2.1 Barley inflorescence development. O2.1.ii. Pyramid gene combinations for grain yield & quality								**M20**		**O2.1.ii**		
O2.2 Crumbly fruit development in raspberry. O2.2.ii. Determine environmental triggers associated with crumbly fruit							**M17**		**O2.2.ii**			
O2.3 Blackcurrant development in changing climatic conditions. O2.3.ii. Assess expression of key genes at various stages of dormancy leading to budbreak.				**M12**		**O2.3.ii**						
O2.4 Potato tuber dormancy O2.4.ii Markers for allelic variants of dormancy control genes will be developed and tested				**M13**		**O2.4.ii**						

O3 Manipulating barley recombination. O3.1.ii. Explore effects of temperature on recombination (lines/mutants/F1s)						**M15**		**O3.1.ii**				
O4.1 Abiotic stress responses in barley. O4.1.ii RNA-seq data analysis; identify key genes centrally involved in conditioning stress responses and resulting in tolerant or sensitive phenotypes										**M21**		**O4.1.ii**
O4.2 Stress tolerance in wheat. O4.2.v. Establish procedures for understanding environmental triggers of poor seed set						**M16**		**O4.2.v**				
O4.3 Abiotic stress responses in potato. O4.3.iii Develop hierarchical models for genomic data integration										**M22**		**O4.3.iii**
O4.3 Abiotic stress responses in potato. O4.3.iv Initiate functional validation of selected genes using genome editing										**M23**		**O4.3.iv**
O4.4 Abiotic stress responses in soft fruit. O4.4.vi Develop relational database to maximise value of phenotypic datasets associated with abiotic stress in raspberry and blueberry O4.iv. Initiate functional validation of selected genes using genome editing							**M18**		**O4.4.vi**			

O5.1 Potato tuber greening O5.1.i. Identify candidate genes for tuber greening.										**M24**		**O5.1.i**
O6.1 Biotic stress in potato. O6.1.ii. Mapping *S.speggazinii* resistance gene on chromosome 5.										**M25**		**O6.1.ii**
O6.2 *Phytophthora* root rot in raspberry O6.2.ii. Study gene expression in raspberry to determine how differing phenotypic response to pathogen							**M19**		**O6.2.ii**			
KE Events: Potatoes in Practice					**KE6**							
KE Events: Cereals in practice				**KE4**								
KE Events: Fruit for the future				**KE5**								
Annual Report (year 1)												**R2**

Name of RD: 2.1.3 – Plant-pest Interactions

Research aim and key drivers

To meet projected global food requirements in 2050 the Food and Agriculture Organisation (FAO) of the United Nations estimates that food production will need to increase by 70% overall and by 100% in developing countries. A major constraint on achieving food security is crop loss due to pests and diseases. Within the EU, the need for sustainable agriculture with reduced inputs has led to the implementation of directive 91/414/EEC, limiting the current choice of pesticides. In many cases no replacements for withdrawn pesticides are available and resistance against some pathogens is still lacking in commercially viable cultivars. There is thus an acute obligation on the scientific community to find new, durable and sustainable means to combat crop diseases. Many of the interactions between crops, their pests and diseases and the likely effects of climate change on these interactions, are poorly understood. We will undertake research that identifies and characterises key factors that define the outcome of plant-pest interactions in the major Scottish crops. Climate change will be central to this RD, and we will establish how host-pathogen interactions are likely to be affected by temperature and other stresses in relation to future climate change scenarios. Research from this deliverable will provide targets for improving pest and disease resistance and novel control methods. The work will inform research to improve host resistance (RD2.1.2), integrated pest management methods (RD2.1.6) and food safety issues (RD3.1.3). The overall outcomes will result in increases in the yield and quality of Scottish crops, thereby boosting the Scottish economy. The work described has been established by scientists with expertise in the relevant areas and after consultations with agchem and breeding companies and other relevant stakeholders including SASA and AHDB.

Summary of the proposal:

Crops are under constant threat from pests and diseases. In Scotland, major disease threats to potato include the late blight pathogen *Phytophthora infestans,* bacterial pathogens (*Pectobacterium* and *Dickeya* spp.), plant viruses, aphids and the potato cyst nematode *Globodera pallida,* while on barley two major fungal pathogens, *Ramularia collo-cygni* and *Rhynchosporium commune,* are of key importance. The main aim of this RD is to develop a better understanding of the plant-pest interactions that threaten arable crop production in Scotland and elsewhere. Understanding the mechanisms that pathogens use to invade and colonise host plants, in parallel with the processes by which plants resist infection, will provide key insights to drive long term plant protection strategies. Crops also encounter a wide range of non-pathogenic micro-organisms, but little is understood about the interactions that occur in this ecosystem. Determining the effects that non-pathogenic micro-organisms have on pests and crops will provide novel insights into how the natural ecosystem can be used to improve crop health and yield potential.

Natural resistance is the most cost-effective and sustainable method for controlling pests and diseases. New resistance sources against key pests and diseases that affect Scottish agriculture are available in germplasm collections held at the MRPs, including the Commonwealth Potato Collection (CPC) and the Barley Landrace collections. Most resistance is activated by detection of effectors, pathogen molecules that manipulate the host to the benefit of the pathogen. Effectors that are recognised by the plant are termed avirulence genes. Upon recognition of the product of an avirulence gene, a strong localised cell death (the hypersensitive response - HR) is often induced by the plant, preventing growth and spread of the pathogen. Characterised avirulence genes will be used as tools for identification of novel and durable resistance genes (RD2.1.2), for monitoring pathogen populations for emergence of resistance breaking strains and predicting durability of existing resistance (RD2.1.4) including under changing environmental conditions.

Stable yields in crop plants are vulnerable to environmental pressures including biotic and abiotic stresses. Elucidating the molecular aspects of the cross talk between the crop response to stress and the link to developmental processes is a pre-requisite to identify new targets for crop improvement via breeding. Pathogen effectors, which typically promote infection, represent new tools to study these processes. Previous work (CWP6.4) has shown that effectors interact with diverse targets in their host plants and that as well as suppressing defence mechanisms, they also alter developmental processes to create an environment that is conducive for pathogen growth. We will therefore undertake work that examines how plants recognise and respond to pathogens and other biotic and abiotic stresses in combination. This will allow us to better predict and respond to the potential effects of climate change on disease susceptibility and durability of resistance in crop plants.

The timing and severity of disease symptom expression is affected by changes in crop development and the abiotic environment. Developing a better understanding of how key host development processes regulate disease symptom expression will highlight novel breeding targets that can advance the production of high yielding disease resistant crops. We will test hypotheses that will link host processes which alter source-sink relationships with changes in disease symptom expression, developing work conducted in CWP6.4. We will also study the phenomenon of mature plant resistance and the factors which influence its onset. The effect of external factors that alter crop development such as the plant response to environmental and nutrient stresses, treatment with green leaf duration promoting fungicides and non-pathogenic microbial communities on disease symptom expression will be examined. This research will also exploit mechanisms of multiple stress tolerance in crops which will be of value to crop genetic improvement (RD2.1.2) whilst increasing the understanding of epidemiology of plant diseases (RD2.1.4) and identify non-pathogenic micro-organisms that will be used as biological control agents in integrated pest management strategies (RD2.1.6).

Technical approach

Pathogen biology

Objective 1 - Functional analysis of effector-host interactions

Building on previous investments in genome resources for key pathogens, including *P. infestans, R. commune, Ramularia collo-cygni*, aphids and *G. pallida,* effector sequences that are recognised by host resistance sources will be identified. Plant collections will be tested with pathogen strains of different race specificities, and association genomics will be used to identify polymorphisms in candidate effector sequences that are associated with differences in virulence and resistance. Comparative genomics and expression analyses will be used to identify key effectors and their regulators that are essential for pathogenesis. Some pathogens are able to survive prolonged periods of asymptomatic development within the host. Information on how these pathogens evade host defences during this asymptomatic development is limited. This work area will therefore use bioinformatic approaches and transcript profiling to identify effectors and cell wall components that play key roles in latent infection.

Outputs will include functionally defined pathogen avirulence genes (O1.1) that will be used as tools to identify new and durable resistance genes (RD2.1.2) and for monitoring pathogen populations for emergence of resistance breaking strains and predicting durability of existing resistances, including under changing environmental conditions

(RD2.1.4). Pre-breeding lines and potato accessions from the CPC with new sources of resistance against key pests and pathogens, including resistance that is recognised by key effectors/interactions, will be identified for use in commercial breeding programmes (O1.4). Pathogen effectors frequently target essential nodes in host immune signalling pathways and can be used as probes that allow the function of the immune system to be investigated. The host targets of the key effectors will be potential novel targets for resistance breeding (O1.2). Functional studies will determine how these effectors modify their targets in order to suppress immune responses or to allow nutrient uptake by pathogens. We will investigate whether different pathogens target similar host proteins during infection, providing information on key host nodes (including apoplastic targets) that may be essential for immune function (O1.5). Work in CWP6.4 has revealed that the plant nucleus and nucleolus are targeted by diverse pathogens including nematodes, *P. infestans* and viruses. Work on these pathogens will focus on identifying the host proteins targeted by nuclear effectors as well as identifying the changes in gene expression that occur as a result of these interactions (O1.3, O1.6). For viruses, various roles for the nucleolar protein coilin have been identified. We will investigate how coilin is able to function as an apparent sensor of virus infection and what changes in plant defence pathways occur after virus sensing by coilin (O1.6).

Outputs from these work areas will include plant proteins and compounds essential in defence that will be candidates for resistance breeding/new breeding strategies that can be used in RD2.1.2 (by prioritising resistance that protects essential host processes). In addition, agbiotech approaches will be enabled that will be exploited through existing and newly developed externally funded industrial partnerships. Information on pathogen biology will inform development of new control chemicals (RD2.1.6, RD2.2.4 and RD2.2.5).

Plant response

Objective 2 – The interplay between resistance, biotic stress and development

Understanding the molecular aspects of the cross talk between biotic and abiotic stresses and interactions with developmental processes is a pre-requisite to identify new targets for crop improvement. For example, heat stress can compromise pathogen defence responses and plants often become more resistant to pathogens as they age. The work will allow us to better predict and respond to the potential effects of climate change on disease susceptibility and the durability of resistance. Work conducted in CWP6.4 has identified pathogen effectors that interact with diverse targets in host plants to suppress defence mechanisms and alter developmental processes promoting infection. This knowledge will be exploited together with findings from Obj. 1 to determine the molecular mechanisms that impact on plant development and resistance to stresses. Key questions will include: i) What is the level of cross talk between abiotic and biotic stresses and developmental processes in crop plants?; ii) What are the effects of simultaneous exposure to different stresses?; iii) How does plant development affect host resistance?; iv) What is the diversity of key plant regulators in breeding/pre-breeding material that can be exploited to develop crop plants that resist infection?; v) How robust are non R gene forms of resistance to abiotic stresses?

Approaches will include analysis of gene expression networks (CWP 6.4, RD2.1.2) to identify candidate interacting hubs associated with biotic/abiotic stress and development (O2.1). Assessment of host progeny that segregate for tolerance to abiotic stresses (from plant populations in RD2.1.2) for pathogen resistance and subsequent genetic analyses will reveal key signalling nodes that mediate biotic and abiotic stress responses (O2.1). To examine how plants recognise and respond to combinations of stresses we will focus on pathogen resistance in diploid *S. phureja* germplasm. We will study R genes and non-R gene targets (including polyphenolics and Mx, (a protein that provides broad spectrum virus resistance in animals) (O2.2, O2.3). We will identify key components for use in breeding and marker development (RD2.1.2) and to determine the robustness of this resistance to future climate-related temperature changes. *Outputs* will include new markers for targeted pathogen resistance for rapid screening of pre-breeding material in potato and other crops, as well as strategies to protect existing and new resistance against key pathogens under a changing climate. A marker for the onset of age-related resistance will be found (O2.4) and incorporated into a predictive model for disease risk in different climate-change scenarios (external collaborators and RDs 2.1.4; 2.1.6).

Objective 3 - Key host mechanisms controlling disease expression & yield response in major crops.

Phenotypic screening and molecular analyses will be used to determine the mechanisms that control responses to plant-pest interactions in cereals. As cereals develop, major changes in source-sink relationships occur. Research will link signals released during plant source-sink changes with the disease response (O3.1) and provide new targets for disease tolerance in barley breeding (RD2.1.2). The impact of disease will be examined on grain filling in barley plants, where stem storage reserves and functional leaf area to grain number ratios are varied (O3.1). The hypothesis that crops have the ability to up-regulate photosynthesis to compensate for disease-related green leaf area (GLA) loss to minimise yield penalties will be tested (O3.4).

GLA duration in cereals can be extended by certain fungicides. Mechanisms of fungicide-related grain number increase in the presence and absence of visible disease will be investigated (O3.1). An alternative hypothesis is that the greening effect of fungicides is associated with chemical control of non-pathogenic saprophytes. The effect of non-pathogenic saprophytes on crop yield will be tested under controlled conditions in the presence and absence of disease (O3.4). *Outputs* will include guidance into how microbial factors effect plant-pest interactions (RD2.1.4), and plant-soil-water interactions (RD2.1.7) to inform integrated crop management strategies (RD2.1.6).

Leaf senescence is associated with foliar nutrient remobilisation during grain filling and disease symptom expression is accelerated by exposure to adverse environmental conditions. Interactions between barley leaf senescence and disease expression will be examined. Bioassays to test the effects of biotic/abiotic stress combinations will be developed to phenotypically assess varietal variation for stress tolerance to multiple stress factors (O3.2) providing insights into the level of genetic diversity (RD2.1.1) for these traits. The role of reactive oxygen species (ROS) imbalance during disease will be examined (O3.3). *Outputs* will identify combinatorial stress tolerance mechanisms in barley as potential targets for genetic improvement (RD2.1.2), and potential host and environmental risk factors that can influence plant-pest epidemiology (RD2.1.4).

Detailed work plan

Pathogen biology

Objective 1 - Functional analysis of effector-host interactions

Natural diversity of pathogen effectors and key host targets within wild plant species and (pre-) breeding material will be assessed. Work will be undertaken in conjunction with screens of barley cultivars and landraces (*R. commune* M17, y2) and potato germplasm (*P. infestans* (M19, y2) and *G. pallida* (M26, y2) in order to identify which pathogen strains, if any, can overcome resistance present in different barley and potato genotypes. For *R. commune,* genome-wide SNPs identification will be combined with virulence data for sequenced strains with a view to identifying SNPs in effector sequences that are associated with differences in virulence (M4, y1). For PCN and *P. infestans,* for which

detailed characterisation of effectors has already been undertaken in CWP6.4, this analysis will use bespoke enrichment strategies including Agilent SureSelect libraries for effectors (M10, y1). Candidate avirulence genes will be expressed in appropriate barley or potato plants (M29, y2).
For *R. collo-cygni* the focus will be on identifying effectors that are expressed during latent fungal development. Candidate genes that enable pathogens to sense and respond to limited nutrient availability will be identified and transcript profiling used to characterise the expression of each candidate during different nutrient conditions (RD.2.1.3 O 2) (M38, y1). Experiments will combine *in vitro* and *in planta* bioassays to mimic nutrient stress to characterise the effects of cell wall structure and plasticity (y1, y2). The function of proteins that modify the cell wall will be probed using structural analyses (M39 – St Andrews, continues in y3-5). The effect of altered cell wall component structure on disease will be tested by *in planta* fungal inoculation bioassays. Genes differentially regulated under nutrient stress will be validated by *in vitro* growth assays and functional characterisation by gene knock-out analysis y3-5).
Building on work started under CWP6.4, transcriptomic and genomic analyses will be used to identify core effectors, and their regulators, that are present in multiple strains of key pathogens (M1, y1). Functional analysis, using gene silencing, will be used to identify which are essential for pathogenesis (M5, y1). Host targets of key pathogen effectors, if not already known, will be identified via Yeast-two-Hybrid (Y2H) analysis or pull-down assays and confirmed *in planta* (M8, y1). The structural basis of the interactions between effectors and targets will be investigated (M11, y1 – St Andrews). Work will focus on effectors from *G. pallida*, *R. commune, P. infestans,* viruses and aphids.
Key host nodes will be identified by comparing the host proteins identified as targets of effectors from various pathogens (M20, y2). In addition, pools of host proteins targeted by one pathogen will be screened with key effectors from another (M27, y2). Transient silencing or overexpression of host targets will be conducted via virus-based transient expression systems such as virus induced gene silencing (VIGS) that are in place for potato (e.g. PVX) and barley (e.g. BSMV) or *Agrobacterium tumefaciens* based systems (M33, y2). The diversity of host nodes in potato will be assessed by RNAseq analysis of wild potato accessions. BioSS will develop tools (e.g. TOPALi) for gene diversity/ selection pressure analysis (y2 O1.7) and to facilitate alignment/ phylogenetic/ selection analyses. This will underpin structural analysis of interactions between host nodes and targets (Year 3-5, St Andrews). *Outputs* will include avirulence genes from *G. pallida*, *P. infestans* and *R. commune* that will be used as markers for resistance screening (RD2.1.2)(y1), identification of essential and/or conserved effectors from *G. pallida*, *P. infestans* and *R. commune* that can be used as targets for identifying durable resistance and host targets of effectors, including common host targets (y3-5).
For *P. infestans* and *G. pallida* and viruses, effectors that target the nucleus will be screened against Y2H libraries to identify nuclear proteins targeted by these pathogens (y1, O1.3.1). The potential functional roles of these targets will be analysed using VIGs and/or over-expression assays, followed by infection with the relevant pathogens (M21, y2). In order to better understand the role of host proteins in virus infection and resistance we will examine their interactions with key proteins of economically important viruses (M28, y2). Interacting plant proteins will be determined using Y2H screens, and their contribution to defence against virus infection will be assessed (M34, y2). Whether these host proteins also respond to other pathogens, such as bacteria, will be tested (M40, y2). The roles of such proteins in temperature dependent responses will also be analysed (y 3-5). *Outputs* from this work area will include the identification of nuclear

proteins targeted by pathogen effectors that will be targets for resistance breeding approaches in RD2.1.2 (y1) and information on the links between these proteins and disease processes (y2+). Work on nuclear modulation of by pathogens will yield new approaches that are enhance expression of foreign proteins from virus vectors for enhanced plant production of novel vaccines (RD2.2.5) and diagnostic kit components (RD2.2.4).

Plant response

Objective 2 - Achieving sustainable resistance under abiotic stress

Effectors which target host proteins that may have roles in tolerance to abiotic stresses will be stably expressed in suitable crop plant accessions using established transformation technologies (M6, y1). Pathogen growth assays will be performed using established protocols and nodal cuttings will be used to ascertain resistance towards heat and water stresses (M12, y1).

Transcriptional profiling (microarrays) of plants where resistance is compromised at warmer temperatures (28°C) will be used to derive a better understanding of signalling networks and to study R protein (and other defence-related host proteins) for stability/defence signalling vs heat adaptation (as well as pathogen fitness) (M18, y2). Candidate genes differentially regulated in the different treatments compared with control (susceptible) plants will be selected and the microarray results validated by qPCR (M22, y2). From this the most promising genes will be selected for transient (VIGS) and then stable knock down (RNAi) to test the effect on infection in controlled conditions (M30, y2). We will also test whether these genes influence infection by other important pathogens (M41, y2). The function and mechanism of action of selected genes will be determined by cell biological studies, protein-interaction analysis and structural biology (M13, y1 – St Andrews, continues in y 3-5). This will include analysis of the expression of Mx in potato in response to virus infection (M13, y1) and analysis of the role of Mx in resistance to viruses (M31, y2). *Outputs* will include genes required for virus infection at differing temperatures, information on role of these genes in infection by other pathogens, stable transformed potato lines in which important genes are knocked out and an assessment of the function of candidate genes. This will allow us to better understand resistance processes and hence devise better breeding strategies. In addition, gene variants that confer improved resistance performance under changing climate conditions may be targets for breeding.

Epifluorescence microscopy and/or mass spectrometry will be used to detect and quantify antimicrobial compounds such as phytoalexins in leaves of accessions of *Solanum phureja* in response to challenge by bacterial pathogens (M14, y1). This will be informed by disease resistance previously measured in CWP6.4. The antimicrobial activity of phytoalexins extracted from leaves of selected accessions will be investigated using GFP-labelled bacteria (M23, y2). Once the role of phytoalexins in resistance to bacterial pathogens has been established, their production at 28°C will be analysed to determine any effects that increased temperature might play (M35, y2).

To determine the mechanism of age-related resistance (MPR) in relation to plant physiology and developmental stage we will study source-sink relations and solute transport using fluorescent tracers, FTIR spectroscopy and chlorophyll fluorescence measurements. For virus transport studies, fluorescently-tagged infectious clones will be used (M15, y1). We will identify markers that can be used to predict the onset of MPR and determine the efficiency of MPR to protect plants against different pathogens (M36, y2).

Objective 3 - Key host mechanisms controlling disease expression & yield response in major crops.

Barley starch metabolism mutants will be tested for their effect on disease expression (M2, y1). Measurements of fungicide effects on photosynthesis and respiration, carbon partitioning to the developing ear, ear development and spikelet survival/abortion along with tissue soluble sugar concentrations will be taken to address how fungicides affect grain number and prolong GLA retention using infra-red gas analysis, ^{13}C pulse-labelling and enzymatic determination of metabolites (M16, y1). Isolated non-pathogenic saprophytes will be tested for their sensitivity to major fungicides (M7, y1). Varietal variation for stress tolerance to abiotic/biotic stress combinations will be assessed in combinatorial stress phenotyping assays. The effect of abiotic stress on symptom expression will be tested using a developed hydroponic cultures system (M3, y1) to alter carbon and nitrogen levels of barley plants (M9, y1). The roles of chloroplast breakdown and ROS imbalance in the onset of disease symptom expression will be examined using barley mutants deficient in chlorophyll biosynthesis or redox-related genes (M24, y2). Levels of ROS will be measured using spectroscopic assays (M32, y2). Seedling assays will test the hypothesis that increased senescence in plants exposed to abiotic stress accelerates the transition of necrotrophy by increasing ROS concentrations (M42, y2). Effects of non-pathogenic saprophytes on photosynthetic activity will be measured in controlled environments (M25, y2), whereas sampling of saprophyte isolates throughout the growing season in fungicide treated and untreated plants will be used to link changes in saprophytes with leaf senescence and costs to crop fitness (M37,y2). Photosynthesis will be measured during the grain filling process in treated and untreated plants to test the hypothesis that crops have the ability to up-regulate photosynthesis to compensate disease-related GLA loss to minimise grain losses (M43, y2).
Expertise: The partnership in RD2.1.3 is one of the largest groups of researchers working on pathogens in the world and was judged to be internationally leading in a recent external peer review. This work is an extension of previous RESAS programmes including CWP6.4 and builds on previous investment in genomics. It requires access to UC including the Commonwealth Potato Collection, Barley and soft fruit germplasm collections as well as pest and pathogen collections and BioSS UC service 7. It will also require access to facilities available at The University of St Andrews (lipid analysis, protein expression and structural biology), as outlined in **HEI bid 1** "Structure-function relationships of pathogen effectors and surfaces". Access to core research facilities at Hutton including Imaging Technologies, Functional Genomics, Genome Technologies and the Centre for Sustainable Cropping – Balruddery, will be required.
Key linkages, interdisciplinarity & collaboration: RD2.1.3 will provide information that underpins outputs from other parts of the SRP including: *Other areas of WP2.1 – RD2.1.2, RD2.1.4, RD2.1.5, RD2.1.6:* Work in RD2.1.3 is extensively interlinked with that undertaken in other areas of WP2.1. Information and tools, in particular avirulence genes, will be used in RD2.1.2 for new resistance screening strategies and to identify sources of durable resistance. Information from mechanistic studies (O1) will inform genetic screens conducted in O6.1 of RD2.1.2 (y1-5). In addition, O3 will use methods for analysing combined omic datasets emerging from O4 of RD2.1.2 to help identify signalling networks important in responses to combined abiotic and biotic stress (O3). Information on diversity in avirulence genes will be used in RD2.1.4 in order to predict the durability of resistance and to inform sustainable deployment strategies. These sequences will also be used as targets for pathotype diagnostic tools in RD2.1.5. In addition, these areas of work will be used in order to develop more efficient IPM strategies (RD2.1.6). This will include information on pathogen biology that will underpin development of new chemical controls (RD2.1.6).

Evaluating risks associated with abiotic/abiotic stress on disease symptoms will be used as defined risk modifiers that will improve guidance to growers on the use of resistance to control disease as part of IPM programmes under a changing climate (RD2.1.6 O2). The work on nuclear modulation of plant responses will yield new plant lines and approaches that are better able to drive the expression of foreign proteins from virus vectors. This improved expression will be exploited in for enhanced production of novel vaccines (RD2.2.5) and diagnostic kit components (RD2.2.4) *WP1.1 - Soil:* A better understanding of how nutrient stress affects disease development and consequent yield penalties will link RD2.1.3 with crop genetic improvement (RD2.1.2). The long-term aim of this work will be to improve crop genetics such that chemical inputs are reduced (RD2.1.6) resulting in improvements to agricultural soil and associated ecosystems (WP1.1). *RD2.3.3 – Disease threats in the environment:* Work in RD2.1.3 will have direct links to RD2.3.3 through the identification of novel pest effectors and avirulence genes responsible for disease outbreaks and by improved understanding of how changes in environmental conditions affect crop susceptibility to disease. *RD3.1.3 – Food safety:* Work in RD3.1.3 will include studies on retention of food-borne pathogens by plants. Work on mechanisms of infection of plant pathogens (RD2.1.3) will provide information about how these pathogens are able to enter plants and avoid or suppress, plant defence responses. Staff in RD3.1.3 link to staff in RD2.1.3, through joint projects. RD2.1.3 staff have expertise in the biology of effectors and link to Dundee University through the Dundee Effector Consortium. Funded links exist with Leeds and Ghent (nematode effectors), Warwick University (*Phytophthora*) and The Sainsbury Laboratory (pathogen resistance). Several groups have joint projects in China (Nanjing, Wuhan, Zheijan & Hohhot). *Seedcorn PhDs:* Many aspects of the proposed work are aligned with strategic priorities of HEIs allowing researchers to attract funding for studentships through the Seedcorn PhD scheme. PhD student projects allow new areas to be developed for funding applications aligned with RESAS strategic priorities.
Added Scientific Value: Links with key players in this area are underpinned by competitive research funding. The range of work, from fundamental to applied studies, is reflected in the diverse funding sources and partnerships that have been established. Fundamental studies are supported by BBSRC (with support from CRF in some cases) in areas including *P. infestans,* PCN and aphid effector biology, effector determination of host range, novel resistance sources against *P. infestans,* PCN and viruses and mechanisms underlying pathogen nutrition. Research on infection mechanisms of aphids is funded by ERC. The industrial pull for this work is illustrated by the fact that many of these awards are Industrial Partnership Awards (IPA), with significant funding contributions from industry. Funding has also been obtained from other industry driven or industry led sources including Innovate UK (Virology – in collaboration with Enza NV), Agri-Tech Catalyst (Durable Resistance to *Rhynchosporium* – in collaboration with KWS), Genomia (brassinosteroid signalling in plant-pathogen interactions in collaboration with KWS), a Walsh fellowship on disease management with TEAGASC co-funded by BASF, BBSRC-Crop improvement research club (*Rhynchosporium* resistance) and AHDB (PCN avirulence, *Rhynchosporium* resistance, interactions of *Ramularia collo-cygni* and leaf physiology). The work described here attracts international funding. Links with key players within China have been funded via a BBSRC-China partnership award. Funding for international linkages has been obtained through ZAAS (virology), The Danish government (control of *R. collo-cygni)*, The Royal

Society and The British Council (various). Many aspects of the proposed work are aligned with strategic priorities of Scottish HEIs including The Universities of Dundee and St Andrews, reflected by joint appointments with these institutions.
KE, Audiences and Impact: One of the primary beneficiaries of the work being undertaken will be the plant breeding industry, benefitting from new markers for disease resistance genes and new tools for screening germplasm. The main route for transfer of relevant information will be through existing linkages and events, the CKEI through the sectorial lead, and jointly funded projects, often managed through James Hutton Ltd and linking to the Hutton pre-breeding programme, e.g. fundamental studies undertaken in CWP6.4 on virus movement has led to a partnership with a seed company that uses these viruses in their screening programmes. Ultimately, this work will result in new cultivars with enhanced resistance against key pests and diseases that will drive reduced inputs of pesticides and will improve industry competitiveness. The agrochemical and agbiotech industries will use information on new control targets in pathogens and crops and will benefit from new tools for probing mechanisms of pathogen attack developed in this RD. The main impacts will be new, sustainable, control compounds and tools that allow such compounds to be developed. A main route for KE will be joint funding applications with industrial partners (as evidenced by our previous success), with the potential for collaborative projects flagged by presentations at events at which industry is strongly represented. These will include Potatoes in Practice (KE1, y1 & KE5, y2), Cereals in Practice (KE2, y1 & KE6, y2) Crop Protection in Northern Britain and Scottish Society for Crop Research meetings as well as international events such as the International Symposium on Crop Protection. We will hold an industry KE event (KE4, y1) to disseminate work plans and progress to interested parties and to describe opportunities for future collaboration. *Growers* will be the ultimate beneficiaries of the work described here, through access to improved varieties, new control compounds and new crop protection strategies. The translational pipeline to growers will include links with relevant breeding companies, agrochemical companies, agbiotech companies and biopesticide companies as described above. The potential applications of the work described here will be publicised at relevant KE events. This work covers the full breadth of the translational pipeline from fundamental studies on mechanisms of infection through to more applied studies leading to development of practical crop protection solutions. The scientific community will therefore be another key audience for the work, benefitting from studies that provide information on mechanisms of pathogenicity, pathogen biology and function of the plant immune system. Results will be communicated through publications in high-impact journals and presentations at relevant meetings. RD expertise will also be available, where relevant, to contribute to CKEI Think Tank Agenda Setting publications. Various KE routes will be used to ensure that the *general public* are aware of the work: many of the issues tackled are of interest to non-experts, including pesticide use, natural resistance and agbiotech approaches to pest management. Scientists will disseminate and discuss findings at events such as the Fascination Of Plants days and the Royal Highland Show (KE3 & 7). Work undertaken in RD2.1.3 feeds directly into *government agencies* including Plant Health policy, SASA and the new Plant Heath Centre of Expertise.

RESEARCH DELIVERABLE NUMBER: 2.1.3
Work planning and timetable for Year 1:

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Identify avirulence gene(s) and/or core effector(s) from key pathogens							**M4**					**M10**
O1.2 Identify host target(s) of effectors from key pathogens			**M1**				**M5**			**M8**		**M11 O1.2**
O1.3 Identify host processes targeted by nuclear effectors							**O1.3**					
O2.1 Identify and functionally characterise potato gene(s) important in response to pathogens linked to abiotic stress and/ or development							**M6**					**M12**
O2.2 Determine link between elevated or reduced Mx expression and virus resistance												**M13**
O2.3 Identify correlation between antimicrobial compounds and host resistance to bacteria (O2.3)												**M14**
O2.4 Determine developmental stage for onset of Mature Plant Resistance												**M15**
O3.1 Determine effect(s) of on host physiology and microbial communities on source-sink relationships						**M2**		**M7**				**M16 O3.1**
O3.2 Determine barley response phenotype to disease						**M3**					**M9**	**O3.2**

symptom expression during biotic/abiotic stress												
KE Events: Potatoes in Practice					**KE1**							
KE Events: Cereals in practice			**KE2**									
KE Events: Royal Highland Show			**KE3**									
KE event – pathogen informed resistance								**KE4**				
Annual Report (Year 1)												**R1**

RESEARCH DELIVERABLE NUMBER: 2.1.3
Work planning and timetable for Year 2:

Year 2: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Identify avirulence genes and/or core effectors from key pathogens							M29			M38	M39	O1.1
O1.4 Prioritise barley and CPC germplasm	M17		M19			M26	O1.4					
O1.5 Identify host nodes targeted by pathogens			M20			M27			M33			O1.5
O1.6 Mechanistic links between nuclear processes targeted by pathogens and defence signalling			M21			M28			M34		M40	O1.6
O1.7 New software tools for gene diversity										O1.7		
O2.1 Identify and functionally characterise potato gene(s) important in response to pathogens linked to abiotic stress and/ or development	M18		M22				M30				M41	O2.1
O2.2 Determine link between elevated/ reduced Mx expression and virus resistance							M31		O2.2			
O2.3 Identify correlation between antimicrobial compounds and host				M23					M35			O2.3

resistance to bacteria												
O2.4 Identify markers to detect onset of MPR									M36			O2.4
O3.3 Effect of reactive oxygen species imbalance during stress on disease expression					M24			M32			M42	O3.3
O3.4 Determine effects of disease and non-pathogenic saprophytes on photosynthetic capacity in barley					M25				M37		M43	O3.4
KE Events: Potatoes in Practice						KE5						
KE Events: Cereals in practice			KE6									
KE Events: Royal Highland Show			KE7									
Annual Report (Year 2)												R2

Name of RD: 2.1.4 – Plant Pest Epidemiology
Research aim and key drivers: The risk management and control of plant diseases can be improved through an understanding of key rate-limiting processes (epidemiological parameters) and optimal ways of manipulating them. These parameters underpin the development of epidemiological models that can be used to predict the effect of management strategies, including crop protection and host resistance. This work aims to define the parameters for problematic and economically important diseases of crops of particular importance in Scotland, to deliver practical disease control solutions. These diseases include Late blight, blackleg, PCN and PVY on potato, *Rhynchosporium* and *Ramularia* on barley, *Fusarium* on wheat and Spotted Wing Drosophila (SWD) on soft fruit. With the exception of SWD and *Fusarium*, we have developed considerable resources, knowledge and expertise for these diseases allowing progress towards their effective control and making them model organisms for informing other research. To achieve sustainable crop production, an approach that rationalises inputs by the use of improved forecasting and risk assessment tools is needed and is driven by ongoing dialogue with farmers, agronomists, advisors and levy boards. Important and relevant data (crop histories, rotations, climate fluctuation and disease data) and significant information derived from CWP6.4 are available to help achieve this aim. Our priorities will be a) to develop specific forecasting models for diseases of major crops such as potato, where there is potential for substantial pesticide savings and b) improved disease control and improved disease risk assessment to inform on-farm decision making and research prioritisation. A major strength of the research will be to combine diverse epidemiological data from important crop pests, extensive cropping and climate data and innovative modelling approaches to build a new generic modelling framework applicable in real farm environments. Knowledge gaps that will improve risk assessment and disease forecasting in a changing climate will be targeted. These developments are critical to the development of National Action Plans (NAP) required to meet the obligation on Member States under Article 4 of EU Directive 2009/128/EC to establish a framework for community action to achieve the sustainable use of pesticides transposed in the UK by the Plant Protection Products (Sustainable Use) Regulations 2012 (the PPP (SU) Regulations 2012; SI 2012 No' 1657). This includes a requirement to adopt the principles of IPM at advisor and professional user level from 2014 (Article 14.1). It also contributes to Food Security policy by delivering improved disease forecasting and pathogen diagnostics together with effective and durable disease control methods with less detrimental impact on the environment. Better targeted and reduced use of pesticides will contribute to reduced likelihood of run-off and pollution of water courses, a major component of the Water Framework Directive. KE through an efficient extension service will ensure uptake of new developments from this RD to advance IPM (RD2.1.6) and through integration with larger management systems (RD2.3.9) and subsequently taken up in practice (RD2.3.12) to enhance the sustainability of Scottish agriculture.

Summary of the proposal: Extensive existing expertise with the major diseases of potato, barley and soft fruit provides the basis of research to understand key epidemiological parameters and to inform disease control strategies. In CWP6.4 changes in the populations of *P. infestans*, Ramularia and aphid populations in response to management practices were identified and practical changes to advice for the control of late blight on potato and Ramularia on barley resulted. Additionally, the potential importance of asymptomatic infection by Ramularia and Rhynchosporium and the phylloplane organisms that interact with disease development were identified. Modelling will be used in RD2.1.4, where appropriate, to allow incremental improvements in various aspects of disease management. This will result in lower disease risk, improved resource efficiency and reduced losses due to pests and diseases. We will build on our expertise base, UC resources including the crop and pathogen germplasm collections and the Centre for Sustainable Cropping (CSC) and considerable progress made under CWP6.4, together with many associated externally-funded research grants. We will continue to utilise the extensive data available through IACS, the June Agricultural Census, the plant health data held by SASA, meteorological data, UK, EU and international pathogen population surveys and analysis collaborations and other sources as appropriate through agreements, contracts and collaborations. The experimental research farms and trials network across Scotland available to Hutton and SRUC for sampling and demonstration will be used. The overall approach takes modelling as an overarching component, then focuses on contributing components of an epidemic: understanding and identifying inoculum sources, characterising populations and changes therein in response to environmental variables and informing disease control.
O1: Epidemiological modelling: Key deliverable: An epidemiological modelling framework which integrates weather and spatial crop and pathogen data to determine disease risk and identify critical knowledge gaps. This will be done at both the host-pathosystem level and at a more complex systems level. Complementary crop disease management choices with respect to risk will be studied in an HEI collaboration with Universities of Stirling and St Andrews **(HEI bid 9).** The outcomes will be 1) a prototype modelling framework for simulating plant disease epidemics and projecting future risk, 2) simulation models which predict how land managers respond to perceived and actual disease risk (HEI), 3) an aphid-weather abundance model, and 4) behavioural data from choice experiments with land managers with respect to risk-income trade-offs and changes in disease risks, linked to the simulation model from 2) (y3-5 HEI).
O2: Inoculum sources: Key deliverable: Determine the importance of pathogen and phylloplane microbial inoculum in epidemic development to advance understanding of their influence on major crop diseases. This will aid the design of an effective control strategy as part of IPM (RD2.1.6) safeguarding sustainable production systems by using benign or beneficial microbes to help control pathogens or keep them in a benign state. The outcomes will be 1) an improved risk assessment model and topic sheets for Ramularia on barley, 2) determination of the extent of toxin-forming Fusarium species and toxin levels in wheat and barley across Scotland, 3) a topic sheet on the impacts of sustainable and conventional crop management on disease, 4) principles leading to practical recommendations for optimum component proportions and patch size in mixed cultivar barley, and 5) an annual assessment of the incidence of SWD integrated with a UK-wide assessment.
O3: Pathogen populations: Key deliverable: Characterise the response of key pests and pathogens to environmental change and management practices to inform selection and deployment of appropriate and durable control measures. It will also allow a measure of the effect of future disease risk/spread on host crops and

alternative/emerging hosts. The outcomes will be 1) a fully characterised representative *G. pallida* UK population for use in resistance evaluation and monitoring virulence distribution, 2) recommendations for improved management of potato blight primary inoculum, 3) effective deployment of late blight disease management decision models via KE events, publications and the Euroblight consortium, 4) improved risk assessment model of Ramularia leaf spot through understanding of the population, 5) an online resource for rapid molecular fingerprinting of *Dickeya* and *Pectobacterium* and functional/metabolic predictions for phenotyping and assessing risk to be combined with a tool (RD2.1.5) for in-field diagnosis and detection, 6) an assessment of the potential for improved crop protection of grass in Scotland, 7) an improved model for virus spread in potato.

Technical approach

O1: Epidemiological modelling: Defining knowledge gaps in risk assessment and forecasting by through development of an epidemiological modelling framework. Extensive cropping and climate data, together with innovative modelling approaches, will be used to build a new generic modelling framework that can accommodate the diverse epidemiological data from the real heterogeneous Scottish farm environment generated in CWP6.4 and RD2.1.4, and compare it to (inter)national data. The resultant framework will be modular, allowing sub-models tailored to the extent of pathosystem/management information available, and will focus on crops and pests important to Scotland and globally. The model will be adaptable to weather-based risk assessments for emerging pests/pathogens that may have limited epidemiological information or complex epidemic/agronomic scenarios, where knowledge of host-agent-environment interactions is more extensive. It will also identify critical pathosystem knowledge gaps for key epidemiological parameters. The advanced model will be used to provide a quantitative analysis of risks for existing and emerging crop pests and pathogens. An online version may be developed for KE of key epidemiological principles with stakeholders, policy makers, regulators, growers, and the public. In the HEI collaboration (Universities of Stirling and St Andrews) a combination of simulation models and choice experiments will be used to understand disease management options by comparing forestry and agriculture decisions. Regression and mechanistic models will be used to examine the abundance of aphid vectors over the potato growing season and from year-to-year in relation to changing weather events. The applicability of advanced regression methods to modelling of relationships between waterborne zoonotic protozoa and rainfall (WP1.2) will be explored.

O2: Inoculum sources: Defining the importance of inoculum sources on epidemic development. Despite progress made in CWP6.4 significant gaps remain in our understanding of the biology of the major crop diseases including Ramularia leaf spot and Rhynchosporium on barley, Fusarium head blight on cereals, spotted wing drosophila (SWD) on soft fruit and Alternaria and Sclerotinia on potato. Research will therefore examine i) asymptomatic infections on resistant and susceptible crops and the role of crop debris and seed as reservoirs of inoculum and the effects of agronomic inputs (e.g. fungicides, cultivation) thereon under various farming systems (CSC conventional vs sustainable management regimes); ii) the impact of phylloplane communities on disease establishment and whether population changes through the growing season under different management practices relate to disease development (link to RD2.1.3); iii) the benefits of mixed cropping systems on reducing disease incidence by examining the impacts of crop morphologies on pathogen splash dispersal and canopy penetration, as well as patch size and distribution of component cultivars; iv) the location of spore production in the field, spore dispersal, and shifts in sensitivity and species composition in disease complexes, including the role of environmental factors e.g. leaf wetness on spore release. This builds on spore trapping work (CWP6.4) and will allow appropriate crop protection protocols to be devised; v) the efficacy of control using conventional fungicides v. biocontrol agents (RD2.1.6), by examining levels of deoxynivalenol and zearalenone in cereal samples which are often currently above recommended limits, to provide improved control options for growers, and vi) the presence and spread of new pests and pathogens (particularly SWD) in and across agricultural and non-agricultural land (including woodland and imported planting materials), and the role that a northern climate, might have on their spread and establishment. Outcomes will include practical advice for growers and a strong focus on IPM implementation (RD2.1.6).

O3: Pathogen population biology: Characterising pathogen response to changing climate and control measures to determine risk. To implement effective use of new germplasm, IPM tools and agronomic practices, knowledge of the population structure of key pathogens is critical to understanding how they overcome management interventions. Populations of a range of pests and pathogens including *Phytophthora infestans*, PCN, aphids and *Pectobacterium* on potato, and *Ramularia* on barley, will be investigated with a focus on five host-pathosystems. Late blight (*P. infestans*) populations change during epidemics across Scotland, UK and EU scales in response to inoculum sources, the effectiveness of cultivar resistance and the environment. Knowledge of pathogen effectors (RD2.1.3) and resistance of cultivars will be combined to relate resistance to genotype and to forecast risk. Rcc populations will be studied to provide similar information that can be deployed in RD2.1.6. PCN populations, both *G. pallida* and *G. rostochiensis,* will be related to known resistance in potato cultivars. Resistance to *G. rostochiensis* is effective for different genotypes, but for *G. pallida* is only partial and therefore field populations will be characterised to ensure that new resistances are tested against appropriate isolates. The effectiveness of *G. pallida* pyramided resistance (RD2.1.1) will be determined against defined populations. The peach potato aphid *Myzus persicae* and the grain aphid *Sitobion avena*e are vectors for several important potato viral diseases, including PVA and PVY and an *S. avenae* clone has pyrethroid resistance. Distribution will be monitored to predict the spread of PVY and the data fed into a UK-optimised model. Further work (y3-5) will focus on the application of a PVY model derived from a USDA-BBSRC project to a Scottish landscape scale incorporating mature plant resistance data from RD2.1.3. *Dickeya* and *Pectobacterium* populations continually change in Europe and are a constant threat to Scottish potato production. Data from high-throughput sequencing will be incorporated into an online resource that will allow rapid molecular typing of new isolates based on genome sequence information, together with functional/metabolic predictions for phenotyping as an essential tool for epidemiological studies leading to better control. The resource will integrate into the Global Microbial Identifier (GMI) initiative (a global system of DNA genome databases for microbes) to ensure international uptake, and could be adapted as part of a common platform for genomics research and typing on other plant and animal pathogens.

Scottish farming land is dominated by pasture for grazing stock. The more productive low hill or lowland pasture is often improved but still has relatively low inputs compared with arable crops and negligible inputs in terms of crop protection. However, there is evidence that crop protectants can protect yield and digestibility of grass. Whether crop-protection is cost-effective, the parameters needed to determine this and the effect on potentially beneficial grass-microbe interactions are unclear. Beneficial fungal endophytes in grasses are worth an estimated NZ$ 200 million to New Zealand agriculture. The potential for their exploitation in Scottish agriculture should be determined alongside the possible conflicts with crop protection methodologies and products. Should this lead to a requirement for new diagnostics for grassland management, these will be developed in RD2.1.5.

Detailed work plan

O1: Epidemiological modelling. New epidemiological knowledge will be synthesized in an overarching, modular risk assessment framework based on a user-defined combination of generic crop growth, disease/disease risk, and dispersal models. UK Met Office baseline data will provide current weather conditions. Weather data for climate change scenarios will be derived from the UK Met Office Climate Projections database (UKCP09) 11-member ensemble of spatially coherent climate projections (SCPs). Annual data defining the spatial coverage of crop species in Scotland will be derived from the IACS and JAC datasets. These data will be used to provide realistic distributions of pest/pathogen/host populations. We have prior experience in working with these large climate and crop datasets. Initial development of the framework (y1-2) will proceed using the MATLAB numerical computing environment (M4). Potato late blight will be used as a model system, as we are currently in the process of obtaining licenses for landscape-scale outbreak data for late blight, and the corresponding weather data. This will be used to validate the modelling framework at a national level and will link with RD2.1.6 O5.2 where the model for potato late blight will be re-parameterised for the contemporary *P. infestans* pathogen population. The framework will be refined and a user interface developed in y3-5, and case studies for existing and emerging crop pests and pathogens. In the HEI collaboration "Disease management options: Insights from comparing forestry and agriculture" (Kleczkowski & Hanley **HEI bid 9**) we will study disease management options through modelling response to disease risk with models calibrated by measured preferences of land managers under disease risks (comparing forestry and agricultural systems). In collaboration with SASA, using UK suction trap data, we will review and develop approaches to modelling abundance and timing of aphid flights at a single site then generalise to accommodate spatial variability and to consider wider applications.

O1.1 Output: Prototype modelling framework for simulating plant disease epidemics and projecting future risk (M12).

O1.2 Output: Prototype modelling framework for decision making by land managers in response to perceived and actual disease risk (M10)

O1.3 Output: Report on approaches to modelling abundance and timing of aphid flights (M24).

O1.4 Output: Design of behavioural choice experiments for land managers with respect to risk-income trade-offs in response to changes in disease risks (M24).

KE1 Models implemented on-line/made available to other researchers as required and publicised as components of their exploitation (M24).

O2: Inoculum sources. Secondary spores of Ramularia (Rcc) will be produced and the effect of differing environmental conditions, e.g. temperature, oxygen, light and humidity on spore maturation and germination studied. The effect of cultivation and trash movement on Rcc levels in crops will be studied in field trials (y1&2). Rcc isolates will be produced from symptomatic leaves at trial sites (M1) and tested for i) population diversity using recently developed SSR markers and ii) sensitivity to fungicides determined by a multi-well plate assay. Testing of isolates will be carried out in years 1-5 and results compared to field efficacy of fungicides to determine shifts in risk of resistance. *R. commune* will be isolated from cultivars of winter barley at selected standard GPS

locations in the CSC regimes throughout the second rotation cycle. Isolates from symptomatic and asymptomatic leaves will be genotyped using SSR and pathogenesis markers as available from effector work (RD2.1.3). Pathogenicity characteristics will be determined for some isolates if they are shown to be divergent populations. Together with microbial diversity data (below) and disease data (RD2.3.9) for these locations, the effects of these management systems on sustainable crop protection will be determined. Findings and recommendations will be fed through CSC KE and SRUC barley disease management guides. Subsequently we will investigate the management treatments that affect these crop-pathogen-microbial relationships. Microbial diversity samples will be taken throughout the growing season from the same GPS locations as *R. commune* samples. Using molecular DNA fingerprinting techniques, changes in epiphytic bacterial and fungal populations will be monitored (M5) and related to disease development. This should indicate whether a change in microbial population is a pre-requisite or a consequence of disease development and be used to further develop risk assessments and disease forecasts in the field. This work links to studies investigating the effects of non-pathogenic microbes on the plant-pathogen interaction (RD2.1.3).
Structured trials of differing genotype unit areas of diverse canopy morphology and resistance types of barley, including minor components that contribute disproportionately to traits, will be carried out and disease progress measurements made (M6). These will be compared with model predictions to identify the key epidemic rate-limiting steps. These principles will be identified and disseminated in mixture design topic sheets and updates to EU ENDURE e-learning resources, and subsequently tested in trials to address practical agronomic and management issues. This will feed into a major crop diversity EU- proposal where validation and uptake will be developed considerably.
A spore sampler and meteorological station will be run at the Bush estate to gather information on spore movement. This site is host to barley, wheat, oilseed rape and grassland trials. Additional spore samplers will run through the summer at trial sites in Lanarkshire and South Ayrshire, close to cereal and potato trials. Potato trials will be inoculated and data on inoculum densities and environmental conditions gathered: information can be used in the evaluation of blight and other disease forecasting schemes and to provide information to the UK industry for the first time on the control of disease related to the risk forecast and emerging threats (RD2.3.3). Extracted DNA will be added to a comprehensive library that can act as a resource in investigating the appearance of new pathogens into Scotland. Model predictions and robustness will be validated by these data analyses in subsequent work. Multiplex PCR assays will be developed (RD2.1.5). as required for improving detection. Fusarium contamination problems will be investigated by sampling wheat, barley and oats from Scottish growers (y1, y2, M7), utilising links to the SASA, SRUC and independent consultants. A combination of assays will be used to identify and in some cases quantify the Fusarium species present (M8), linking with the PCR multiplexing assays proposed in RD2.1.5. Samples will be tested (by Aberdeen University) for mycotoxin levels (links to RD3.1.3). This work will be developed in subsequent years to determine the risks to human health and data on Fusarium species related to spore sampler and weather data (RD2.4.1) and the information will assist in model evaluation.
Weekly trap catches (Apr-Nov) and fortnightly (over-winter) from four established sampling sites in Scotland (M2) will be assessed for SWD and feedback returned to growers to initiate control measures. Additional sites will be monitored to identify 'hotspots' for targeted control measures. Trap catches and fruit will also be assessed to identify possible pathways of SWD into Scotland. An emergence test (RD2.1.5) will be used to help interpret trap data and devise containment strategies. Subsequent work will

include monitoring and incorporation of the most up to date best practice and control measures. Blueberry grower sites within 50 miles of Hutton will be assessed for disease and leaf samples collected for analysis.

O2.1 Output: Updated Ramularia life cycle, improved risk assessment model and Rcc Topic sheets (M18).

O2.2 Output: Disseminate information to growers/processors about levels of toxin forming Fusarium species in wheat and barley around Scotland (M24).

O2.3 Output: Determination of impacts of sustainable and conventional crop management on phylloplane and disease onset – Topic sheet (M24).

O2.4 Output: Parameter values for scale modelling optimum component proportions and patch size in mixed variety barley. (M20).

O2.5 & O2.6 Output: Annual season report on incidence of SWD (M12, M24).

O2.7 Output: Data for development and evaluation of risk models for *Alternaria*, *Sclerotinia* and late blight of potatoes (M24).

KE2 Activity: Presentations at AHDB/SRUC disease roadshows (KE2), crop protection conferences (KE3), SRUC Technical notes, potatoes (KE4), cereals (KE5),SRUC blight event (KE8), SWD reports to AHDB, SG and SSCR (KE9).

O3: Pathogen population biology. A detailed evaluation of the population structure of *P. infestans* will be undertaken using previously collected data on >2000 British potato late blight outbreaks (y1, y2). The spatial and genetic diversity (neutral markers and pathogen effector) data collected over the last decade and associated outbreak data will be standardised and entered into the Euroblight database for analysis using novel population genetic tools. In addition. this will be interpreted in the context of spatio-temporal disease risk models developed in RD2.1.4. This will provide the industry with knowledge to improve the short (disease risk and primary inoculum) and longer-term (improved decision support and breeding programmes) management of late blight. Such models and resultant management advice will be refined (y3-5) in response to changes in the pathogen population and industry requirements. This will link with work on *Phytophthora* activity on dispersal of endemic/invasive species in the wider ecosystem (RD1.3.3). Rcc populations sampled and isolated from two SRUC trial sites (y1, y2, M9) will be genotyped using SSR markers, the information related to disease control and sensitivity of isolates to key fungicides (O5) and fed into IPM programmes (RD2.1.6). Information will be gathered and used to design and evaluate IPM programmes for field control of RLS (y3-5). Families of ~300 PCN cysts/single cyst line will be obtained for genotyping and phenotyping. A sub-sample from each single cyst line will be characterised using mitochondrial and nuclear markers and a panel of ~20 that represent the molecular and geographic diversity will be selected for phenotyping. A panel of potato genotypes including those combining resistances to *G. pallida* (RD2.1.2) will be tested with selected single cyst lines to provide evidence for the industry of the effectiveness of the resistance to Scottish *G. pallida* populations in new potato cultivars. A panel of molecularly and phenotypically characterised *G. pallida* for use in resistance tests will be delivered. Samples of *M. persicae* and *S. avenae* collected from Scottish suction traps will be genotyped (y1, y2, M3, M10). The proportions of known clones with different R types and new invading clones will be identified and the insecticide resistance profiles of any new clones characterised. Results will feed into UK models developed for virus epidemiology and will facilitate the selection of targeted control measures. Continued monitoring (y3-5) will validate these data.

An integrated on-line resource for bacterial pathogens will be developed using open-source frameworks (e.g. InterMine, Galaxy) on a virtual server, which will liaise with GMI to ensure that community standards are followed (y1, y2). *Dickeya* and *Pectobacterium* sequences will be identified from local, national, European and global collections and collaborators, and extended with novel isolate samples where applicable (y1-5). Sequence data will be passed to RD2.1.5 for development of improved diagnostics for *Dickeya* and *Pectobacterium*. The online resource will be extended to cover diagnostics and metabolism and is anticipated to feed into a H2020 consortium on federation of plant pathogen resources for remote computing and data integration. A review of the literature on crop protection on grass will be undertaken informed by work on potential cereal crop endophytes (RD2.1.7) and pilot pasture fungicide trials. It will also be informed by pilot investigations of the Ramularia and Fusarium inoculum load carried on pasture samples as representative of putative fungal pathogen challenges that have a potential defence cost to the grass. Targeted crop protection will then be tested, sampling and diagnostics requirements of key pathogens assessed and a grassland pathogen management strategy will be evaluated (y3-5).

O3.1 Output: Molecularly and phenotypically characterised *G. pallida* for resistance evaluation and virulence monitoring (M18).

O3.2 Output: A strategy for the improved management of potato blight primary inoculum via detailed analysis of late blight populations (M8).

O3.3 Output: Improved long and short-term management strategy for decisions delivered via more robust models of late blight epidemic development (M24).

O3.4 Output: Report on population structure of *R.collo-cygni*, input into risk assessment model of Ramularia leaf spot(M24)

O3.5 Output: Genotyped *M. persicae* and *S. avenae* samples caught in Scottish suction traps fed into national network (M12 and M24).

O3.6 & O3.7 Outputs: Publically available resource integrating genomic analyses, sequence typing, phylogenomic classification and diagnostics (M24).

O3.8 Output: Review of the potential of crop protection in grass in Scotland.

KE3 activity: Demonstrations to SASA and Fera; European statutory testing service partners via Euphresco; CoZEE; FSA; MRPs (Moredun, SRUC and Rowett); integration with GMI; Stakeholder events such as PiP (KE6) and Potato Council seed meeting, agricultural press and the Euroblight web site (KE7).

Expertise: The expertise to carry out the proposed work is evident in the research track-record of the staff named above. Modelling and socio-economic expertise is strengthened by state-of-the-art approach by University of Stirling and University of St Andrews through **HEI bid 9**. UoS staff member has a long experience in epidemiological modelling, particularly of plant diseases and more recently bioeconomic modelling, and excellent research links including Cambridge and York Universities. UoStA staff member has an environmental and behavioural economist with internationally recognised expertise in environmental valuation, environmental cost-benefit analysis, ecological economic modelling, design of Payment for Ecosystem Service schemes and agri-environmental policy. Both bring highly complementary skills to the collaboration. Expertise in population biology has similar international profile: SRUC and Hutton have led in the epidemiological understanding of potato late blight and Ramularia in particular. Expertise in key potato and barley pathogens is backed by culture collections and genetic resources for host resistance, and we have a strong track record of industry collaboration.

Key linkages, interdisciplinarity & collaboration: This RD work programme is interdisciplinary, highly collaborative and integrated across Hutton and SRUC. Six key linkages include: **1.** Other RDs: from crop genetic diversity and improvement (RDs 2.1.1 & 2.1.2) as source material driving epidemiological change, through the mechanistic interactions of RD2.1.3, analysis of population diversity (RD1.3.3) and development of

new diagnostics and further analysis in field (RD2.1.5, RD2.3.3), threat to human health (RD3.1.3) and application of the knowledge in IPM (RD2.1.6), where communication and coordination of material and data will be facilitated in Work Package meetings. RDs 2.1.4, 2.1.6 and 2.1.8 deployment of heterogeneity work links with ecological understanding developed in crop in RD1.3.1. Knowledge will be taken up in the IMS studies in RD2.3.9, trade-off implications analysed in RD2.3.11 and uptake route in RD2.3.12. **2.** EU collaborations such as ENDURE, the Euroblight consortium and several 2020 projects are currently submitted, or will be soon. These are crucial for studying pathogens that cross borders. **3.** AHDB (AHDB Cereals & Oilseeds, Potatoes and Horticulture) through many grants, but also participation in their other function such as the AHDB Recommended List committees and the UKCPVS. Monitor Farms, Workshops and national collaborative field events such as Potatoes in Practice, Cereals in Practice and Cereals. **4.** Collaboration with a USDA project consortium on PCN populations in Europe, N and S America with the aim of developing durable resistance. **5.** Collaborations with international academic community through joint appointments, PhD studentships, teaching and examining and specific HEI collaborations. Active involvement in academic and industry professional bodies e.g. BSPP, SGM, AAB, BMS, ACPNB, and with Rothamsted, Harper Adams University and John Innes Centre. **6.** Active involvement in the PHCOE and regular and close links with SASA and Northern Forest Research Station on plant health issues.
Added Scientific Value: The Ramularia work is closely linked with a large Danish Strategic Research Council grant (SRUC, Hutton, Universities of Aarhus and Copenhagen, Sejet Plant Breeders), resulting in many synergies. Work is closely aligned with the priority research areas of AHDB Potatoes, with whom a regular dialogue helps to combine funding support from end-users and science funders. Studies also link strongly with BBSRC HAPI initiatives and Innovate UK funding. The cereal pathogen work is in line with AHDB Cereals and Oilseeds 2015-2020 research priorities, particularly “develop and promote tools for monitoring and managing risk”. Links to AHDB-funded work on improved risk forecast for Ramularia leaf spot and Light leaf spot in oilseed rape.
KE, Audiences and Impact: Work will be presented at national and international scientific and at industry-targeted conferences e.g. Crop Protection in Northern Britain and SSCR meetings, AHDB-SRUC annual regional workshops and AHDB Potatoes forums; at Hutton-SRUC regular joint field events e.g. CIP, PIP and FFF and at LEAF Open Farm Sunday or Technical Events hosted on research farms and other open days. Opportunities to present newsworthy items are taken in the press, television and radio. We contribute to blogs e.g. LEAF topics are selected for press articles to communicate concepts, approaches or newsworthy findings. Audiences range from academics to policy-makers, advisors and growers and end-users. Knowledge derived from epidemiological data and models informs advice delivered at these meetings and publications for farmers and growers produced by SRUC, AHDB Cereals and Oilseeds and AHDB Potatoes (KE2, KE3) which are widely disseminated at events, through advisors and via the internet. Policy briefs will be developed for SG where applicable. Most dissemination and events are collaborative at the RD, WP and CKEI levels (e.g. indicative activities for Annual Campaigns, Annual Showcase, Think Tank). Associated research grants (e.g. BBSRC CIRC) and EU networks offer multiple KE opportunities. The overall impact of this work will be improved targeting of products by the crop protection and agrochemical industries, tailoring of crop protection methods and products for greater impact and efficiency by advisors and facilitation of the knowledge in an IPM and crop systems context by agronomists. The impact will largely be incremental

as epidemiology is about understanding complex, dynamic interactions between not only host and pest/pathogen but also all other biotic and abiotic factors in the environment. Intended targets for much of this work will be knowledge for application in IPM and crop systems management RDs in this WP, so measurement of their impact will be a reflection of this. Some will be reflected in the continued relevance and uptake of advisory publications such as the AHDB/SRUC Barley Management Guide, SRUC Technical Notes (KE2,3,4 & 5).

RESEARCH DELIVERABLE NUMBER: 2.1.4
Work planning and timetable for Year 1:

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1: Prototype plant disease epidemics modelling framework. Draft version for interaction with cropping and epidemiological data generated in RD2.1.4 and RD2.1.6.												**O1.1**
O1: Prototype modelling framework: Description of model for decision making by land managers in response to perceived and actual disease risk used to help design subsequent land manager choice experiment.										**O1.2**		
O2 Update on sensitivity status of *Ramularia collo-cygni* in Scottish barley. Practical implications reported to growers in AHDB-SRUC regional workshops.								**M1**			**KE2**	
O2: Annual season report on incidence of SWD Report of Scottish and English SWD trap catches from a range of soft fruit crops. KE9: Dissemination of findings to funders growers, SSCR soft fruit winter event and Fruit for the Future											**KE9**	**O2.5** **M2**
O3: Improved management of potato blight primary inoculum. Report on the strategy for improved management of potato blight primary inoculum. Delivered to KE events such as the winter forums,					**KE6**			**O3.2**				

Potatoes in Practice and the agricultural press.												
O3: Genotyped *M. persicae* and *S. avenae* samples caught in Scottish suction traps fed into national network.							**M3**					**O3.5**
R1 Year 1 Report to RESAS												**R1**

RESEARCH DELIVERABLE NUMBER: 2.1.4
Work planning and timetable for Year 2:

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Aphid modelling report. Report will summarise advantages of different modelling approaches												**O1.3**
O1: Behaviour experiment design. Report on design of behaviour choice experiments for land managers to inform model development												**O1.4**
KE1: On-line model implementation. Models implemented on-line/made available to other researchers as required and publicised as components of their exploitation.								M4				**KE1**
O2: Ramularia Topic sheets. Report will used by growers to assess risk of RLS and tailor IPM programmes accordingly. KE: Methods for assessing risk and potential IPM options available will be reported at CiP and Disease Roadshows			**KE5**					**O2.1**		**KE2**		
O2: Fusarium toxin data disseminated to growers/processors Report will be used by growers and processors to assess risk of disease and subsequent toxin production and provide guidance on appropriate IPM control methods												**O2.2**

O2: Crop management topic sheet. Information on the effects on phylloplane and disease of crop system management for use in KE events.							M5					O2.3
O2: Patch and proportion parameters for mixed variety barley. Validation that beneficial traits can be disproportionately expressed using by spatial and proportion manipulation.					M6			M2.4				
O2: Annual season report on incidence of SWD Data collected will help to determine when and where to apply control measures and best practice systems to incorporate into soft fruit management.												O2.6
O2: Data for evaluation of risk models for potato diseases Generate robust datasets that allow linking of inoculum availability, meteorological data and the onset of disease of particular benefit for developing and testing of potato disease forecasting schemes					KE1	M7 KE8			O2.7		M8	
O3: Characterised representative *G. pallida* populations. To be used for R evaluation in breeding material development.					O3.1							
O3: Blight management strategy. Report on how management decisions can be improved using updated late blight epidemic models delivered via KE events such as CPNB and AHDB.					KE4						KE6	O3.3

O3: Population structure of Ramularia, report and risk assessment. Link resistance risk with population diversity within Scotland. Shifts in population will be reported at Roadshows and linked to efficacy of control programmes.							**M9**			**KE3**		**O3.4**
O3: Aphid genotype report 2: Updated *M. persicae* and *S. avenae* sample genotypes caught in Scottish suction traps fed into national network and results disseminated at KE events such as CPNB and PIP							**M10**					**O3.6**
O3: Online integrated bacterial pathogen genomic database Report genome sequences and their annotations. Used to deliver specialized and genomic and biological information and support diagnostics/ epidemiology												**O3.7**
O3: Review of the potential of crop protection in grass in Scotland Report British Grassland Society (Scotland) and SG evaluating the needs and potential for crop protection to prioritise work.												**M3.6**
R2 Year 2 Report to RESAS												**R2**

Name of RD: 2.1.5 In-field detection

Research aim and key drivers

High value crops grown in Scotland (barley, potatoes and soft fruit) are susceptible to damage caused by a wide range of endemic diseases. In the future, these crops are likely to face additional disease challenges from new pests and pathogens due to factors including: the loss of key pesticides through legislation or reduced efficacy; increased global movement of diseased plant material and a changing climate. Integrated Pest Management (IPM) strategies aim to control diseases of particular crops or cropping systems using a combination of tools and approaches. RD2.1.5 underpins IPM by delivering improved methods of detecting, identifying and quantifying the key pests and pathogens in a timely manner in 'the field'. Using recent and emerging technologies (e.g. remote sensing technologies, 'point of care' diagnostics and next generation sequencing), new developments in pest diagnosis will exploit existing 'proof of concept' funding (often with industrial partners) with the aim of developing diagnostics that are both relevant to stakeholder needs and fit for the future. An assessment of crop protection needs in grassland in Scotland will be completed by the end of year 2 (RD2.1.4) and if new diagnostics/detection methods are required this need will be addressed within RD2.1.5. Outputs from RD2.1.5 will include new and improved detection and monitoring methods for key pests and pathogens and a consolidation of those which already exist from previous SG and industry funding. New methods, tools, information and services, will be delivered primarily through RDs 2.1.4, 2.1.6, 2.3.9 and 2.3.12 to maximize outputs and benefits to Scottish agriculture and to promote their development and implementation in partnership with key stakeholders including agronomists, growers and statutory organisations including SASA. AHDB feedback (following consultation) shows clear support for research within this RD.

Summary of the proposal:

The overall aim is to improve detection of economically important pests/pathogens/diseases affecting key Scottish crops. This will improve decision making for growers and control recommendations and inform policy and statutory recommendations, leading to improved disease control. Much of the proposed research in RD2.1.5 capitalises on outputs from the current RESAS programme CWP6.4 and externally funded research. Focus in the first two years will primarily be on developing/improving the necessary assays, tools and techniques. In years 3-5, the new detection methods will either be validated directly within RD2.1.5 and incorporated into relevant toolboxes within RD2.1.6, or be deployed within RD2.1.4 to develop disease risk assessments and/or forecasting to inform IPM strategies within RD2.1.6. The major activities over the 5 year programme will be:

Objective 1. Improved detection of potato pests and pathogens

O1.1: In-field diagnostics for soil-borne pests and pathogens

Key deliverable: An improved method for quantifying soil-borne potato pests and pathogens, with assessments of associated disease and/or yield risk, which will be validated and then incorporated into the IPM toolbox for potato (RD2.1.6, O5.2). Soil-borne pests and pathogens of potato, specifically; *S. subterranea* (powdery scab), *C. coccodes* (black dot), *S. scabiei* (common scab) and free living nematodes (FLN; primarily virus-vector trichodorids) cause significant losses to the industry. Current testing for some soil-borne pathogens and FLN exist, but in different formats. Through the synthesis of existing knowledge, in combination with new research inputs, detection of soil-borne pests/pathogens of potato and assessment of yield/disease risk will be harmonised (y1, y2). In years 3-5 the validation process will continue and a testing package with interpretation guides for specific pathogens will be developed to a format suitable for delivery through service providers (SRUC and James Hutton Ltd) to the Scottish potato industry.

O1.2: Diagnostics to underpin in-field detection of air-borne pathogens

Key deliverable: Specific, sensitive and, where possible, multiplexed assays to facilitate disease risk forecasting for aerial potato pathogens within RD2.1.4 to underpin IPM as part of RD2.1.6). Diagnostic assays will be validated and/or multiplexed (y1, y2) to underpin research on disease risk forecasting for the air-borne potato pathogens *Alternaria solani*, *Alternaria alternata, Sclerotinia* and *Phytophthora infestans* (RD2.1.4). This work compliments Innovate UK projects aimed at late and early blight forecasting, and builds on recent industry funded work that demonstrates the potential of detecting and identifying pathogen spores captured through spore-trapping.

Objective 2. Soft-fruit pests and pathogen diagnostics and population analysis

O2.1: Putting diagnostics for soft-fruit pests and pathogens into practice

Key deliverable: A quantitative (PCR) test for Raspberry leaf blotch virus (RLBV) to establish threshold levels for in-field disease which will allow growers to deploy control measures more effectively. RLBV has recently been identified as a serious threat to raspberry production. A specific and sensitive diagnostic (r-RT-PCR) assay will be developed (y1) and combined with existing diagnostics for other viral diseases to look at disease severity associated with multiple infections (y2). In years 3-5 work will focus on developing new molecular tests for existing and emerging diseases to meet Community Plant Variety Office approved testing requirements and engage fully with SASA to promote the adoption of the new diagnostics within statutory testing regimes.

O2.2: Improved in-field detection of Spotted Winged Drosophila (SWD)

Key deliverable: Improved interpretation of in-field detection of SWD for use in SWD epidemiology research (RD2.1.4), in turn informing control options to be incorporated into the soft fruit toolbox (RD2.1.6) and policy (SASA). In years 1-2, a natural emergence test will be developed to enable better interpretation of trap catches of SWD within the HDC/RESAS joint funded UK SWD monitoring project (2013-2017) and RD2.1.4 In years 3-5, SSR markers with the potential to reveal colonization patterns and to identify likely sources of new introductions of SWD will be developed based on existing markers for the closely related species *D. melanogaster*. This will assist growers in targeting control measures, and inform policy decisions (Centre of Excellence for Plant Health and SASA) with regard to identifying introductions and formulating avoidance strategies for similar pests.

Objective 3. Improved detection of cereal pathogens

Key deliverable: Specific, sensitive and, where possible, multiplexed assays to underpin modelling and disease risk forecasting for cereal pathogens within RD2.1.4 which in turn will be used to develop an IPM cereal toolbox as part of RD2.1.6 and for use by growers, seed industry and regulatory authorities. Rhynchosporium leaf scald is the major barley disease in Scotland. Recent advances in taxonomy have revealed that the disease is a complex of four species, with *R. commune* identified as the causal agent. Diagnostics produced before the re-classification need to be re-evaluated for specificity to *R. commune* (y1, y2). Fusarium Head blight is an increasing problem in cereal production in Scotland. The blight complex consists of a number of different species that change in abundance over time. Fusarium infected seed affects crop

emergence and mycotoxins produced by some species are dangerous to humans and animals (RD3.1.3). In 2012 toxin producing species were widespread in Scotland and levels of toxin that exceeded the safe limits for human consumption were found. In years 1 and 2, conventional qualitative primers for *Fusarium* species will be multiplexed to assist in seed testing and for use in RD2.1.4.
Ramularia collo-cygni is an increasingly important pathogen of barley. Advances in sequencing of other *Mycosphaerella* species have indicated that the ITS region used in diagnostic design may be highly conserved in this family of fungi and current diagnostics may not be specific. A new assay will be developed if an evaluation of the current one indicates lack of specificity (y1, y2).

Objective 4. Improved application of sensors and satellite imaging into early warning systems Key deliverable: Develop alternative methods of early disease warning that are appropriate for different spatial scales, timescales and levels of detail. This comprises highly complementary work using different technological and processing approaches which will be developed in this objective to detect disease but are also being used for phenotyping of resistance traits (RD2.1.1) and for detection of abiotic stresses (RD2.3.9). The main crops/pathogens to be studied will exploit existing field trials. However, the work will focus on methods that are transferable to a wide range of pathogens and crops.
Development of proximal sensing methodologies: hand-held devices used in close proximity to the crop/soil, to provide an assessment and quantification of crop disease. This work comprises the development and integration of low-cost mobile phone-based sensor equipment. This will provide sensor data for model calibration and inform development of field protocols for this type of work. Statistical evaluation of this data and linkage with disease presence/absence information will lead to sensor calibrations for rapid 'indicative' testing for infections by farmers for little or no cost. This will include assessment of the level of uncertainty, which is particularly important where detection limits are close to the sensitivity of the tests. Additionally, disease detection through portable infrared spectroscopy (FTIR) will be evaluated, with potential for incorporation into the development of a mobile (tractor-based) field phenotyping platform operating across multiple spectral ranges which will provide information at a scale appropriate for integration with methods for precision agriculture. This work complements recently funded InnovateUK research to evaluate hyperspectral imaging on an unmanned aerial vehicle platform to detect early stage potato disease. Approaches that integrate remote sensing and other spatial datasets will provide assessments of disease prevalence at the field scale.

Objective 5. In-field detection of important pathogens of key rotational crops
Key deliverable: Pathogen detection in field soils using molecular diagnostics to assess risk and evaluate control treatments and aid management of key rotational crops in an IPM (RD2.1.6) and IMS (RD2.3.9) approach.
This work links to O1.1, but addresses pathogens which infect key crops within typical Scottish rotations, including vegetable brassica spp., oil seed rape (OSR), sugar beet and carrots, often reducing yield and quality. Knowledge gaps currently hinder our ability to take a cross-rotation approach to disease control. Specifically;
O5.1: The relative importance of sub-groups (AGs) of *R. solani* responsible for disease on different crops is unknown and sample handling techniques to enhance pathogen detection, where threshold pathogen levels are not adequately detected, must be optimised (y1, y2), validated (y 3-5) and incorporated into a soil-borne

pathogen testing package (O1.1) which will extend to non-potato crops.
O5.2: Club root (caused by *P. brassicae*) is a major threat to OSR and other brassica crops in Scotland but the biological test currently used does not allow rapid information to be returned to the farmer to facilitate decision making. A rapid quantitative molecular diagnostic will improve knowledge of the pathogen distribution and biology in order to develop enhanced risk assessments (y1, y2). Projects with Levy partners (AHDB) will use the new diagnostic to investigate historical sites and the pathogen distribution within fields and across the UK. The rapid molecular diagnostic will be useful for farmers and consultants to manage OSR crops and will be used in RD2.1.6 (O4) to evaluate alternative club-root control treatments.

Objective 6. Novel genome-based methods for the rapid development of molecular diagnostic primers Key deliverable: Open source software for the development of diagnostic primers for new and existing bacterial threats. Primer design critical to successful molecular diagnostics. As part of the sequence analysis for *Pectobacterium* and *Dickeya* species (CWP6.4, RESAS CRF, Potato Council funding), a method, and corresponding software, was developed for the generation of highly specific PCR primers which are currently being tested by statutory testing laboratories throughout Europe (Euphresco diagnostic initiative). The software was further validated in association with Munster University, the control centre for the outbreak, for the *E. coli* O104:H4 pathogen responsible for a major outbreak of gastrointestinal disease in Germany in 2011: the resulting diagnostic primers were a significant improvement on those used during the outbreak. As blackleg disease-causing Pectobacterium and Dickeya species change rapidly, it is our intention to make available fit for purpose molecular diagnostics, where necessary designing new ones. The main aim of the work will be to improve the capabilities and speed of use of the software before making it available to the wider research, commercial and policy communities across plant, animal (WP2.2) and human pathology. The software will enable users to design bespoke primers to a wide range of microorganisms without the need for computational expertise and should become the first port of call, both within and out with the SG programme, for the development of diagnostics as new plant and animal disease threats emerge (O7).

Objective 7. New and emerging threats
Key deliverable. Identify the need to develop and implement detection methods for new and emerging pest and disease threats through regular contact with RD2.1.4 and RD2.3.3, SASA and the PHCOE and informed by the new Pest Risk Analysis for Scotland. This will include any requirements identified for new diagnostic and detection methods for improved grassland protection. Resources will be partitioned (as happened for the emergence of SWD in CWP6.4) from RD2.1.5 to deal with upcoming threats and to leverage industry funding as appropriate.

Technical approach (5 year plan)
Key outputs from this deliverable will be practical guides on the use of tools and methods for pest/pathogen/disease detection to assess disease risk and to improve disease control. Stakeholder uptake of tools/methods and advice developed in RD2.1.5 to improve IPM strategies in RD2.1.6 will be promoted via links developed between RD2.1.6 and RD2.3.12.

Objective 1. Improved detection of potato pests and pathogens

O1.1 In-field diagnostics for soil-borne pests and pathogens of potato. Previous research undertaken through AHDB funding in collaboration with Australian researchers identified soil sampling, DNA extraction and assay conditions suitable for predicting disease risk associated with the soil-borne pathogens *C. coccodes* and *S. subterranea* and tests are available from SRUC and Fera. Additionally, a soil testing service for FLN (currently not a molecular diagnostic) available through JHL is widely used by the seed industry. The aim of the work in years 1 and 2 will be to develop molecular diagnostic tests for FLN and *S. scabiei* in a format suitable for integration with existing procedures (or with modifications according to outputs from O5.1). Initial yield/disease risk thresholds for these pests/pathogens determined in years 1 and 2 will be further validated through a combination of pot experiments and sampling/testing using the CSC, commercial potato fields and experimental farm plots in association with stakeholders (y3-5). As robust yield/disease risk assessments for the range of target soil-borne pathogens of potato become available they will be incorporated into the potato IPM toolbox (RD2.1.6) and appropriate interpretation guides produced. A similar approach to a coordinated testing service in Australia (Diagnostic Services | PreDicta Pt) will be adopted as a suitable format for delivery to growers and other potato industry stakeholders from service providers. This work depends on the underpinning capacity of the pest/pathogen core-collections and the CSC.
O1.2 Diagnostics to underpin in-field detection of air-borne pathogens of potato. In order to evaluate the timing and quantity of release of spores of air-borne potato pathogens, samples from designated spore samplers will be assayed for pathogen presence (RD2.1.4). Assays for the simultaneous detection of the early blight pathogens *Alternaria solani* and *A. alternata* and *Sclerotinia* and the late blight pathogen *Phytophthora infestans* will be developed and/or applied. Existing PCR assays will be tested and multiplex assays re/designed. Testing of multiplex assays will be undertaken using DNA extracted from pure pathogen cultures and the sensitivity of the individual assays compared with a multiplex assay. Cross reactivity will be tested against other potato pathogens and DNA from other fungi.

Objective 2. Soft-fruit pests and pathogen diagnostics and population analysis
O2.1 Putting diagnostics for soft-fruit pests and pathogens into practice. An r-RT-PCR assay for RLBV will be developed to elucidate the relationship between disease severity and virus load. As more than one virus could be exacerbating disease, this assay will then be combined with testing for other prevalent viruses (previously developed) to reveal the effects of multiple infections on disease symptom severity. This work requires use of the Underpinning Virus Collection.
O2.2 Improved in-field detection of Spotted Winged Drosophila (SWD). A natural emergence test using infected fruit will be developed that will provide an estimate of the gender ratio of the population. This data will be used in RD2.1.4 to provide more accurate data on insect numbers based on trap catches and risk of damage.

Objective 3. Improved detection of cereal pathogens
Methods to improve detection of cereal pathogens and aid disease prediction and control will be on-going over the five years. This work will take into account pathogens of grasslands which can also affect cereals. Work in years 1 and 2 will focus on developing sensitive and specific assays for target pathogens. After evaluating specificity of existing assays, a quantitative real-time PCR assay for *R .commune* will be developed if necessary and validated against other barley pathogens. Additionally, conventional qualitative primer sets for *Rhynchosporium* species will be multiplexed to

allow rapid screening of samples from spore tapes and field trials in RD2.1.4. Conventional qualitative primer sets for *Fusarium* species will be multiplexed to allow rapid screening of samples collected from the Official Seed Testing Station (OSTS, SASA) and extension services within RD2.1.4. *Fusarium* species identification will be linked to mycotoxin results (Aberdeen University) being investigated in RD3.1.3 Human Health.Existing diagnostics for *Ramularia collo-cygni* will be evaluated and improved if necessary.

Objective 4. Improved application of sensors and satellite imaging into early warning systems
Early disease detection prior to symptom development facilitates timely and effective disease control. Sensor technologies, which can be deployed in-field, will be evaluated for their ability to detect disease. Information will be extracted from mobile phone imagery (e.g. leaf morphology and colour), and augmented with low-cost hyperspectral add-on equipment that is currently at the working prototype level. Image texture and spectroscopy analysis methods will be developed to optimise extraction of data from field measurements (with BioSS, underpinning capacity service 7). Ongoing and continuing development of this technique will provide the ability to develop a large set of baseline data for sensor calibration and modelling approaches, leading to the development of a mobile phone app for field-based visual crop disease assessment to assist land managers with decision-making. FTIR sensors will be used to detect chemical changes in crop plant species, in response to pathogen infection. FTIR spectroscopy provides a unique chemical profile of a sample allowing the qualitative analysis of a large variety of samples. Quantitative estimations of disease will be made through calibration with spectral data sets and laboratory reference data. A mobile field phenotyping platform integrating thermal, visual, near and short wave infra-red sensors/cameras to measure changes in canopy temperature and leaf spectral properties will be developed. This will indicate plant stress associated with early disease development under field conditions and allow the utility of imaging as a tool for high throughput detection and diagnosis of biotic stress to be evaluated. Field-acquired sensor data (mobile phone camera imagery, visible-wavelength spectroscopy) will be integrated with remote sensing data and existing spatial datasets (topography, climate, soil, land cover) using “cloud-based” processing, for crop disease monitoring in real time.

Objective 5. In-field detection of important pathogens of key rotational crops
O5.1 Optimised methods for the detection of intractable pathogens in soil. In glasshouse trials we will use existing real-time PCR assays to identify which *R. solani* AG groups are important in causing disease on a range of Scottish crops. Post soil-sampling handling procedures will be tested to establish maximum probability of detection of pathogens (*R. solani* AGs and FLN) at levels currently at or below threshold of detection.
O5.2 For *P. brassicae* (club root), published methodologies will be evaluated for their efficiency and sensitivity. If necessary a new assay will be developed and evaluated by testing soil that has previously undergone biological testing. Methods to differentiate between viable and non-viable DNA will be explored, e.g. the use of a DNA binding agent such as propidium monoazide.

Objective 6. Novel genome-based methods for the rapid development of molecular diagnostic primers.

Our prototype primer design software will be improved by replacing the PrimerSearch *in silico* validation step with an alternative approach based around graph theory, and extension of parallelization to SGE/DRMAA methods to speed up the process. Improved software will be validated on sequenced isolates of *Pectobacterium*, (obtained from the underpinning pathogen collection, an ongoing RESAS/Potato Council-funded blackleg project and RD2.1.4 investigating the main threats from *Pectobacterium* in Europe). Improved software for rapid and accurate primer design will be released (y2) as open-source software *via* standard institution routes (e.g. GitHub). In years 3-5, the use of the software in other areas, e.g. RD2.2.4 animal health diagnostics, RD2.3.3 disease threats in the environment and RD3.1.3 food safety, will be investigated as a single source solution to molecular diagnostics design throughout the Programme and possibly beyond, e.g. healthcare through FSA and/or the Cooperative of Zoonosis Experience and Expertise (CoZEE) in Scotland and potentially internationally. Specific primers for other pests and pathogens will be made available as data becomes available and emerging threats arise. Outputs are expected to be transferred internationally.

Objective 7. New and emerging threats
Meet with RD2.1.4 and RD2.3.3 leads to discuss and agree future research on any relevant threats (O7).

Detailed work plan (years 1 and 2)
O1.1i Establish whether diagnostic tests for target soil-borne pest/pathogens can be integrated into single soil testing procedure (y1), after first developing real-time PCR assays for FLN target species and *S. scabiei* (M4, y1).
O1.1ii Produce draft guide on method and interpretation of testing for soil-borne potato pathogens (y2), which will be revised according to further validation in years 3-5, for use in IPM toolboxes. This will rely on completing an initial determination of yield/disease risk thresholds for FLN and *S. scabiei* with respect to potato (M6, y2). Results will be delivered to industry at CPNB Feb 2018 (KE11).
O1.2i Develop specific and sensitive assays for the detection of target air-borne pathogens of potato including cross reactivity tests and initial duplex assays (y1).
O1.2ii Develop and optimise multiplexed assays for air-borne pathogens affecting potato crops (y2). The new tests will be used in disease risk forecasting in RD2.1.4 and their application publicised at PiP 2018 (KE8) and CPNB 2018 (KE12).
O2.1i Produce a quantitative (r-RT-PCR) test for RLBV (y1).
O2.1ii Elucidate relationship between disease severity and RLBV load in multiple infections (y2). Results will be presented at the East Malling Research/AHDB Horticulture soft fruit day in Nov 2017 (KE9).
O2.2i Develop a natural emergence test for SWD to aid interpretation of in-field SWD monitoring (y1).
O2.2ii Refine (according to results from y1) and repeat the SWD emergence test (y2). Results of in-field detection of SWD will be delivered to industry at key stakeholder events, FFF - 2016 (KE2) and 2017 (KE7) and SSCR- 2017 (KE5) and 2018 (KE13).
O3.1 Evaluate existing diagnostics and develop new specific and sensitive assays for *R .commune* and *Ramularia collo-cygni* as necessary (y1).
O3.2 Develop and optimise multiplex assays for *Rhynchosporium* and *Fusarium* species (y2). Improved detection of cereal pathogens for use in RD2.1.4 to aid disease prediction and control will be publicised at AHDB/SRUC disease roadshows, open days, and Cereals in Practice 2016 (KE1) and 2017 (KE6).

O4.1 Evaluate the application of sensor technologies for disease detection (y1). This will include the development of a prototype low-cost hyperspectral imaging system for integration with mobile phones (M1, y1). Early phase prototype models and apps will be presented at key potato, PiP (KE3) and soft fruit, FFF (KE4) events to get stakeholder feedback. Assessments of plant disease detection using hand-held FTIR sensor (M2, y1) and evaluation of data from hyperspectral, proximal and IRT sensors for detection of canopy traits associated with disease (M3, y1) will be completed in the first field season.
O4.2 Evaluate the application of sensor technologies for disease detection, with milestones as described for O4.1 (M8, M9, M10, all y2). Results from the two field seasons will be compiled and presented at a cross-theme workshop (KE10, y2), and the focus of work in years 3-5 within O4 will be targeted at those methods identified as being sensitive enough to detect disease at levels appropriate for aiding targeted control strategies (decision making milestone O4DMM).
O5.1i Identify *R. solani* AGs and FLNs pathogenic to key rotational crops (y1).
O5.1ii Produce draft guide for soil testing for pathogens of rotational crops (y2), after optimizing sample handling for improved detection of target *R. solani* AG's and linking to sampling in O5.2 (M5, y2) and relating pathogen levels (*R. solani* AGs and FLN) in soil with disease risk on key rotational crops (M7, y2).
O5.2 Evaluate existing club root assays and develop a new assay if necessary (y1) to be made available to growers and advisers through SRUC crop clinic and for use in RD2.1.6.
O6.1 Improved software for rapid and accurate primer design (y1).
O6.2 Design and validation of new and improved diagnostics for current *Pectobacterium* species in Europe (y2).
O6.3 Implementation of the software from O6.1 in other areas of the RESAS Strategic Research Programme (y2).
O7 Review new threats with RD2.1.4 and RD2.3.3. Meet with RD2.1.4 and RD2.3.3 leads to discuss and agree future research on any relevant threats (y1 and y2).

Key linkages, interdisciplinarity & collaboration

Methods developed and employed within this deliverable underpin research into sustainable crop production within WP2.1 and WP2.3. The objectives presented here are integrated across three MRPs; Hutton, SRUC and BioSS.

Key linkages with RD2.1.5 include:

RD2.1.4 Plant-pest epidemiology. Advances in in-field detection of pests/pathogens made in this deliverable will link directly to epidemiological research on key pathogens of crops specified in RD2.1.4. *Objective 1.2,* the continued development of specific and sensitive assays for the detection of air-borne pathogens (*P. infestans* and *A. solani*) of potato links to development of disease forecasting in association with pathogen detection in spore samplers. *Objective 2.2,* improved methods of detection for SWD (soft fruit) will be employed within RD2.1.4 to study epidemiology to improve pest control. *Objective 3.1 and 3.3 Rhynchosporium* and *Ramularia* (barley pathogens) disease forecasting models developed in RD2.1.4 rely on accurate and specific diagnostics developed in RD2.1.5. *Objective 6,* diagnostic tools developed in RD2.1.5 for *Dickeya* and *Pectobacterium* spp. will be used within RD2.1.4 to inform control of potato soft-rots (use of new primer design software will also be expanded to RDs 2.2.4, 2.3.3 and RD3.1.3 where applicable). *Objective 7,* new and emerging disease threats will be identified in RD2.1.4 and 2.3.3 and links with RD2.1.5 will enable diagnostics for new pest and pathogen risks to be developed as appropriate.

RD2.1.6 Integrated pest management. Much of the work in RD2.1.5 feeds either directly (or indirectly through RD2.1.4) into RD2.1.6, through the development of disease risk assessments based on the detection of pest/pathogen levels in the field. A cross-MRP and cross-sector (potato, cereal, soft-fruit, brassica) workshop on development and delivery of IPM to stakeholders will be held as part of the delivery of KE within RD2.1.6. **RD2.3.9 Integrated management systems.** Many of the pest/pathogen in-field detection techniques developed in RD2.1.5 will be employed as part of 'demonstrating best practice' (RD2.3.9), offering direct delivery of advances to relevant stakeholders. The same teams developing techniques for in-field pathogen detection using proximal sensors and IR spectroscopy within RD2.1.5 will be employing the techniques within RD2.3.9 for the detection of abiotic stresses. Therefore, a combined approach to data collection and validation for both biotic and abiotic stresses will be employed to improve sustainable crop management. A workshop (y2) will examine progress and identify best practice. **RD2.3.12 Uptake of best practice.** As new or improved pest/pathogen/disease detection techniques are validated they will be used to assess disease risk. Interpretation guides and translation of test results into management practices will be produced and fed into IPM toolboxes within RD2.1.6. Direct links between RD2.1.6 and 2.3.12 will facilitate end-user engagement.
Added Scientific Value Work in RD2.1.5 builds upon previous funding from sources such as AHDB (PC, HGCA, HDC), BBSRC HAPI initiatives and Innovate UK and remains closely aligned with funding within the priority research areas of the AHDB. There are numerous non-MRP collaborations (including commercial) in UK, Europe and globally. Nationally these include SASA, FERA, AHDB, DEFRA. European links include numerous industries and networks such as Euphresco, PURE, ENDURE (IPM) and Euroblight. Globally includes AfSIS (African Soil Information Service) and ICRAF (World Agroforestry Centre), SARDI (Australia). There are strong communication and collaboration links with JRC (Joint Research Centre) and the FAO Global Soil Partnership. There are also UK links to scientists at Rothamsted, ADAS and various Universities. These collaborative links, maintained through external funding, provide significant 'added value' to RD2.1.5 through aligned research.
KE, Audiences and Impact Pathogen and disease detection tools developed in RD2.1.5 underpin research outputs in other RDs, particularly RD2.1.4 and 2.1.6 and KE activities will therefore often be coordinated across RDs. KE will take the form of stakeholder interactions and talks/presentations given at events, e.g. SRUC field open days, crop protection conferences (e.g. CPNB), AHDB/SRUC disease roadshows, SSCR meetings, Fruit for the Future and Potatoes in Practice, but also participation in IPM KE events led by RD2.1.6 (e.g. LEAF Open Days, Royal Highland Show, CSC open days). KE will be linked from RD2.1.5 to the CKEI indicative activities through interactions with the WPMT and the KE sectorial leads. Audiences include a wide-range of stakeholders for the three main sectors (potato, barley and soft fruit); growers, agronomists and advisors/consultants and representatives of industry bodies e.g. AHDB-PC, -HDC and HGCA. The proposed work delivers to multiple aspects of plant health policy, delivered through policy workshops, advice and statutory advisory services (SASA, FERA, FSA), particularly for soft-fruit certification. It will deliver policy relevant research through the Plant Health Centre of Expertise and will contribute to the UK National Action Plan for IPM and sustainable use of pesticides. Diagnostic outputs in RD2.1.5 also link to WP

2.2 work such as CoZEE events for zoonotic pathogens.
All aspects of RD2.1.5 have an impact through improvements in pest/pathogen detection and control of key endemic diseases and/or reducing reliance on chemical inputs to control disease. A new primer design software tool will facilitate the development of diagnostics for new and emerging threats. Many key impacts will be cross-sector: new sensor technology and improved detection of soil-borne pathogens in rotations. Other elements are specific to individual crop sectors, e.g. the improved detection of soft-fruit pests and diseases will directly impact the profitability of growers and increase security of fruit production to maintain market share. There is strong potential to deliver to innovation/ commercialisation: new innovations co-constructed with industry include novel diagnostics and precision monitoring tools of interest to a wide range of service providers including commercial diagnostic companies. Techniques developed in RD2.1.5 will be transferrable to food safety, forestry and potentially human health.

RESEARCH DELIVERABLE NUMBER: RD2.1.5
Work planning and timetable for Year 1:

Year 1: 2016/17 **Objective/ Activity**	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i Establish if diagnostic tests for soil-borne pest/pathogens can be integrated into single soil testing procedure									**M4**		**O1.1i**	
O1.2i Develop assays for the detection of target pathogens including cross reactivity tests and initial duplex assays												**O1.2i**
O2.1i Produce a quantitative (r-RT-PCR) test for RLBV									**O2.1i**			
O2.2i Develop natural emergence test for SWD to aid interpretation of in-field SWD monitoring				**KE2**			**O2.2i**				**KE5**	
O3.1 Evaluate existing diagnostics/develop new assays for *R .commune* and *Ramularia collo-cygni* as necessary.			**KE1**									**O3.1**
O4.1 Evaluate sensor technologies for disease detection.				**KE3**	**KE4**			**M1** **M2** **M3**	**O4.1**			

O5.1i Identify which *R. solani* AG's and FLN's are pathogenic to key rotational crops							**O5.1i**					
O5.2 Evaluate existing club root assays and develop a new assay if necessary											**O5.2**	
O6.1 Improved software for rapid and accurate primer design												**O6.1**
O7 Review new disease threats with RD2.1.4 and RD2.3.3								**O7**				
R1 Year 1 Report to RESAS												**R1**

RESEARCH DELIVERABLE NUMBER: RD2.1.5
Work planning and timetable for Year 2:

Year 1: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Objective/ Activity												
O1.1ii Produce draft guide on method and interpretation of testing for soil-borne potato pathogens for use in IPM.								M6			KE11	O1.1ii
O1.2ii Develop and optimise multiplexed assays for air-borne potato pathogens					KE8						KE12	O1.2ii
O2.1ii Elucidate relationship between disease severity and virus load in multiple infections.								KE9			O2.1ii	
O2.2ii Refine and repeat SWD emergence test				KE7				O2.2ii			KE13	
O3.2 Develop and optimise multiplex assays for *Rhynchosporium* and *Fusarium* species		KE6										O3.2
O4.2 Evaluate application of sensor technologies for disease detection									M8 M9 M10	KE10	O4.2	O4 DMM
O5.1ii Produce draft guide for soil testing for pathogens of rotational crops	M5							M7			O5.1ii	
O6.2 Design and validation of improved diagnostics for *Pectobacterium* species.								O6.2				
O6.3 Implementation of software in other areas of the RESAS Strategic Research Programme												O6.3
O7 Review new threats with RD2.1.4 and RD2.3.3								O7				
R2 Year 2 Report to RESAS												R2

RD: 2.1.6 Integrated Pest Management

Research aim and key drivers:
This RD aims to understand the importance of factors that affect reliance on pesticides and to integrate these into Integrated Pest Management (IPM) toolboxes tailored to key Scottish horticultural and arable crops. Novel control options, which reduce reliance on pesticides, are required because of reductions in available plant protection products due in significant part to recent EU pesticides legislation. IPM tools will be developed and evaluated in optimised combinations to suppress key pest and disease threats for each cropping system. RD2.1.6 will integrate contributions from other RDs, e.g. new varietal resistance, pest monitoring and forecasting tools and will work closely with stakeholders to prioritise IPM research and promote uptake of best practice. The work described has been established by scientists with expertise in the relevant areas following consultation with relevant stakeholders including industry, SASA and AHDB.

Summary of the proposal:
The overall aim of the RD is to develop sustainable systems of crop protection which minimise yield and quality losses from pests, weeds and diseases, whilst reducing current reliance on pesticides. This is driven by the need to maintain, or increase, crop yields and quality for priority Scottish crops (barley, potato, soft fruit) whilst diversifying crop protection options, such that Scottish crop production systems will be greener and wealthier (CAMERAS). Integrated management of pests, weeds and diseases by maximising the beneficial effects of varietal resistance, crop agronomy, action thresholds, new chemicals with improved environmental profiles and alternative control measures are key strategies. Pesticide losses as a result of legislative changes (Sustainable Use Directive, Water Framework Directive) and the development of resistance provide a further driver for research into alternatives. Member States are required by law (1107/2009/EC) to implement IPM plans under their National Action Plans (NAP) to reduce risks from pests (‘pest’ denotes all pests, weeds and diseases). Diseases and pests have been prioritised according to impact and to allow for coherent links between this RD and the wider programme. The major activities over the 5 year programme are:

Objective 1 KE Project.
Key Deliverable: to act as a key linking objective, coordinate links with associated RDs and ensure a co-innovation approach to delivery.
Full summary, technical and deliverable details for this objective are given in the KE section to avoid repetition. RD2.1.6 objectives have strong links to other WP2.1 RDs (2.1.2 – 2.1.8) and RDs 2.3.3 and 2.3.9, to KE activities which promote uptake of effective practices (RD2.3.12) and to the CKEI. The acceptability and benefits to stakeholders (including farmers, crop advisors, crop protection industry, environmental NGOs, policy makers, food industry and consumers) of new IPM solutions will be examined.

Objective 2 Analysis of risk modifiers.
Key Deliverable: Quantification and ranking of disease risk modifiers using information-based methods.
There is currently a poor understanding of how IPM measures can provide sustainable solutions for each cropping system and therefore important modifiers of

pest, weed and disease pressure (termed 'risk modifiers') will be identified and methodologies to quantify and rank their relative contributions developed. Current knowledge will be synthesised and new methodologies for the quantification and ranking of risk modifiers for key pests will be developed, so that effective IPM strategies can be formulated. Effective and efficient use of this information in evidence-based risk assessment and decision making requires new methods of quantifying evidence from different sources in a common format along with safeguards to ensure against double-counting of evidence. This will include examination of long term data sets held at MRPs and SASA and field trials in different Scottish cropping systems to identify and rank the most important risk factors. Pesticides are risk modifiers and they will be analysed using the same common scale of risk assessment used for environmental risk factors. This will also inform policy on a NAP for IPM.

Objective 3 Improved risk forecasts and treatment thresholds.
Key Deliverable: Improved disease risk forecasts for barley**.**
Methods which combine information on pest and disease risk and crop loss will be developed to determine flexible treatment thresholds and aid farm-scale decision making. Uptake and application of risk modifiers and the use of personalised risk thresholds will be a key component. The principles will be applicable to precision agriculture techniques with both immediate and future applications. Initial focus (y1-2) will be on pathogens and weeds but will be developed for other pest types (y3-5). Methods for forecast evaluation e.g. weather forecasts, and disease predictions that depend on weather forecasts will be developed for effective deployment as part of IPM. New applications for disease risk curves in the development of crop risk assessments for *Ramularia* (cereals), *Phytophthora* (potato) and root rot (soft fruit), (CWP6.4), will be examined.

Objective 4 New IPM Tools.
Key Deliverable: Identify new crop protection tools which can be combined and incorporated into IPM strategies.
Key themes include targeted use of selective pesticides, varietal resistance to pests and alternative tools. These will be examined for impact on pest burden using long term research platforms (e.g. the Centre for Sustainable Cropping (CSC) and long term crop trial data sets). Tools for evaluation may include combinations of: targeted use of pesticides (in response to thresholds and predictions); biological control agents (including predators, parasitoids and phages; host resistance elicitors and plant defence primers; biopesticides and semiochemicals); potential new targets for chemical control in pathogens through the exploitation of pathogen genomes; host plant resistance, predictive models and other novel methods. Crop fitness (e.g. yield, quality) will be assessed to confirm that combined IPM tools have no detrimental effect on other agronomic factors and on non-target organisms (e.g. natural enemies and pollinators (links to SASA Pesticides Unit and CEH)). Crop-specific IPM 'toolboxes' will consolidate optimal combinations of individual tools to suppress the key weeds, pests and diseases.

Objective 5 IPM Toolboxes.
Key Deliverable: Evaluate and combine IPM tools and evaluate efficacy in improving control of key pest targets in crop-specific 'toolboxes'.
O5.1 Soft Fruit IPM Toolbox: Targets may include virus vector aphids, raspberry

beetle, vine weevil, Spotted Wing Drosophila (SWD), root rot and vector-borne viruses).
O5.2 Potato IPM Toolbox. Targets may include aphids, free living nematodes (FLN), late blight, blackleg and important tuber blemish diseases.
O5.3 Cereal IPM Toolbox: Key targets will be foliar diseases caused by *Rhynchosporium* and late season pathogens caused by *Ramularia* and *Fusarium*.
O5.4 Oilseed rape IPM tool box. Key targets will be rotational soil borne pathogens e.g. clubroot and foliar pathogens e.g. light leaf spot.

Technical approach
Objective 1 KE Project. See KE section for details.

Objective 2 Analysis of risk modifiers.
Information-based methods will be used to quantify and rank risk modifiers identified as key IPM components, focusing in years 1-2 on key pathogens and later adapting the approach to other pests. The aim is to quantify and weight evidence from different sides of the "disease triangle" (host-pest-environment) in a common format and to discount the impact of conditional non-independence among factors. This work will use long term crop data sets (MRPs and SASA) and will include field trials to identify and rank important risk factors. The impact of fungicides as risk modifiers will be analysed using the same common scale of risk assessment used for environmental factors. Disease risk modifiers, e.g. cultivar resistance and fungicide input, have very large effects in the potato/late blight pathosystem. The substantial dataset generated by a recent LINK project (SA533, SRUC/Hutton) will be utilised to rank risk modifiers for this system. Barley risk modifiers will be studied using long term data (20 years) held at SRUC (CWP4) which incorporates site, season, varietal resistance, sow date and fungicide treatment. In years 3-5, this approach will be adapted for other pest types and used within the IPM toolboxes for each crop system (Objective 5). A key output will be an IPM planning tool for growers, co-constructed with NFUS and the Scottish Voluntary Initiative (VI).

Objective 3 Improved risk forecasts and treatment thresholds.
Methodologies will be developed to combine information on disease risk and crop loss (years 1-2) to develop flexible treatment thresholds and aid farm-scale decision making. This will later be developed for other pest types (weeds, invertebrates). O3.1 Development of Disease Risk Algorithms: recently-developed Disease Risk Curve methodology (CWP6.4) will be used to develop methodologies for evaluating information and setting thresholds. Different risk threshold choices give rise to different levels of uncertainty (entropy) in the decision process and the aim will be to be able to identify low entropy solutions. Characterisation of optimal decision thresholds will allow for "individualised" thresholds to be identified. Generic approaches to the crop loss decision problem are planned, so as to be broadly applicable to a range of pathosystems. Specific applications will use data from specific pathosystems as it becomes available, beginning with *Ramularia* data. The principles developed will be applicable to future precision agriculture techniques. To improve the usefulness of predictions and thresholds, new methods for evaluating longer term weather trends, specifically related to the quantification of evidence related to disease risk, will be developed to allow earlier warning of disease threat.
Objective 4 New IPM tools.
Current knowledge on alternative and conventional approaches to pest management

will be synthesised and work prioritised for the latter years of RD2.1.6 based on identified gaps, threats and potential solutions. Pathogen genomics and biology (RD2.1.3) provide an opportunity for discovery of new specific and environmentally benign chemical controls and genes encoding essential components of key biochemical pathways or structural proteins will therefore be investigated for their role in pathogen survival to generate new targets that can be screened for efficacy (with University of Dundee and industry). Phenotypic assays will be developed and external funding sought to allow these to be assessed for suitability for high throughput screening (with UoD). We will evaluate recently developed IPM tools (links to Hortlink SCEPTRE, TSB, EU PURE), develop new tools to manage weed, pest and disease risk and test these in combination for specific cropping systems. These tools may include pest and disease resistant varieties, elicitors and plant defence primers, biopesticides and semiochemicals (e.g. attractants, repellents, anti-feedants), precision mapping tools, integrated weed management systems and other novel methods of modifying the past and disease burden and minimising yield losses.

Objective 5 IPM Toolboxes
O5.1 Soft Fruit IPM Toolbox:
The focus will be on established pests for example, aphids, raspberry beetle, vine weevil, *Phytophthora* root rot, FLN and vector-borne viruses and the emerging pest SWD which threatens to undermine existing IPM by increasing use of broad spectrum insecticides. Soft fruit genotypes that exhibit resistance or tolerance to *Phytophthora,* aphids and other target pests/diseases in RDs2.1.1/2 and recent projects (InnovateUK) will be identified as candidates for IPM trials (y1, O5.1I). Biological control options for specific pests will be examined (y2-3). Individual IPM tools (y1-3) will be combined (y3-5) by glasshouse and/or field testing of the most promising IPM tool combinations (based on mechanistic studies in RD2.1.3). IPM advice and the toolbox of control measures may comprise resistant/tolerant soft fruit genotypes, agronomy, virus diagnostics, biological and/or chemical control measures, and management of non-crop/margin vegetation (RD2.3.8, O5.1.3) to promote Ecosystem Services (e.g. biocontrol, pollination; with SASA and CEH) and ensure profitable crop production.
O5.2 Potato IPM Toolbox:
IPM tools will be optimally combined for key pests (e.g. aphids, free living nematodes) and pathogens (e.g. soil-borne tuber disease pathogens, bacterial soft-rot causing pathogens (*Pectobacterium* and *Dickeya*) and air-borne pathogens (e.g. early blight (*Alternaria spp.*) and late blight *(Phytophthora infestans*). Existing knowledge will be synthesised with new results from glasshouse and/or field testing, and new diagnostics (RD2.1.5), epidemiological modelling and disease risk forecasting methods (RD2.1.4) and improved host resistance (RD2.1.2). Previous and ongoing work on the epidemiology, prediction and control of late blight will be consolidated and the CSC used to test and demonstrate economic and environmental benefits (y2-5) to bring IPM into practice (O1). The potential contribution of resistance elicitors to the control of early blight, which exhibits multiple fungicide resistance and for which legislative losses of pesticide threaten control, will be investigated with a view to incorporating elicitors into IPM. Field experiments (CWP6.4) showed that resistance elicitors and primers can contribute significantly to the control of early blight, complementing partial host resistance. Optimal deployment strategies for resistance elicitors, alongside fungicide programmes and partial host resistance (EU PURE), will be examined. Glasshouse trials will assess the efficacy of elicitors, relating directly to

RD2.1.3 (molecular mechanisms of defence priming). Refined diagnostic methods (RD2.1.5) will be tested for key soil-borne pests and pathogens, building upon existing work and informing IPM strategies (y1). The data-set from the complete CSC 6 year rotation (2011-2016) will be analysed to develop a draft of the soil-borne disease component of the potato toolbox (y1), ensuring no detrimental impacts are associated with control measures; allowing outputs to be combined beyond the field/crop scale at the farm scale and delivering to other IPM crop toolboxes and to RDs2.3.9/2.3.12. As work in O4, RD2.1.5 and RD2.1.4 and aligned external funding proceeds (e.g. late blight DEFRA LINK, HAPI and InnovateUK projects), useful new IPM tools can be tested at the field scale (y3-5) and incorporated into the toolbox. These may include i) biological control agents such as phages to control bacterial pathogens ii) the assessment of biofumigant control of FLNs using an optical screen iii) contribution of host resistance elicitors to control early/ late blight and black leg. Work on disease forecasting for early blight, aphid species and PCN (RD2.1.4) will become available.

O5.3 Cereals IPM toolbox
Key cereal diseases including *Rhynchosporium*, *Ramularia* and *Fusarium*) will be targeted and the most promising tools tested in the field and glasshouse, in combinations likely to be complementary (based on mechanistic studies in RD2.1.3, spore trapping and detection in RD2.1.5 and predictive models in RD2.1.6. Research into risk modifiers (O2) and forecasts and individualised risk thresholds (O3) will be incorporated and evaluated for impact on disease risk profile and reduced pesticide usage. The development and use of elicitor products (e.g. Regalia) to reduce yield and quality reductions in barley caused by *Ramularia collo-cygni* (*Rcc*) and *Fusarium* spp. will be tested and results integrated into enhanced IPM strategies. Microorganisms with the potential to be biofungicides against *Rcc* have been identified (CWP6.4) but their efficacy in the field has not yet been tested. Field trials at arable sites (low and high disease pressure) will test the efficacy of BCAs on increased resistance and improved yield.

O5.4 Brassicas IPM toolbox (oilseed rape)
The contribution of host resistance elicitors to the control of clubroot in OSR will be prioritised because of its prevalence in Scottish soils, its impact on yield and the lack of sustainable solutions. This work links closely to industry-funded projects and to breeders, so that alternative resistance sources can be incorporated. Links with RD2.1.8 will allow the impacts of novel crops in rotations to be considered. Initial studies (CWP6.4) demonstrated the potential for elicitors to be incorporated into conventional OSR fungicide programmes for improved management of foliar diseases and levy funded work on Brussel sprouts has shown similar potential. The efficacy of elicitor products in managing clubroot will be investigated with a view to incorporation into an ICM system. Trials will be conducted annually at clubroot infected sites. Effects on clubroot and on the foliar disease light leaf spot will be determined as will impacts on yield and any negative impacts on crop safety. Experiments will examine optimal deployment strategies for resistance elicitors (for example seed drenches and foliar applications at a range of timings) alongside available fungicide programmes and varietal partial resistance. This work directly links to RD2.1.3.

Detailed work plan

Objective 1 KE project: see KE section.

Objective 2 Analysis of risk modifiers:
O2.1: A list of risk modifiers will be developed for discussion with stakeholders by synthesising current knowledge (M1, y1) and methodologies to quantify and weight impact will be developed (M6, y1). O2.2: Risk modifiers will be evaluated for impact using weighting to build risk algorithms (M9, y2), initially for potato late blight using existing project data. Historic databases will be explored (for example the adopt-a-crop 30 year crop monitoring data set) to examine the impact of identified modifiers on barley diseases (M14, y2). This work will be extended to other priority pests and problems as identified by stakeholders (y3-5).

Objective 3 Improved risk forecasts and treatment thresholds:
Work on the extension of disease risk curve methodology will utilise the disease risk curve method developed in CWP6.4 and characterise these for information value (y1, O3.1). In year 2 there will be a focus on developing methodologies for disease forecasting. The Ramularia pathosystem will be used to parameterise treatment thresholds and develop methods that can be used for other systems (y3-5) (y2, O3.2). Likely utilisation of forecasts and thresholds by stakeholders will be explored through RD2.3.12.

Objective 4 New IPM tools:
Current knowledge on recently developed tools that can be tested for specific crops in the later years of objectives 5-8 will be synthesised (y1, O4.1). To identify potential control targets (O4.2) co-expressed genes will be identified (using mutual information coefficient measurement and clustering coefficient-based methods or clustering options in gene expression software packages (*e.g.* Genespring) and grouped according to their expression at specific lifecycle stages (M3, y1). Gene expression profiles will be validated using qPCR and products of genes specifically expressed or strongly upregulated at a specific lifecycle or infection stage identified as candidate targets for inhibition by chemical agents (M5, y1). Changes in the surfaces of pathogens will be characterised (M7, y1 **HEI bid 1**) to allow whole organism assays to be developed for screening candidate active chemicals (M10, y2) and assessed for suitability for high-throughput microscopic screening, initially focussing on spore germination and hyphal growth (*P. infestans, R. commune*) and hatching and motility (*G. pallida*) (M15, y2).

Objective 5 IPM Toolboxes
O5.1 Soft fruit IPM toolbox:
Germplasm and resistant sources (e.g. UC Rubus, Ribes) will be recommended for root rot resistance/tolerance and cross-tolerance to other biotic stressors and aphid resistance (y1, O5.1i). Vine weevil biological control options will be examined (y2-3). Biopesticides, monitoring traps and lures will developed with industry partners (eg Koppert, Biobest, Syngenta, Russell IPM, International Biocontrol Manufacturers Association) (y1-5, O5.1ii). Recommendations for composition and management of uncropped vegetation will be proposed (y2, informed on socio-economic drivers, uptake barriers and Ecosystem service related issues by RD2.3.8, O5.1iii).

O5.2 Potato IPM Toolbox:
In consultation with stakeholders (M2, y1) a late blight IPM plan will be developed

(O5.2i) using the IPM 'infrastructure' of existing tools which can be tested from year 2 onwards at the CSC and other field sites. New tools and re-parameterised (y1, O5.2ii) and validated (y2, O5.2iii) late blight models (M11, y2,: collation of data for model) will be added as they become available. Analysis of the data-set from the complete 6 year rotation at CSC 2011-2016 (M4, y1) will result in a first draft of the soil-borne pathogen component of the potato toolbox to be developed for testing at the CSC (y1, y2, O5.2i). Novel bioassays used to test biopesticides and elicitors against FLN (transparent soil systems) will be optimised (Media conditions M8, Imaging Dye M12 and Imaging method M13, all y2). Work will integrate individual IPM tools (pests, diseases, weeds) from CWP6.4 and related RDs and stakeholder engagement will be carried out through O1 and the centralised KE facility.

O5.3 Cereals IPM toolbox:
Field trials will evaluate the use of biological controls, defence primers and thresholds integrated into fungicide programmes leading to recommendations for alternative IPM strategies in barley (y2, O5.3i).

O5.4 Brassicas IPM Toolbox: Current approaches to managing clubroot and horizon scanning of funding calls which could be used to leverage additional funding will be compiled (y1, O5.4i). Field trials will be conducted annually (y1, 2, O5.4ii) at clubroot infected sites (in consultation with BioSS to account for the patchy nature of the disease). Effects on clubroot and on the foliar disease light leaf spot will be determined as will impacts on yield and any negative impacts on crop safety. Experiments will examine optimal deployment strategies for resistance elicitors (for example seed drenches and foliar applications at a range of timings) alongside available fungicide programmes and varietal partial resistance (y1, 2). Work on field mapping and pathotypes (subject to industry funding) will be incorporated into treatment designs (y2 onwards)
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Key linkages, interdisciplinarity & collaboration

This RD consolidates and underpins outputs from other areas of the RESAS programme. RD2.1.6 is highly interdisciplinary and the research is collaborative and integrated across Hutton and SRUC facilitating the management of linkages across the RESAS programme and beyond.

Key linkages include:
WP2.1 RD2.1.6 is dependent on work originating from several other RDs within WP2.1 in order to develop sustainable systems of crop protection. IPM seeks to maximise the beneficial use of new and available tools for disease control including new characterised sources of host resistance to important pests and diseases of key crops (RD2.1.1, RD2.1.2) and novel in-field diagnostics and associated disease risk assessments (RD2.1.5). The deployment of host and chemical control strategies is directly informed by an understanding of pest and pathogen populations and epidemiology (RD2.1.4) and the development of novel pest control targets within RD2.1.6 derives from a mechanistic understanding of plant-pest interactions (RD2.1.3).

WP2.3 IPM strategies developed and delivered in RD2.1.6 are highly relevant to delivery at farm and landscape scales through sustainable land management (RD2.3.8), IPM tools will be incorporated into decision support systems in formats suitable for use at the farm scale in integrated management systems (RD2.3.9), uptake of best practice (RD2.3.12) and an understanding of trade-offs (RD2.3.11). Work will also be informed by RD2.3.3, as new emerging threats relevant to key crops must be considered in IPM strategies.

Stakeholders Important stakeholder links with RD2.1.6 include AHDB funded projects and participation in their other functions such as the HDC and HGCA Recommended List committees and the UKCPVS. Interactions with stakeholders at monitor farms, workshops and national collaborative field events will inform the research and its outputs. Information on new targets for pathogen control will be exploited in collaboration with several major AgChem industry partners and will require access to facilities at St Andrews university as outlined in **HEI bid 1** 'Structure-function relationships of pathogen effectors and surfaces' (HEI contract Jim Naismith).

Centre for Plant Health: It is anticipated that key researchers in RD2.1.6 will be actively involved in the SG Centre of Expertise for Plant Health and have regular and close links with Cameras partners (SASA, NFUS, CEH) and Northern Forest Research Station on many plant health issues.

Underpinning capacity: The CSC, access to agronomist services and pest and pathogen collections will be required to test components of IPM for efficacy against varied and contemporary isolates of pathogens and pests. Sources of host resistance for use in IPM will be identified from the Commonwealth Potato Collection and Rubus/Ribes germplasm collection. Long-term meteorological data, crucial for IPM strategies, is recorded and held at Hutton and supported through UC. Statistical design and analysis will be carried out in collaboration with BioSS, whose inputs will be supported by BioSS funding for UC Function 7.

Added Scientific Value: This work is strongly aligned with priority research areas of industry, EU and other funders and benefits from critical mass, allowing leverage of additional funding. Soft fruit IPM is funded through DEFRA Hortlink, AHDB Horticulture and the EU and we have links to generic IPM work through EU PURE (various crops), EU AMIGA (use of GM and conventionally bred crops in IPM), Bioforsk (IPM systems for brassica vegetables), InnovateUK (breeding for pest resistance). Cereals research is aligned with AHDB Cereal and Oilseeds priorities and work on varieties (Recommended List), fungicide performance and disease monitoring and funded work on pesticide efficacy including the trialling of new products. Similarly, work aligns with the priority research areas of the AHDB-Potatoes helping to combine funding support from end-users and science funders and with BBSRC HAPI initiatives and Innovate UK funding on late blight and early blight. These projects and associated stakeholder networks provide added value to RD2.1.6, through close links with other IPM experts, industry developments, UK and EU policy makers for IPM, food industry, environmental NGOs dealing with pesticides/biodiversity.

KE, Audiences and Impact

Objective1 KE project.
Key deliverable: A Scottish IPM planning tool for growers in collaboration with NFUS,

members of the Voluntary Initiative and policy (KE2, y1).
This key linking objective will draw information from RDs 2.1.1 – 2.1.8 to deliver best practice information to WP2.3.12 so that likely uptake by stakeholders can be explored and barriers to uptake amongst end users identified. Co-construction workshops with stakeholders (y1, y2) will develop a KE plan, prioritise research targets and develop outputs including: the development and delivery of pesticide stewardship/sustainable use communication tools for remaining pesticide chemistries (pesticide resistance management and use reductions).
Plans for work on identifying new targets have been drawn up in collaboration with four of the five major AgChem industry players and regular meetings to discuss work in this area and to formulate follow-on plans will take place throughout the project. Contributions to policy will aid the development of the UK Nation Action Plan for IPM and sustainable use of pesticides and uptake by farmers.
Well developed routes for KE (on-farm IPM demonstrations and interactive workshops) including CSC (Hutton), SRUC/HGCA trial events will be used, IPM approaches developed and tested on a crop and field-scale and up-scaled to the farm and landscape using models (RDs 2.1.4, 2.1.6). Outputs will be incorporated into pest risk profiles for key Scottish crops taking into consideration new threats (RD2.3.3). Outputs from RD2.1.6 will be used to inform IPM strategies (RD2.3.9) and uptake at LEAF Innovation Centre. Each MRP will have a link person contacting the research in RD2.1.6 with RDs dealing with socio-economic assessment, uptake of best practice, barriers to uptake and future stakeholder demands for sustainable crop protection.
Key deliverables in year 1 and 2 will include co-innovation workshops from which a list of key pest, disease and weed control priorities for each cropping system will be agreed with stakeholder representatives (y1, O1.1 y2, O1.2). A cross MRP and cross sector (potato, cereal, soft-fruit, brassicae) workshop on methods of development and delivery of IPM to stakeholders will be held (KE3, y1). KE events will be used to identify research gaps for planning research priorities (y 2-5). Annual stakeholder KE events for IPM and crop-specific solutions will also be held (KE1, y1, KE4, y1, KE5, y2, KE6, y2). Key link people will attend project meetings for relevant RDs. KE will be linked from RD2.1.6 to the CKEI indicative activities through interactions with the WPMT and the KE sectorial leads

Our key stakeholder audiences will include:
- Farmers, crop agronomists and advisors for potato, barley, soft fruit.
- Scottish Voluntary Initiative (VI) members
- Crop protection industries, including chemicals, biopesticides, biocontrol, trapping and monitoring tools, DSS / precision farming providers
- Policy makers at SG (e.g. CAP reform and crop policy unit), pesticide use and impact surveys (SASA), DEFRA, CRD/UK government, European Commission (DG Sante), EFSA (pesticidal plant protection products, environmental risk management, non-target impacts of crop protection)
- Schools and universities (visits to MRPs during LEAF Open Days, Royal Highland Show, visits by experts to schools to discuss farming issues
- Environmental NGOs (e.g. SNH, Scottish Wildlife, RSPB).
- Food industries (high health Scottish soft fruit, potato food chain, barley brewing and distilling, Scottish Food and Drink Federation, Nourish Scotland)
- Pollinator/pesticide impact research groups (SASA, CEH, EU, EFSA).

Impact: RD2.1.6 will benefit multiple stakeholders, particularly farmers, crop protection industry, policy makers dealing with sustainable use of pesticides, pesticide residues, NGOs protecting biodiversity, consumers' food quality, Scottish, UK and EU policies on food security, education (environment, food). An extensive KE programme will ensure impacts reach their intended targets. Outputs will be quantifiable by examining changes in practice (SASA pesticide usage and environmental impact surveys) changes in pest burdens (crop monitoring) and changes in yield (annual agricultural statistics). Established methods and routes of KE (described above) will be used to maximise impact, and the proposed CoE Plant Health will be a key conduit to effect impact on policy. Anticipated impact includes increased uptake of intelligence sources (crop monitoring, forecast information) that allow inputs to be targeted to risk. Reduced reliance on pesticides and increased use of interventions (e.g. improved varieties) and alternatives to pesticides (e.g. biologicals) will be a key impact. Scottish growers will be able to use an on-line IPM planning tool by the end of the programme.

RESEARCH DELIVERABLE NUMBER: RD2.1.6

Work planning and timetable for Year 1:

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 On- line IPM plan An on-line IPM plan for use by Scottish growers will be developed in collaboration with SG policy, NFUS and Voluntary Initiative members.							**KE2**					
O1 Co-innovation workshops Co-innovation stakeholder workshops will scope and list risk modifiers and possible interventions jointly with RD2.3.12. Output = A KE plan.			**O1.1**									
O1 KE Events Delivery of events e.g. CIP, PIP, series of winter workshops with growers and agronomists partnered with AHDB.				**KE1**					**KE4**			
O1 Cross-MRP interdisciplinary IPM workshop Deliver workshop on methods of development and delivery of IPM to stakeholders across sectors (potato, cereal, soft-fruit, OSR)								**KE3**				
O2.1 Analysis of risk modifiers Develop list of risk modifiers and methodologies to quantify and weight impact.			**M1**								**M6**	**O2.1**
O3.1 Improved forecast and treatment thresholds Utilise and characterise existing disease risk curves method												**O3.1**
O4.1 Synthesis of IPM tools for key crops Describe a generic IPM toolbox plan adaptable for different cropping systems, pests and management.							**O4.1**					
O4.2 Identify potential control targets for bioassays Clustering and validation of co-expressed pathogen /pest genes to identify						**M3**				**M5**	**M7**	**O4.2**

potential control targets												
O5.1i Recommend soft fruit genotypes for IPM toolboxes Data from screening for resistance/cross-tolerance to soft fruit pests and disease will be assessed to select genotypes											**O5.1i**	
O5.2i First draft potato late blight and soil-borne disease IPM plan In consultation with stakeholders practical options for late blight and soil-borne IPM will be collated to inform field testing					**M2**				**M4**			**O5.2i**
O5.2ii Re-parameterise spatially explicit, multi-scale simulation model for potato late blight Parameters related to pathogen infection and spread will be updated for the contemporary pathogen population using output from field and laboratory studies											**O5.2ii**	
O5.4i Approaches to managing clubroot Current approaches to clubroot control will be compiled			**O5.4i**									
O5.4ii Efficacy and deployment of elicitors in OSR. Elicitors will be tested for efficacy against clubroot in OSR in the field.							**O5.4ii**					
Annual Report (Year 1)												R1

RESEARCH DELIVERABLE NUMBER: RD2.1.6

Work planning and timetable for Year 2:

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 Co-innovation workshops: Stakeholder co-innovation workshops with RD2.3.12 will scope and develop best practice interventions and identify barriers to uptake amongst end users			O1.2									
O1 KE Events / IPM sites / workshops. Delivery of events such as Cereals in Practice, Potatoes in Practice and a series of winter workshops with growers and agronomists in partnership with AHDB				KE5							KE6	
O2.2 Analysis of Risk Modifiers Risk modifiers will be evaluated for impact to build risk algorithms. Historic databases will be explored to examine the impact of identified modifiers on barley diseases.				M9						M14		O2.2
O3.2 Improved forecasts. Disease forecast methodology applied to Ramularia in barley and an improved risk assessment allowing deployment of better varieties and more targeted use of pesticides delivered.												O3.2
O4.2 Develop whole organism or cell based assays. Test suitability for high throughput microscopy screening platform.				M10						M15		O4.2
O4.3 Identify Effective control agents and soft fruit germplasm New IPM tools will be assessed via pest-specific industry-researcher collaborations.						O4.3						

O5.1ii Preliminary IPM recommendations for soft fruit Resistant breeding lines, monitoring tools and elicitors will be rated for efficacy and practical implementation.									**O5.1ii**			
O5.1iii Recommend crop margin compositions to enhance biocontrol Data on impact of margin composition on pest abundance and control will be assessed											**O5.1iii**	
O5.2iii Validate Late Blight Model The model will be tested against field and national outbreak data, in close collaboration with the GB industry.				**M11**				**O5.2iii**				
O5.2iv Optimised transparent soil assays for FLN control Assess the optimal dye, media conditions and optimal imaging technique for real-time imaging of FLN			**M8**			**M12**			**M13**			**O5.2iv**
O5.3i Preliminary IPM recommendations for barley A summary of IPM recommendations for use on barley will be prepared and used in KE events and RD2.3.12 Technical note produced.											**O5.3i**	
Annual Report (Year 2)												**R2**

Name of RD: 2.1.7 Plant, Soil, Water Interactions

Research aim and key drivers

This RD aims to identify the interactions between plants and soils that can be exploited to achieve food security and sustainable production of sufficient, safe, and nutritious food. Plants form the base of the terrestrial food chain and plant roots, which acquire the water and essential mineral elements required for crop production, are key to food security. Indeed, they are considered a necessary focus of the next "Green Revolution". Many Scottish soils exhibit non-optimal water relations for root growth, for example periodic waterlogging or soil drying, or lack sufficient mineral elements, such as nitrogen (N), phosphorus (P) and potassium (K), for optimal crop production. This results in a need for soil water and fertility management, which incurs financial costs. In addition, resources for fertiliser production are finite and geopolitically insecure, and the inappropriate use of fertilisers can have negative environmental consequences. In the interests of sustainability it is important to optimise the use of water and fertilisers in agriculture. One strategy is to understand the interactions between plant roots and the soil environment that affect resource use, and identify crop genotypes and management practices that maintain or increase yields with reduced inputs. This work will measure specific root traits and investigate their effects on, and interactions with, the structure, composition and biology of the soil. The consequences of these interactions, for the acquisition of water and mineral nutrients, will be quantified and used to predict appropriate crop genotypes and management practices for sustainable agriculture. This work will inform selection criteria for new crop varieties, and sustainable farm management practices. It will be undertaken by a world-leading, multi-institutional and multidisciplinary team. The need for this work has been identified by various stakeholders (e.g. LEAF) and emerges from research projects funded by RESAS, EU, BBSRC (including SARISA, HAPI, CIRC and TSB initiatives), DEFRA, HGCA, AHDB, NERC, ERC, and several commercial companies.

Summary of the proposal:

Crop yield and quality, biodiversity, and soil health are largely determined by the interactions between plant roots and the soil. This proposal focuses on understanding, and modelling, the physical, chemical and biological interactions between plant roots, soil and water, which could improve crop and grassland production efficiency and sustainability. The objectives of this five-year work programme are (O1) to quantify root traits in laboratory and controlled environments, (O2) to characterise the interactions between root traits and the structure, composition and biology of the rhizosphere, (O3) to determine the consequences of such interactions for the acquisition of water and essential mineral elements, and (O4) to develop and validate quantitative models of rhizosphere behaviour. To deliver these objectives a multi-institutional and multi-disciplinary team has been assembled, including root physiologists, soil biologists and microbiologists, soil biophysicists, soil chemists, mathematical modellers, imaging specialists, and image analysis experts. This team has an exemplary track record in root and rhizosphere research.

O1. Quantifying root traits in laboratory and controlled environments. The aims of O1 are (1) to produce a database of quantified root traits and (2) to analyse genetic variation in root system architecture (RSA) and composition of root exudates in cereals and brassicas. This research builds on the team's expertise in characterising plant root systems and their exudates, utilising custom-built facilities including a high-throughput scanner-based phenotyping system, filter paper screens, transparent soils, rhizoboxes and gel chambers, CT scanners, and hydroponics systems. Previous work by the team has identified key traits determining the pattern of root architectural growth and the distribution of roots in various media, as well as Quantitative Trait Loci (QTL) affecting RSAs in cereals and brassicas and root traits affecting the acquisition of mineral nutrients, such as N, P and K. Novel approaches to root phenotyping will be applied. The RSAs of plant genotypes, both commercial varieties and landraces, will be determined using traditional and image analysis based phenotyping systems, and root functionality, including effects of exudate composition, will be assessed using innovative chemical and molecular phenotyping methodologies. This will entail further development of the team's phenotyping, imaging and image analysis pipelines. Data from these studies will (1) be used to explore the genetics of RSA and exudate composition, (2) inform of studies of interactions between root traits and the structure, composition and biology of the rhizosphere in O2 and (3) provide parameters for models of rhizosphere behaviour in O4.

O2. Interactions between root traits and rhizosphere structure, composition and biology. The aims of O2 are (1) to identify root traits influencing rhizosheath formation, rhizosphere biology and interactions with soil structure and (2) to develop a conceptual framework of how plant genotype x soil properties x soil biodiversity interactions influence (a) rhizosheath formation, (b) rhizosphere biology and (c) exploitation of the soil volume. Aspects of this work will be performed with cereals, brassicas and potatoes. Genotypes with contrasting phenotypes, selected from collections held at Hutton and SRUC, will be used to study the interactions between root traits and the structure, composition, and biology of the rhizosphere. This will include studies of genetic and environmental factors influencing (a) the structure and formation of the rhizosheath, (b) interactions between roots and soil structure, and (c) biotic interactions between roots and AM fungi, endophytic bacteria, nitrification inhibitors, denitrification moderators and free-living nematodes. Techniques developed in the CWP3.3 and other projects will be used. A rapid screen for rhizosheath formation has been developed to elucidate the genetics of this process in barley, but the influence of soil environment or microbial community on this trait is unknown. The team can characterise microbial communities both genetically and functionally using modern high-throughput techniques (e.g. sequencing and/or T-RFLP depending on the need for sample or sequencing depth throughput), and has considerable experience in studying AM symbioses, possess novel beneficial bacterial endosymbionts, and knowledge of the effects of nematode feeding on potato production. The team has the ability to characterise soil physical and chemical properties in detail. This expertise will allow the team to dissect the effects of interactions between plant genotype x soil properties x soil biodiversity on (a) rhizosheath formation, (b) rhizosphere biota and (c) exploitation of the soil volume. Knowledge of the interactions between root traits, soil structure and rhizosphere biology will be used to design experiments to test their effects on water and nutrient acquisition in O3. The conceptual framework of plant genotype x soil properties x soil biodiversity interactions will be used to develop mathematical models in O4.

O3. Consequences of interactions between root traits, soil properties and soil biota for the acquisition of water and essential mineral elements, disease suppression and crop production. The aim of O3 is to test the conceptual framework developed in O2. It will utilise techniques the team have developed in previous projects to advance understanding of the interactions between plant genotype x soil properties x soil biodiversity and their consequences for resource acquisition, disease prevention and crop production. The performance of plant genotypes with contrasting root traits believed to influence rhizosphere physical, chemical or biological processes and, thereby, water and nutrient acquisition, will be assayed in laboratory, glasshouse and field environments. Studies linking plant genetics and transcriptomics to water and nutrient acquisition efficiencies will be undertaken. How roots and soil structure interact to affect plant resource acquisition, crop production and soil properties, such as the movement of water and nutrients, carbon sequestration and the distribution of biota, will be studied. Microbial communities will be characterised, and their impact on plant nutrient acquisition will be determined, with a primary focus on biological nitrification inhibition (BNI) and denitrification moderation. The consequences of specific AM symbioses for resource acquisition will be quantified and the hypothesis that three selection pressures common in agriculture (soil disturbance, fertilization, and monocultures) select for poor partners in the AM fungal mutualism will be tested. The potential of newly-isolated endophytes to improve crop production, abiotic stress tolerance and resistance to pathogens will be examined and the mechanism whereby these endophytes work and their interaction with their host genetics will be determined with a view to enhancing efficacy. The effects of pathogenic free-living nematodes on resource acquisition will be assayed in the field. The impacts of soil pathogens and invasive non-native species in agroecosystems will be studied in RD1.1.1 and RD1.3.3. Key deliverables include (1) identification of root traits influencing water and nutrient acquisition, (2) knowledge of the consequences of interactions between plant genotype x soil properties x soil biodiversity on plant acquisition of water and nutrients, and (3) improved understanding of the effects of plant endophytes and AM associations on resource capture and disease suppression. Knowledge and data from the studies undertaken in O2 will be used to develop and validate quantitative models of rhizosphere behaviour in O4.

O4. Develop and validate quantitative models of rhizosphere behaviour. The aim of O4 is to integrate knowledge and data obtained in O1, O2 and O3 into quantitative models describing the effects of RSA, rhizosheath, microbial community structure, and soil structure on nutrient and water acquisition by plants. Emphasis will be placed on incorporating knowledge of plant genetic factors into models, which will provide insight for manipulating plant genotype x soil properties x soil biodiversity interactions to improve water and nutrient acquisition efficiencies, crop production and resilience to environmental change. The team has experience in modelling processes involved in rhizosphere development, the interactions between microbes and plant roots, and the effects of RSA, soil structure and microbial communities on nutrient acquisition. This expertise will enable the team to develop models that are more complete and incorporate key interactions. Model predictions will be validated by trialling plant genotypes and management practices thought to have the potential to improve water and nutrient acquisition in diverse environments. Key deliverables from O4 will be: (1) quantitative models of rhizosphere behaviour, (2) identification of plant phenotypes and rhizosphere manipulations for sustainable agriculture, (3) genetic targets for breeding, (4) knowledge of how rhizosphere manipulations affect the movements of water and mineral elements in the wider environment.

Technical Approach

O1. Quantifying root traits in laboratory and controlled environments. The aims of O1 are: (1) to produce a database of root traits and (2) to analyse genetic variation in RSA and composition of root exudates in cereals and brassicas. Milestones are referenced in the text and described in the Gantt Chart for key deliverables during years 1 and 2 of the 5 year Programme.

A database for images and quantitative data from O1 will be designed (M1) and constructed during the first year (y1, O1.1), populated with first years data (M4), and made available to the research group (y2, O1.4) for updating throughout the project. Genetic variation in RSA will be studied in populations of barley and oilseed rape, including commercial and heritage varieties. Barley collections are held at Hutton and SRUC. Brassica collections are being developed in a BBSRC-LoLa (BB/L002124/1; Hutton subcontract) and will be sourced from M.R. Broadley (Nottingham). Germplasm for O1 will be bulked in 2016 (M2) and future years as necessary.

The RSA of genotypes will be assayed in custom-built facilities (y1, O1.2), including a high-throughput, scanner-based phenotyping system at Hutton and, in collaboration with European partners, at Juelich (http://www.fz-juelich.de/ibg/ibg-2/EN/organisation/JPPC/JPPC_node.html). In these facilities, germination rates, and root gravitropism, root branching intensity and root elongation rates of seedlings will be studied in important germplasm collections (y2, O1.5). Development of protocols for extraction of root phenotype parameters will be completed early in y2 (M5). Selected genotypes will also be studied in 3D in transparent soils. The current system for imaging in transparent soil allows growth of seedlings for less than 7 days. The system will be developed to allow growth for longer periods, in more complex media, and image capture and image analysis procedures will be improved. This will enable its use for studying nutrient and water uptake and the imposition of different types of physical constraints in O2. It will also be used to study the molecular and physiological mechanisms underpinning seedling establishment. The RSAs of barley will also be studied in soil-filled rhizoboxes in the glasshouse. To determine the effects of osmotic and nutritional stresses on root development and gene expression, selected barley genotypes will be grown hydroponically. A hydroponics system will also be used to collect root exudates using techniques established previously (y1, O1.3), which will be analysed for their chemical composition in collaboration with Sheffield University (y2, O1.6). Key root anatomical traits related to soil penetration and anchorage will be examined in model cereal and brassica species using conventional microscopy and non-conventional, ablation techniques. Quantitative Trait Loci affecting RSA traits and exudate composition will be mapped genetically using data collected in O1 for barley and oilseed rape.

O2 Interactions between root traits and rhizosphere structure, composition and biology. The aims of O2 are (1) to identify root traits influencing rhizosheath formation, rhizosphere biology and soil structure and (2) to develop conceptual frameworks of how plant genotype x soil properties x soil biodiversity interactions influence (a) rhizosheath formation, (b) rhizosphere biology and (c) exploitation of the soil volume.

Root traits influencing rhizosheath formation will be identified by various approaches. Root traits affecting rhizosheath formation in barley will be identified using knowledge of candidate genes identified in previous studies. Up to 3 candidate genes will be cloned, sequenced and expressed in a Morex background using the Hutton transformation service. The rhizosheath phenotype of transgenic mutants misexpressing candidate genes will be assayed for abnormalities. The genetics of the rhizosheath trait will also be explored in other cereals, including sorghum (with Hohenheim University), rice (with Aberdeen University) and wheat (with CSIRO) and in selected legume, oil seed and vegetable crops. The evolutionary origins of the rhizosheath will be explored by screening diverse angiosperm species for rhizosheath size, root hair production and other relevant traits. Interactions between the rhizosheath and its microbiome will be studied in up to 12 genotypes with contrasting rhizosheath properties using standard DNA extraction and Next Generation Sequencing techniques and expression analysis of functional genes including those involved in the N and P cycles.

The influence of root traits on rhizosphere biology will also be studied. Root-associated endophytes will be isolated from diverse cereal varieties and from cereals growing in low input habitats to maximise isolate diversity **(**M3**)**. Isolates will be identified and characterised (y1, O2.1). Those isolates potentially beneficial to crop production will be used in O3. Interactions between roots and AM fungi will be examined to test whether three selection pressures common in agriculture (soil disturbance, fertilization, and monocultures) select for poor partners (initial experiments in y1, O2.2; completed, M6, and analysed in y2, O2.4). The relative importance of plant genotype and soil management will be assessed using established experiments at Hutton using legume, grassland and non-crop, forb species. The role of heritability in AM associations will be determined by examining mutualistic associations in successive generations of plants selected from contrasting treatments. The extent to which genotypic diversity and soil community influence plant responses to abiotic stresses will be studied. Molecular mechanisms underlying the influence of soil communities on responses to intermittent and prolonged drought will be examined in laboratory and glasshouse experiments.

Root traits of cereals will be characterised for their effects on rhizosphere microbiology. The effects of root exudates on soil community dynamics, N-fluxes and C-fluxes will be investigated starting with a natural soil microbiome. The size, community structure and presence / absence of critical microbial species will be assayed using conventional techniques. The flow of root-derived C-flow through the rhizosphere microbiome, and its fate within the rhizosphere soil, will be investigated using stable isotope techniques. Barley germplasm will be screened to identify QTL / molecular markers associated with BNI and denitrification moderating processes in collaboration with geneticists in RD2.1.1. The effects of exudates extracted from roots on the microbiome and associated processes will also be studied in soil microcosms. In parallel, the effects of root traits on the rhizosphere microbiology will be investigated under controlled conditions using a synthetic bacterial community. Bacterial constituents of the synthetic community will be selected to represent traits of interests to crop fitness (e.g. growth promotion and pathogen resistance). Further knowledge of the complex interactions occurring in the soil will be obtained by assessing the effect of bacterial-grazing fauna (protists and nematodes) on rhizospheric bacteria and how this relates to root traits. The effects of free-living nematodes on root traits, root morphology and plant growth will be studied on potato genotypes in a glasshouse environment. Mechanisms of Interactions between roots and bacteria will be studied in transparent soil.

Root exploitation of the soil volume will be studied in soils and simplified media initially with development of experiments to study effects of soil structure and stone content (y1, O2.3) and preparation of a paper on soil structure and root growth (y2, O2.5). In further experiments wax layers will be used to assess the effects of anatomical and morphological root traits, characterised in O1, on root penetration of hard soils. A novel optomechanical sensor, developed recently at Hutton, will be used to characterise the growth responses of root tips against mechanical impedance. Timelapse CT imaging will be used to characterise soil deformation fields in situ around growing root tips, extending work previously performed at Hutton in simplified 2D granular media. Phenotyping of seedling root growth traits will be performed to characterise root responses to the range of soil physical limitations (water stress, hypoxia, and mechanical impedance) that are experienced under a contrasting soil water regimes. Mechanisms underlying genotypic responses to the soil constraints will be investigated using RNAi techniques to generate specific mutants.

Data and knowledge from experiments in O2 will inform a conceptual framework of how plant genotype x soil properties x soil biodiversity interactions influence (a) rhizosheath formation, (b) rhizosphere biology and (c) exploitation of the soil volume. Such models will then be used to design experiments to test the effects of these parameters on water and nutrient acquisition in O3 as well as forming the basis of mathematical models in O4. The work will also link to field experimentation in RD2.3.4, in which the efficacy of various interventions will be explored under arable practice.

O3. Consequences of interactions between root traits, soil properties and soil biota for the acquisition of water and essential mineral elements, disease suppression and crop production. The aim of O3 is to evaluate the consequences of interactions between plant genotype x soil properties x soil biodiversity for the acquisition of water and essential mineral elements, disease suppression and crop production. The key deliverables are: (1) identification of root traits affecting water and nutrient acquisition in the field, (2) knowledge of the consequences of interactions between plant genotype x soil properties x soil biodiversity on plant acquisition of water and nutrients, and (3) improved understanding of the effects of plant endophytes and AM associations on resource capture and disease suppression. It will utilise techniques the team have developed in previous projects. This Objective cannot be considered in isolation from O4, which will develop quantitative, predictive models of system behaviour at a variety of scales, and must provide data for both model development and testing model performance.

Up to 12 barley phenotypes with contrasting RSA, identified in O1, will be grown in the field and the effects of RSA traits on water and nutrient acquisition efficiencies will be determined (y2, O3.1). Studies linking plant transcriptional, physiological and morphological responses to vagaries in water and nutrient supply will complement this work. Similarly up to 12 barley phenotypes with contrasting rhizosheath traits will be grown in the field and exposed to a range of abiotic stresses, including soil physical constraints, nutrient deficiencies and drought. Comparisons will be made between the relative ability of genotypes to acquire water and nutrients and to yield under these various conditions. Studies will also characterise how roots and soil structure interact to affect plant water and nutrient acquisition, crop production and soil properties. Barley genotypes will be grown under the abiotic stresses previously identified in surveys of Scottish arable soils. The effects of root-soil interactions on N uptake efficiencies and biomass production will be determined and transcriptional responses to abiotic stresses will be characterised. Mini-rhizotron studies will be used to study root system development in relation to soil structure in collaboration with RD1.1.1, and will inform model development in O4.

The benefits of root endophytes for increasing crop growth will be examined in the first 2 years (linking with work in RD2.1.4), followed by abiotic stress tolerance and resistance to pathogens on isolates of interest. This work will begin with a glasshouse experiment testing the effects of endophytes on growth promotion The effects of endemic endophytes and endophytes known to promote fitness of grasses will be compared. The effect of the host genotype on the efficacy of endophytes will be studied in glasshouse primarily and then in the field. The mechanism(s) whereby endophytes exert beneficial effects will be explored on isolates of interests.

The interactions between root traits and microbial communities will be characterised, and their impact on plant nutrient acquisition and nutrient cycling in the environment will be determined. Barley genotypes will be screened for impacts on soil nutrient cycling processes. Mineralisation of soil organic matter will be quantified as an index of microbial processes mediating gross flux of nutrients from soil sources. Specific impacts on both nitrification inhibition and denitrification moderation will be determined. The mechanisms behind plant-specific effects on rhizosphere processes will be examined and the potential for rhizosphere manipulation of the N cycle through crop genotype will be explored in the field under arable practice. The effect of rhizosphere grazing by soil fauna (protozoa and nematodes) on plant growth and crop yield will be determined for different barley genotypes and considering interactions between genotype and soil characteristics. Knowledge and data from studies undertaken in O3 will be used to develop and validate quantitative models of rhizosphere behaviour in O4.

O4. Develop and validate quantitative models of rhizosphere behaviour. The aim of O4 is to integrate knowledge and data obtained in O1, O2 and O3 into quantitative models describing the effects of root traits, rhizosheath and soil structure on nutrient and water acquisition by plants.

Key traits that determine RSA and the distribution of roots in the soil have been identified. The genetics of these traits will have been examined in O1 and genotypes with contrasting RSA traits will have been identified. Models will be developed linking the development of RSA to the exploration of the soil volume and the acquisition of water and nutrients. Models will include the effects of root exudates on the phytoavailability of mineral nutrients incorporating the effects of plant genotype. Predictions from the models will then be calibrated using genotypes with contrasting RSA in controlled environments. Correlations between these predictions and crop yields will be determined in field

experiments. The effects of the formation of a rhizosheath on water retention, and water and nutrient transport to the root surface will be modelled in collaboration with Tiina Roose (Southampton) through a BBSRC SARISA project. This work will evaluate the importance of rhizosheath formation to water and nutrient uptake along a developing root. The development of the rhizosheath will be visualised using X-ray CT scanning and it will build on knowledge of (a) root traits affecting rhizosheath formation obtained in O2 and (b) their performance in the field obtained in O3. These models will provide insight for manipulating plant genotype x soil properties interactions to improve the acquisition of water and nutrients by plants, crop production and resilience to environmental change. Key deliverables from the modelling will include: (1) models of rhizosphere behaviour, (2) identification of plant phenotypes and rhizosphere manipulations for sustainable agriculture, (3) potential targets for plant breeding, (4) knowledge of effects of rhizosphere manipulations on movements of water and solutes in the soil environment.
Expertise This RD emerges from collaborations between the Research Team and many organisations in projects funded by RESAS, EU, BBSRC (including SARISA, HAPI, CIRC, TSB), Defra, HGCA, AHDB, NERC, ERC, and several commercial companies. Publications and expertise of individuals are provided in CVs.

Key linkages, interdisciplinarity & collaboration

Interactions will be managed via regular meetings between the team's Research Leaders, facilitated by videoconferencing between Aberdeen (Hutton), Dundee (Hutton), and Edinburgh (SRUC) sites. Many research leaders within the team meet monthly as part of the Dundee-based root and rhizosphere group, and have regular, informal contact. Staff will be involved in multiple RDs for various Work Packages and Themes, which aids communication at all levels and enables overarching KE events. There are numerous links with ongoing research projects funded by RCUK, EU, Industry and Levy Boards, managed by individual Research Leaders in the team. RD2.1.7 inputs to Integration Hub RD2.3.12, via links with RD2.3.8 and RD2.3.9 (Integrated Management Systems).

Work performed in RD2.1.7 will link directly with other RDs in WP2.1, including RD2.1.1 (Crop Genetic Diversity) in complementing work on nutrient use efficiency, RD2.1.2 (Crop Genetic Improvement) which will generate genetically characterised germplasm and help dissect the genetic basis of plant traits that affect endosymbiont communities, soil structure, soil microbiology and resource capture in a beneficial manner, and RD2.1.6 (Integrated Pest Management) since the effects of endosymbionts, rhizosheath and rhizosphere biome on pests and pathogens can be used to devise new strategies for IPM. It will also link to other WPs in Theme 2, such as RD2.3.4 (Sustainable Soil and Water Management) by informing sustainable management practices to enhance water and nutrient acquisition, improve soil quality, foster beneficial soil microbial communities, and reduce pests and diseases, and RD2.3.8 (Alternative Approaches to Sustainable Land Management) which will perform experimental studies to validate the concepts and models developed in RD2.1.7 using existing 'platforms' (Balruddery, Glensaugh, SRUC). Finally, it will link to work undertaken in Themes 1 and 3. In particular, it will provide information on root traits to inform experiments on how these impact fundamental soil properties and processes in RD1.1.1 (Soil and its Ecosystem Functions) and the role of soil processes on crop yield, resource-use efficiency, biodiversity and suppression of soil-borne diseases in RD1.1.1 and RD1.3.1 (Biodiversity and Ecosystem Function), and provide an understanding of the effects of plant genotype, soil structure and soil biology on the acquisition of mineral elements essential to human and animal nutrition can be exploited to improve the mineral composition of edible crops in RD3.2.1 (Healthy Diets). Statistical design and analysis will be carried out in collaboration with BioSS, whose inputs will be supported by BioSS funding for Underpinning Capacity Function 7.

Outputs from RD2.1.7 may identify novel crop phenotypes for sustainable agriculture and improved management practices, both to optimise resource utilisation and to control pests and pathogens. These would be exploited in partnership with plant breeders, growers and government, for example via the 14-partner network (established in the EURoot project) who are working with breeders in Asia and Africa. The need for research on understanding root-soil interactions as an integral component of sustainable agriculture has been identified by various stakeholders as a subject of topical concern.

Added Scientific Value
This RD benefits substantially from ongoing, fundamental research projects supported by RCUK etc., collaborations with leading national and international research groups (e.g. Universities of Nottingham, York, Sheffield, Southampton, Juelich), and applied research supported by Industry. The research also benefits from access to well-characterised, long-term experimental sites and access to unique resources of barley, brassica and potato germplasm.

KE, Audiences and delivery: The RD will have a cross-MRP approach to delivery, coordinating with CKEI activities (e.g. Annual Showcase events, Annual Campaign, Think Tank), via the Theme KE Coordinator and KE sectorial leads. The immediate (academic community) audience will be reached via presentations at international conferences (e.g. ISRR, Rhizosphere), incorporating material into lectures, and submitting papers to leading international journals (KE3). We will run annual ISRR Medal Lecture Symposia, attracting international experts in root research, with selected members of the Research Team presenting findings (KE1, KE4). Findings will be presented to members of the agriculture industry in general and agronomy companies (consultants, agronomists, land managers), farmers, agrochemical companies, equipment manufacturers, and plant breeders. We will target one or more industry events per annum from 2017 onwards, including Potatoes in Practice, Cereals in Practice, and LEAF events (KE5, KE6). Trade magazines and advisory documents will be targeted later in the project (2018/19), with face-to-face interactions through ongoing projects (including HGCA and BPC funded projects) and membership of research clubs. The broader implications of the research for sustainable farming will be communicated to the public and to policymakers through, articles in popular magazines, Institute Open Days, and The Royal Highland Show. Work described in RD2.1.7 will feed into larger KE projects incorporating aspects of plants, soils and microbes, as exemplified by the wide range of activities undertaken by this Research Team during “The International Year of Soils 2015”. **Impact**: Work in RD2.1.7 will increase the awareness of researchers, industry and the public of the roles that roots, soil quality and microbial communities play in crop establishment and production. Impact on the academic community is best assessed by the research profiles of the combined Research Team. Work in O1, providing a database of root traits and their genetic basis, will benefit breeding companies pursuing root traits and molecular markers for sustainable agriculture through links with RD2.1.1/2 and via the EURoot project partners. This will have economic and environmental benefits for the nation in the long term. Work in O2, characterising root-soil interactions, will provide new information to plant and soil scientists, and microbiologists, enabling greater understanding of rhizosphere processes that might be used to develop novel solutions for sustainable agriculture. Work in O3, elucidating the effects of plant genotype and soil management on resource acquisition and tolerance of biotic and abiotic stress, will benefit crop production and be of interest to agrochemical companies. Work in O4 to model the effects of root traits and soil properties on resource acquisition will benefit the academic community and can be used to make quantitative predictions to inform targets for plant breeding and the manipulation of agriculture for greater resource use efficiency and reduced environmental impact.

RESEARCH DELIVERABLE NUMBER: 2.1.7
Work planning and timetable for Year 1:

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 (O1.1) Database developed: Produce database for images and quantitative data from O1 work on root traits						M1						O1.1
O1 (O1.2) Protocol 2D phenotyping: Design experimental protocols for phenotyping roots in 2D imaging systems									01.2			
O1 (O1.3) Exudate profiling: Initial chemical profiles for root exudates using hydroponics system with Sheffield University.							M2				O1.3	
O2 (O2.1) Endophyte profiling: Isolate and characterise potentially beneficial endophytes for use in O3.								M3				O2.1
O2 (O2.2) AM fungi selection test: Test whether selection pressures in agriculture select for poor partners in AM fungi symbioses.												O2.2
O2 (O2.3) Soil structure experiments: Design and implement experimental system to look at soil structure and stone content effects on root exploration.												O2.3
KE1 Events: ISRR Medal Lecture		KE1										
KE2 Events: Highland Show			KE2									
R1. Annual Report (Year 1)												R1

RESEARCH DELIVERABLE NUMBER: 2.1.7
Work planning and timetable for Year 2:

Year 2: 2017/18	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
O1 (O1.4) Populate database: Update database with results from project, and make available to research group.				**M4**								**O1.4**
O1 (O1.5) 2D data & phenotyping for paper: Complete experiments and data analysis of results for 2D phenotyping paper.					**M5**			**O1.5**				
O1 (O1.6) Exudate properties analysis for paper: Complete experiments and data analyses of exudate properties for paper on exudate properties.									**O1.6**			
O2 (O2.4) AM Fungi analysis and paper: Complete experiments and data analyses for paper on selection pressures on AM Fungi in agricultural management systems.							**M6**			**O2.4**		
O2 (O2.5) Structure analysis and paper: Complete experiments and data analyses to prepare paper on soil structural interactions between root and rhizosphere.												**O2.5**
O3 (M3.1) RSA, water nutrients field design: Complete field experiment design to determine effects of RSA traits on water and nutrient acquisition efficiencies.							**O3**					

KE3 Write and submit journal paper on root exudate properties												**KE3**
KE4 Events: ISRR Medal Lecture		**KE4**										
KE5 Events: LEAF Event			**KE5**									
KE6 Events: Potatoes in Practice					**KE6**							
R2. Annual Report (Year 2)												**R2**

Name of RD: 2.1.8 - Novel Crops

Research aim and key drivers

The Scottish Government is committed to more sustainable use of Scotland's natural resources including more effective production of crops that can be part of the circular or bio-economy: see '*The Scottish Governments Economic Strategy*' (ISBN 978 0 7559 5548 0). This sets a target of 'sustainable economic growth', which rests upon Scotland's capacity to develop a responsive and successful economy which provides prosperity, a better quality of life and opportunity for all. The move to a low-carbon economy is perhaps the most significant addition to the Scottish government's economic strategy. The research proposed here aligns with these policy objectives and the specific requirements of SRP2016-21, Scottish Government policies on sustainable development, such as, "*Building Security and Creating Opportunity: Economic Policy Choices in an Independent Scotland* (publ. Nov. 2013). The research findings will also help to develop UK-wide CAP reform policy which aims to stimulate exploitation of nitrogen-fixing crops, and the European Union policy towards sustainable growth of the wider bio-economy. Towards that end, we propose a research portfolio that is heavily focused upon the cultivation of novel and minor high protein and energy crops for food and feeds - using legumes and biomass crops such as *Miscanthus.* In addition, research will help foster new knowledge and skills to help develop a suite of novel industries in Scotland. These include hops, native blueberry germplasm and native medicinal plants. The research will also support the integration of these novel and current minor crops into existing rotations, practices, processes and supply chains. RD2.1.8 has been developed through consultation and collaborative working with a wide range of stakeholders including: the National Farmers Union of Scotland; animal- and aquaculture-feed manufacturers (*e.g.* Harbro. EWOS and BioMar); Scotland Food and Drink; Food Standards Scotland; the Brewers Association of Scotland (an umbrella organisation of the Scottish microbreweries); the British Hop Association. Consultation on bio-energy sector has taken place with Anaerobic Digestion (AD) plant companies such as: Keithick Biogas Ltd in Coupar Angus, Perthshire and Claylands Farm, Balfron, Glasgow. These have highlighted he knowledge gap and need for gas-efficient, locally-produced crops for AD plant feed and the Hutton AD Scoping Group has identified expertise to develop full life cycle-relevant research opportunities. As such the activities described here will be pursued with respect to the aims aim of CAMERAS (A Co–ordinated Agenda for Marine, Environment and Rural Affairs Science), to help support Scottish Government policy development and delivery for the rural, environmental and

Summary of the proposal

Objective 1 focuses on nitrogen use efficiency, novel high protein crops and the multiple benefits that arise from innovatively managed cropped systems, and especially legume (*i.e.* biological nitrogen fixation) supported cropping for more sustainable food, feed and energy production, and including novel food and feed formulations.

Objective 2 describes research on novel fruit, floral and flora-based crops and associated novel cropping strategies. This Objective presents an additional focus by which the Scottish economy may be strengthened from more sustainable use of underutilised natural resources. Both Objectives are geared to empower the Scottish bio-economy and accord with objectives to sustainably produce high-protein and biomass crops, the development of novel crops as new revenue streams, and enhancing human and animal health and wellbeing.

Main aims:
1. Address opportunities for producing alternative protein crops in Scottish agriculture for fish and crustacean feed, bioenergy, biorefining, animal feed and human consumption.
2. Develop design criteria for integrating suitable alternative legume and non-legume crops as sole and intercrops within rotations whilst also accounting for agronomic and ecosystem services.
3. Improve production efficiency of biomass crops for marginal land from the identification of best-for-for purpose combinations of *Miscanthus* x PGPB (plant growth promoting bacteria).
4. Identify the best agronomic practices for under-cover production of dwarf hop varieties to help support the development of the rapidly expanding craft micro-brewery businesses in Scotland.
5. Map and establish a collection of wild Scottish low bush berry populations to characterise genetic types and best-fit for purpose populations and practices to underpin their commercial development.
6. Identification of 2-3 native Scottish plant species and their bioactives which show a high potential to improve health *and* which are also suitable for large scale in-field commercial production.

Objective 1 - Novel crops and cropping approaches to realise more sustainable protein and biomass production, plus novel food and feed formulations. This Objective explores the use of high-protein legume and non-legume crops as alternative food and feed ingredients, biomass for energy production and also new markets. Specific deliverables include research on novel cropping strategies and methods to help ensure more sustainable crop production.
High protein plants and nitrogen use efficiency are important to the development of sustainable agriculture and food production systems. However, there is a great need to optimise their agronomy, improve product quality and establish their cultural and economic viability, including the identification of the most promising routes to markets. This stakeholder led initiative will explore the development of high-protein legumes for grain and or forage production and these species include soybean, faba bean, pea, lupin, lentils, vetches, trefoils and clovers. Also, the non-legume species chai, quinoa, buckwheat, flax, rapeseed and hemp. These species have good potential to maximise productivity in low-input systems. However, research needs to identify best-fit-for-purpose varieties, and to optimise the underpinning cropping approaches as sole and inter-crops, as the latter can increase yield up to 50%, and reduce disease by 70%. Agronomic challenges for legume production include yield stability and competitiveness against weeds as identified by stakeholders in the EU Legume Futures project. The same study showed that if farmers are to increase legume production they also need convincing evidence of the longer-term benefits of legumes in terms of the delivery of multiple ecosystem service deliver over the course of a rotation. Understanding the decomposition dynamics of crop residues is an important component of this work which will be linked to modelling within RD2.3.8. This research will be carried out with a view to grain, whole-crop silage/ forage production for feed and/or energy. The aim is provide high and stable yields, whilst also optimising yield- and food/feed-qualities - such as protein content and improved essential amino acids complement. Initial in field trials at plot scale (y 1-2), will be scaled up for large commercial, or near-commercial scale trials in years 3-5. The larger scale trials will involve collaborative research with farmer-stakeholders. It may also be anticipated that

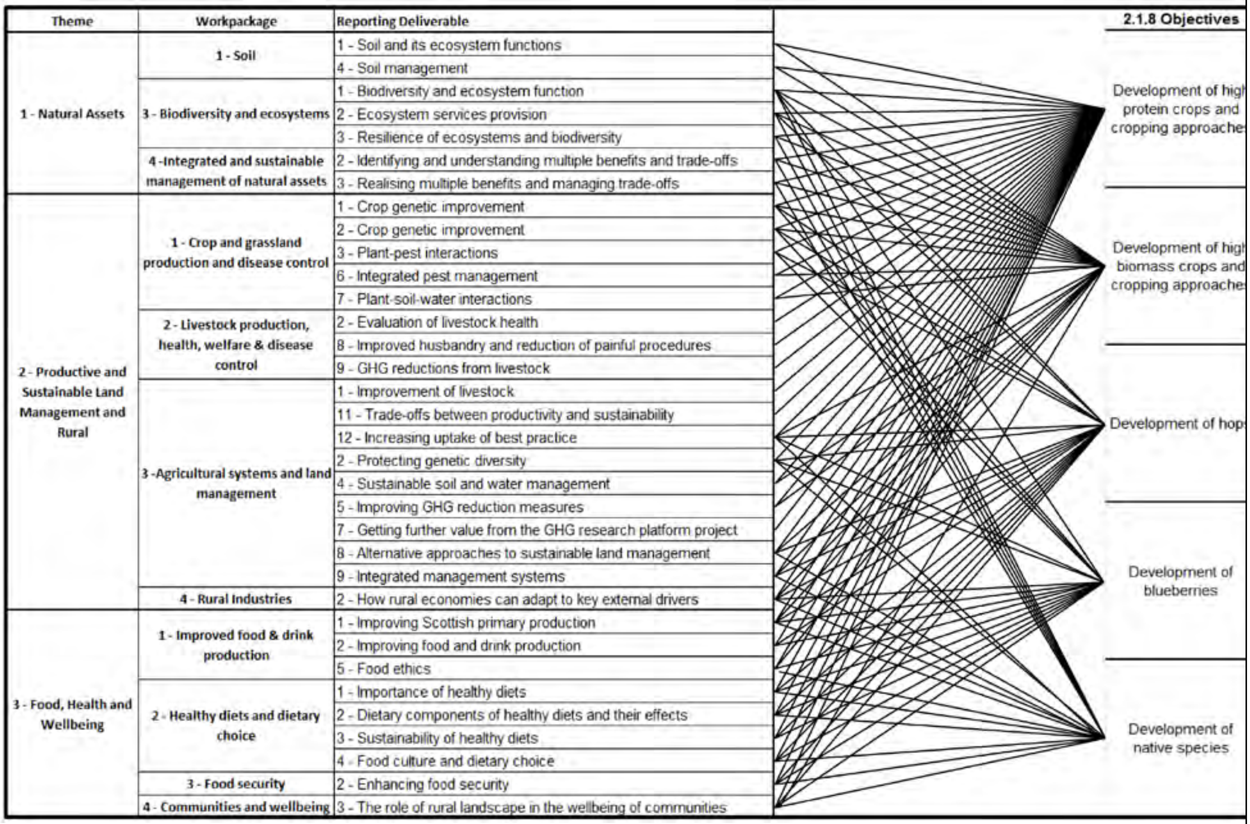
the year 3-5 trials will include development of precision agriculture based approaches for intercropping, including the management of living (legume) mulches and utility of elite-rhizobia inoculum.
Such foci will be allied to the identification of *Miscanthus* genotypes which can realise the success of a novel cropping approach using Plant Growth Promoting Rhizobacteria (PGPR), to minimise inorganic N requirement for this biomass crop which has high potential for use on marginal land. In years 3-5, the utility of the PGPR will be assessed for their utility in supporting low-input production of barley (and wheat), varieties.
This research portfolio will also assess new and emerging markets/processing opportunities such as the pulse-cereal intercropping to support production of food (including brewing and distilling), and novel formulated food and feeds. Human studies will establish the nutritional quality and potential health benefits (links to WP3.1 & WP3.2) and will deliver sustainable and healthy products with a strong economic advantage for the agri-tech and food industries, and additional value from the revalorisation of waste (links to WP3.1 and WP3.2). This will be integrated with research on nutritional value of protein crops in monogastrics (pigs and poultry) that focus on identifying the potential of local grown protein sources to reduce reliance on imported soya, currently around 0.1M tonnes annually for Scotland. This Objective also has strong links to research on residue decomposition in rotations in RD2.3.8 and work on below ground processes in RD2.3.4.
Beyond year 2, deliverables will include, new nutritional information regarding protein consumption to inform dietary advice (by year 5), and novel high-protein plant-based ingredients for healthier and sustainable food reformulation (years 3-5). It should also be noted that robust datasets which can distinguish genetic from environmental effects will need gathered from parallel trials for the whole five-year period of RESAS-SRP period 2016-21. However, specific deliverables in addition to those listed below will include for example: improved agronomic practices for a wide range of species and varieties that will allow greater and more stable yields in the face of environmental perturbations.

Objective 2 - Novel floral, fruit and native crops: *Humulus lupulus* (Hops), *Vaccinium angustifolium* (low- and high-bush berry), and Scottish native flora.
Hops have the potential to be a high-premium product for Scotland as a flavouring and stabiliser for beverages such as beer, and also in therapeutics. Dwarf hop germplasm will be established for polytunnel based production in association with the British Hop Association. Growth characters and agronomic traits will be monitored and pilot-scale testing will also be carried out in collaboration with Scottish micro-breweries, and linked to genetic studies in the longer term. Beyond the initial two year plan, objectives in years 3-5 will include brewing-quality evaluations, both on site and in partnership with end-users. This will produce a blueprint for the upscaling of production to an industrial scale. An initial assessment of the Scottish industry demands into the future will be made.
The first Scottish low-bush berry plantation will be established in Scotland. Low bush berry grows wild across Europe and their fruits have been used to produce a high quality juice in collaboration with Ella Drinks Ltd. In a comparative analysis alongside high-bush (blue)-berry plantations - we aim to understand the factors controlling yield stability and yield qualities in both types. Cross MRP efforts will ensure robust statistical and interdisciplinary relevance with data from field experiments manipulating resources such as water, temperature, soil fertility, plus crop and canopy densities for

genetically typed populations. The approach will link genetic markers to key agronomic traits and so enable future breeding effort. Beyond the initial 2 year work plan the long term objectives are to develop statistical methods to obtain SNP dosage data from GbS SNP marker data in tetraploid blueberries, and to use these markers to construct a high-dimensional blueberry linkage map. This theoretical work will also be relevance to studies on potato and on many other autotetraploid species of interest to the wider scientific community e.g. alfalfa. Furthermore, success in this respect will empower genetic-marker assisted selection, and the development of elite blueberry germplasm with high commercial and environmental potential.
Wild Scottish flora collections based at RBGE will be assessed to serve end-users such as pharma, biocides plus food and drink industries. Initially, this approach will generate the first systematic review of Scottish flora with respect to their ability to align potential for health and well-being as well as suitability for commercial production and processing. Key species with highest commercial potential will be developed as a source of health-promoting bioactives in collaboration with RINH. To deliver on this an initial assessment of the available Scottish flora will be undertaken from a biochemical diversity viewpoint to identify potential. Following the initial two year work plan, years 3 to 5 will take selected exemplar species for further bioactivity and functionality testing and with a view towards their commercial development. The year 3-5 activities will be performed in collaboration with a range of key Scottish sectoral representatives, *e.g.* food and drink, pharma and crop protection.

Key linkages, interdisciplinarity & collaboration

Five key linkages of the 2.1.8 SRUC/Hutton/RINH/RBGE collaboration include:
1. Other RESAS SRP 2016-21 RDs: Research will link to RDs including RD1.1.1, RD1.3.1, RD2.1.1/2/7/8, RD2.2.8/9 and most significantly RDs 2.3.2/4/5/7/8/9/12 (enable uptake of low-input/-impact systems whilst increasing production), and RDs 2.5.1/2/5 (improving economic-resilience/-adaptation), RD3.1.1/2 and 3.2.2/3, the latter exploring health effects of novel crops mediated by the gut microbiota. There will be shared experiments with RD2.3.8 (O3.2) on intercropping in relation to residue decomposition and biodiversity. RD2.1.8 will explore options for KE and cooperation on emerging policy questions with RD2.4.1.The potential relationship between each RD2.1.8 objective and each RD is illustrated in the linkage-map below. **2**. Industry & NGOs: provision of data and conclusions which inform the activities of consumer- and, environmental-groups, also levy-boards *e.g.* AHDB and Processors and Growers Research Organisation. This will be delivered for products such as informed legume cultivation, horticultural approaches to increase essential mineral content, cultivation of hops and low bush berry. This will extend to Policy Managers within consumers groups such as ‘Nourish Scotland’. **3.** Scottish Government: policy development of more sustainable systems healthier food. **4.** Internationally: though collaborative funding awards (e.g. EU H2020) and open-collaboration including joint PhD studentships and sabbaticals. **5**. Wider UK-academic community: research will be collaborative with other Scottish e.g. Dundee, Aberdeen, St. Andrews, Abertay and Strathclyde Universities and UK institutions e.g. Nottingham and York Universities, Rothamsted Research, NIAB, IBERs and academic bodies e.g. British Ecological Society, Association of Applied Biologists



Added Scientific Value

This work complements previous research on home grown protein alternatives including whole peas, lupin and faba beans (Defra), faba bean fractions (TSB/InnovateUK) and rapeseed (HGCA). Through MRP cooperation we aim to harmonise the often conflicting needs of grower, food & feeds processors, consumers and policy-makers. This work adds value to interests across research councils and academic departments to develop a sustainable diet which is affordable, safe and healthy in both personal and environmental terms, in the UK and globally.

The work will build upon existing industry and academic contacts, and include new ones both nationally and internationally e.g. from InnovateUK projects; www.beans4feeds.net and research aimed to develop novel legume-supported cropped systems (www.legumefutures.eu). Existing industry partners include Monsanto, Premier Foods, Diageo, Marine Harvest Ltd., Harbro Ltd., Tennent's, Inveralmond Brewery (Perth), Barney's Beer (Edinburgh). Academic partners include Abertay University and Oxford University. Critically, close working relationship are already established with PGRO (the Processors and Growers Research Organisation), and other levy boards/NGOs such as HGCA and HDC. For bioenergy and biomass the MRPs are in consultation with Anaerobic Digestion (AD) plant companies such as Keithick Biogas Ltd in Coupar Angus and Claylands Farm, Balfron, Glasgow who highlighted the knowledge gap and need for gas-efficient, locally-produced crops for AD plant feed. The Hutton AD scoping group has identified expertise to develop full life cycle-relevant research opportunities. For fruit crops work on low-bush berry builds on existing research for commercial development with Ella drinks Ltd. Work on bioactives from native flora develops expertise and links form EU-FP7 projects on bioprospecting (DISCO, disco-fp7.eu & BacHBerry; ~€16M). Initial objectives and KE plans have emerged from consultations and active collaboration with many actors involved in all aspects of the crop product supply chain. These interactions have built upon the insights gained from the market research already carried out by those partners. For example, the predicted doubling in salmon farm production by 2025 and consequent demand for vegetable (faba bean) derived protein.

KE, Audiences and Impact

Where outputs relate to primary production, researchers will engage plant breeders, seed-suppliers, growers, food-processors, agricultural extension services, multiple retailers, related NGOs, governmental-policy teams. MRP scientists involved in this work will continue to publish in high impact journals and contribute to national and international conferences on crop and plant science. The public will also be given high priority for KE through targeted publications, open days and science festivals including field-plot demonstrations at key events such as ‘Cereals in Practice’ “Fruit for the Future”, LEAF-Innovation Farm Open Days and “Fascination of Plants” events. Furthermore, in collaboration with work in RDs 2.3.8, 2.3.9 and 2.3.11, the novel field experiments proposed here will be integrated with existing platforms (CSC) as “KE demonstration sites” as a focus for visiting stakeholders, including policy makers. Where agronomic recommendations may be made case-study leaflets with be produced for farmers, advisors and the AD (anaerobic digestion)-based industries. Also, where new bioactive and functional components are exploited within the Scottish economic base, stakeholders including those in health professional, pharma, biocides, food and drink and industrial biotechnology arenas will be targeted at sectorial KE events since success with respect to encapsulated bioactives is likely to achieve global market impact. Impact and legacy will also be achieved via key links to national- and EU-funded projects and science-networks such as ENDURE. Peer-reviewed publications will identify priorities for policy groups and directorates in Scotland, the UK and internationally. Key outputs here will also delimit how diversity in crops and cropping approaches may be exploited to resolve the conflicting demands of environmental sustainability, nutrition, market and consumer expectations with respect to food security. Resolutions in these respects will help overcome several Government policy challenges in Scotland and further afield.

Planned KE activities in RD2.1.8 will link strongly to the CKEI through the sectorial leads and via the Indicative Activities e.g. 4 (‘annual campaigns’), 5(‘annual showcase event’), 6 (‘Think Tank’), 7 (‘practitioner workshops’) and 10 (‘responsive opportunity’). As necessary, RD2.1.8 staff will engage with CKEI Activity 8 - development of KE skills, and this could extend to CKEI Activity 9 (work shadowing, secondments and residencies).

RESEARCH DELIVERABLE NUMBER: RD2.1.8
Work planning and timetable for Year 1

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1: Workshop, workshop report & KE briefs on novel crops and novel cropping strategies.					M3					KE2, O1.1		
O1.2: Potential of protein crops for food reformulation.												
O1.3: Study and reports on trait-complementary of high protein crops.		M1									O1.3	
O1.4: Establish *Miscanthus* plantation and generate PGPR collection.		M2				M4				M5		
O1.6i: Reports on antimicrobial properties and related KE event.						KE1 O1.6i						
O2.1: Report mapping Scottish low bush berry populations.												O2.1
O2.2: Report on establishment of dwarf-hop and low-bush berry plantations.		O2.2										
O2.3: Assess commercial development of native flora.				O2.3								
O2.4: Report on the agronomy and yields for dwarf-hop.							O2.4					
O2.5: Report on the agronomy and yields for low bush-berry.												O2.5
O2.6: Genetic linkage map of GbS markers for UK blueberry populations									O2.6			
O2.7: Study and report on bioactives for key commercial species.								O2.7				
Annual Report (year 1)												R1

RESEARCH DELIVERABLE NUMBER: RD2.1.8
Work planning and timetable for Year 2:

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1: KE briefs on novel crops and novel cropping strategies.												**KE4, O1.1**
O1.2: Potential of protein crops for food reformulation.												**O1.2**
O1.3: Study and reports on trait-complementary of high protein crops.		**M6**							**O1.3**			
O1.4: Establish *Miscanthus* population and PGPR collection.						**M7**				**O1.4**		
O1.5: Joint MRP stakeholder KE workshop and report on novel crops and novel cropping strategies.	**KE3**									**O1.5**		
O1.6ii: Report on novel feed values.									**M8**			**O1.6ii**
O2.4: Report on the agronomy and yields for dwarf-hop.							**O2.4**					
O2.5: Report on the agronomy and yields for low bush-berry.							**O2.5**					
O2.6: Genetic linkage map of GbS markers for UK blueberry populations												**O2.6**
O2.7: Study and report on bioactives for key commercial species.								**O2.7**				
Annual Report (year 2)												**R2**

Work Package 2.2: Livestock Production, Health, Welfare and Disease Control

1. Overview

Livestock health and welfare plays a fundamental role in the sustainable management and productivity of Scottish livestock agriculture, and is of significant importance to the RESAS Research Programme. The knowledge, technologies, and tools to be developed in this Work Package (WP) will have an international impact on livestock productivity, health and welfare. Use of existing databases, collaborative links between the MRPs and resources developed within the 2011-2016 RESAS Programme will enable progress. The WP encapsulates nine Research Deliverables (RDs) covering a range of activities: genetics, genomics, disease mechanisms, diagnostics, vaccinology, epidemiology, behaviour and welfare. The production of healthy animals that can be managed sustainably to produce food is the overarching goal of this WP. This will be achieved by improving animal characteristics, health management and welfare assessment. Genomic studies and targeted gene approaches will be applied to improve livestock productivity and health.

Investigations into ways by which different infections cause disease will give an improved understanding of innate and adaptive immune responses to infection and provide essential knowledge to underpin the design of new diagnostic tests and vaccines. This includes combined approaches that address the DIVA principle (Discrimination between Vaccinated and Infected Animals). This work will use a range of unique models of disease to improve predictions of disease outcome and vaccine performance. The work will take into account requirements for vaccines to be safe, effective, practical and affordable to meet end-user needs. While diagnostic tests must be specific and sensitive, affordability and speed in generating results are becoming increasingly important for end-users. New multivalent tests based on molecular biology and point-of-care technologies will be developed to improve management of livestock diseases, especially those caused by multiple infections. Epidemiology studies, utilising large datasets held by the MRPs and case/field studies, will identify the dynamics of endemic disease transmission, both within and between farms. Thus we will identify, develop and implement successful management strategies (including predictions of disease risk), provide estimates of the economic impact of endemic diseases and inform on best practice for future disease monitoring and data collection strategies.

Sustainable livestock production systems require good animal welfare. Using natural and social science, experimental studies will validate and develop existing and new methods for assessing animal welfare. This will provide a better understanding of the events that positively or negatively influence welfare of an animal over its lifetime. Improved, practical on-farm methods of livestock husbandry, including managing early-life experiences and the welfare status of the mother (and methods of reducing on-farm procedures that cause pain) will be developed and disseminated. Improvements in animal health, welfare and productivity will reduce greenhouse gas (GHG) emissions. The relationships between diet, grazing behaviour, genetics, metagenomics and GHG emissions will be explored by a combination of experimentation and modelling in cattle and sheep. This work is designed to meet the requirements for sustainable production of Scottish livestock.

2. Coordination and management

a) Collaboration, co-ordination and networking between MRPs and with external communities

This WP has been prepared collaboratively by scientists and bioinformaticians from MRI, SRUC, BioSS, Hutton and RINH, covering multiple disciplines, to ensure delivery which relates directly to the areas of research requested in the invitation to tender (ITGF). As described below, the work will be linked to the Centres of Expertise (CoEs) and to research commissioned by other relevant funders (BBSRC, Defra) at Research Institutes (APHA, Pirbright) and HEIs. A wide range of existing and upcoming policy and legislative drivers from Scottish Government, UK Government and The European Commission have been considered during the formulation of the RDs within this WP. These include The Climate Change (Scotland) Act 2009, Recipe for Success - The Scottish Food and Drink Policy (2009), The Land Use Strategy (2011), The Scottish Rural Development Programme including the Beef Efficiency Scheme (2014-20), The Scottish Management of Antimicrobial Resistance Action Plan (2014-18), The Scottish Animal Health and Welfare in Livestock Industry Strategy (2015-20), The UK National Action Plan on Farm Animal Genetic Resources (2006), The Food Standards Agency Strategy (2015-20), The Common Agricultural Policy (2015), and will be responsive to the upcoming EU Animal Health Regulations which is expected in 2016.

The preparation of this WP included dialogue with a variety of stakeholders (including CAMERAS partners) at multiple stages. A specific stakeholder event was held in February 2015 where the principal aims and objectives of WP2.2 were presented to Government, the Livestock Industry and Levy Boards and other stakeholders. Work on livestock improvement tools links to the Beef Efficiency Scheme (BES), Beef 2020 and utilises industry-derived genetic datasets. The development of disease prevention and control strategies and tools for welfare assessment, and improved livestock management will directly address the Animal Health and Welfare Strategy for GB. The epidemiology and diagnostic research will feed into the New Centre of Expertise on Animal Disease Outbreaks (NEPIC) and will contribute to policies for disease eradication (for example BVD) and control (e.g. SCOPS: Sustainable Control of Parasites in Sheep). Improved efficiency of livestock production will reduce waste and therefore reduce greenhouse gas emissions, thus adding value to the BES proposed under Pillar 2 of CAP. Reduced use of chemotherapeutics will improve food safety and mitigate the risks of developing antibiotic and anthelminthic resistance. The nine RDs within this WP contain detailed Objectives and Deliverables for the first two years of the SRP. These will be used as a management tool to evaluate progress, policy and continued end-user relevance. As the SRP progresses, Objectives in subsequent years will reflect relevant policies as they are introduced to maximise impact. The financial details are provided on associated worksheets. IP is managed at Theme level.

There are multiple inter-WP and intra-WP links and stakeholder engagements already established for the nine RDs within WP2.2. Examples of these are provided in Figure 1, more details are provided in each RD. The *improvement in livestock genetics* (RD 2.2.1) will link closely with RD 2.3.1 (Improvement of Livestock) for the identification of strains and genetic markers for traits beneficial for livestock production, health and disease resistance/resilience, including the impact of co-infection on disease susceptibility and responsiveness to vaccination. Collaborative working with 2.4 to understand the economic benefits of improved production will also be established. Outputs from the *evaluation of livestock health* (RD 2.2.2) will have relevance to understanding the impact of disease on GHG emissions from livestock (RD 2.2.9 and 2.3.6). Tools developed within the *mechanisms of disease pathogenesis* RD (2.2.3) will be applied to study the pathogenesis of endemic diseases caused by individual viruses, bacteria, parasites, and to combined infections that result in disease complexes/syndromes or that influence responsiveness to vaccination (in association with RDs 2.2.5 and 2.3.3).

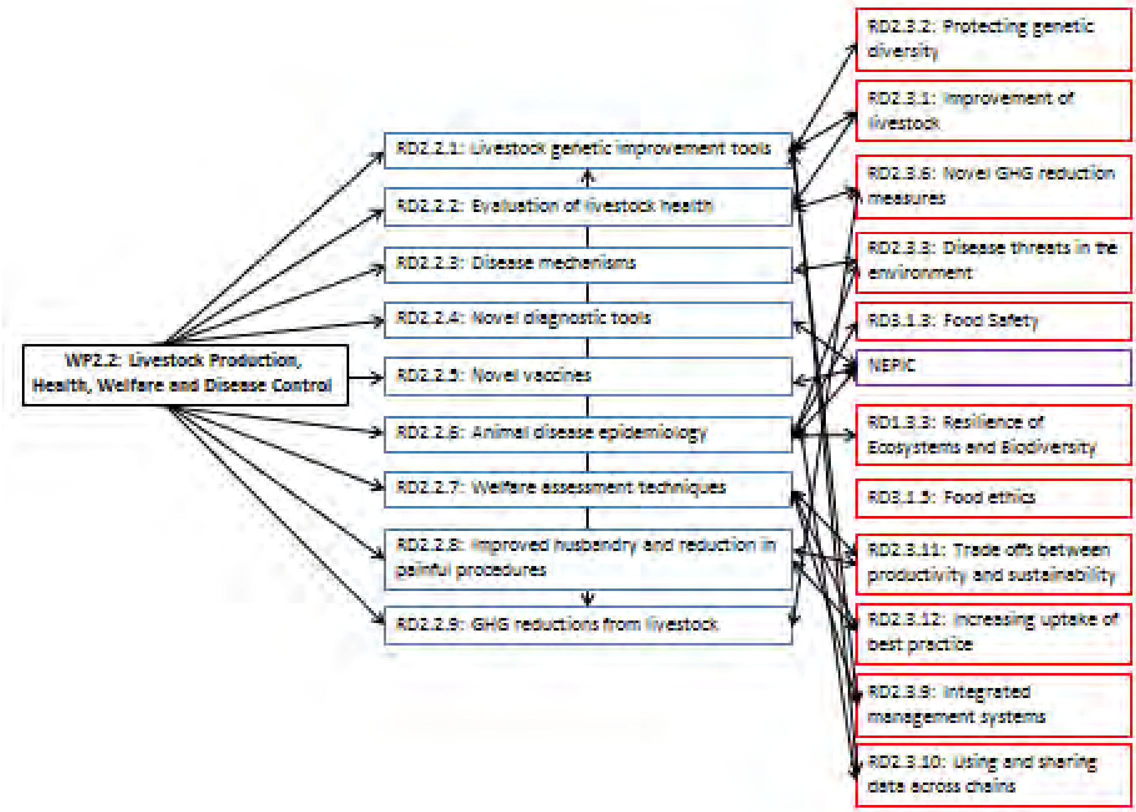


Figure 1. Multiple interactions of RDs within WP2 and with RDs in Themes 1, 2 and 3 and CoE.

Within the MRPs there is considerable expertise, technological infrastructure and underpinning capacity for development of *novel diagnostic tests* (RD 2.2.4). MRI and Hutton will build on their previous success using microbiological and plant-based systems to express peptides and proteins to develop new diagnostic platforms for detection of animal diseases. This shared and cross-MRP technology will also be applied to vaccine development. Molecular assays will be developed and used to identify pathogen strains/subtypes and their epidemiology (in conjunction with 2.2.6 and NEPIC). Immunological parameters identified in RD 2.2.3 will be evaluated for applicability as diagnostic targets, particularly in the context of combined DIVA approaches to disease control. *Novel, deployable vaccines* (RD 2.2.5) impact on disease incidence and transmission (RD 2.2.6 and NEPIC). Selection of vaccine candidates will take into account the need for DIVA management strategies. MRI will collaborate with Hutton on technologies that underpin vaccine design (RD 2.2.4).

Research in *animal disease epidemiology* (RD 2.2.6) will include work on endemic diseases of livestock of prioritised importance and build on work partially supported by the 2011-16 RESAS programme, such as ovine pulmonary adenomatosis (OPA), gastrointestinal nematodes and liver fluke. There will be projects exploring important zoonotic diseases such as VTECs, Lyme Disease, Johne's disease and anthelmintic and antimicrobial resistance. This RD will link closely with the research being conducted within RDs 2.2.2 and 1.3.3 (*Resilience of Ecosystems and Biodiversity*), and NEPIC. There will also be close inter-MRP links (MRI, SRUC, Hutton, RINH, BioSS) and sharing of knowledge, datasets and approaches to monitor diseases that link animal, plant and human health in accordance with the global One Health initiative (links to RD 2.3.3). Potential control points that break antimicrobial resistance (AMR) gene transfer will be identified in a 2-phase approach (links with *Food Safety* (RD3.1.3) and NEPIC). Collaborative research into a systems modeling approach to the persistence and control of E. coli O157, currently under SPASE, will also be continued in this RD.

Welfare assessment techniques (RD2.2.7) will link to work to the recognition of higher welfare in some management systems (RD2.2.8), use animal disease models also relevant to RDs 2.2.5 and 2.2.4 to validate welfare measures and the uptake of best practice (RD2.3.12) and embed animal welfare assessment within sustainable land use strategies (RD2.3.11). Work on the use of sensors to assess animal welfare will also form part of integrated management as explored in RD2.3.9. Research into methods to improve husbandry (RD2.2.8) of livestock will build on the work in SPASE and work on animal welfare under the RESAS 2011-2016 programme. This work links to RDs 2.2.7 and 2.3.11 to include high welfare livestock management systems as a component of potential trade-offs in land use. Work to reduce painful procedures on farm follows directly from work in the 2011-2016 RESAS programme by using those data on lamb castration to develop methods to understand farmer attitudes and decision-making with respect to these procedures and investigate why lower pain methods are not used (with substantial links to RD2.3.12). This will also make use of novel methods developed in RD2.2.7 to assess pain. These linkages will be facilitated through joint projects where the design, implementation and analysis of studies feed directly into more than one RD.

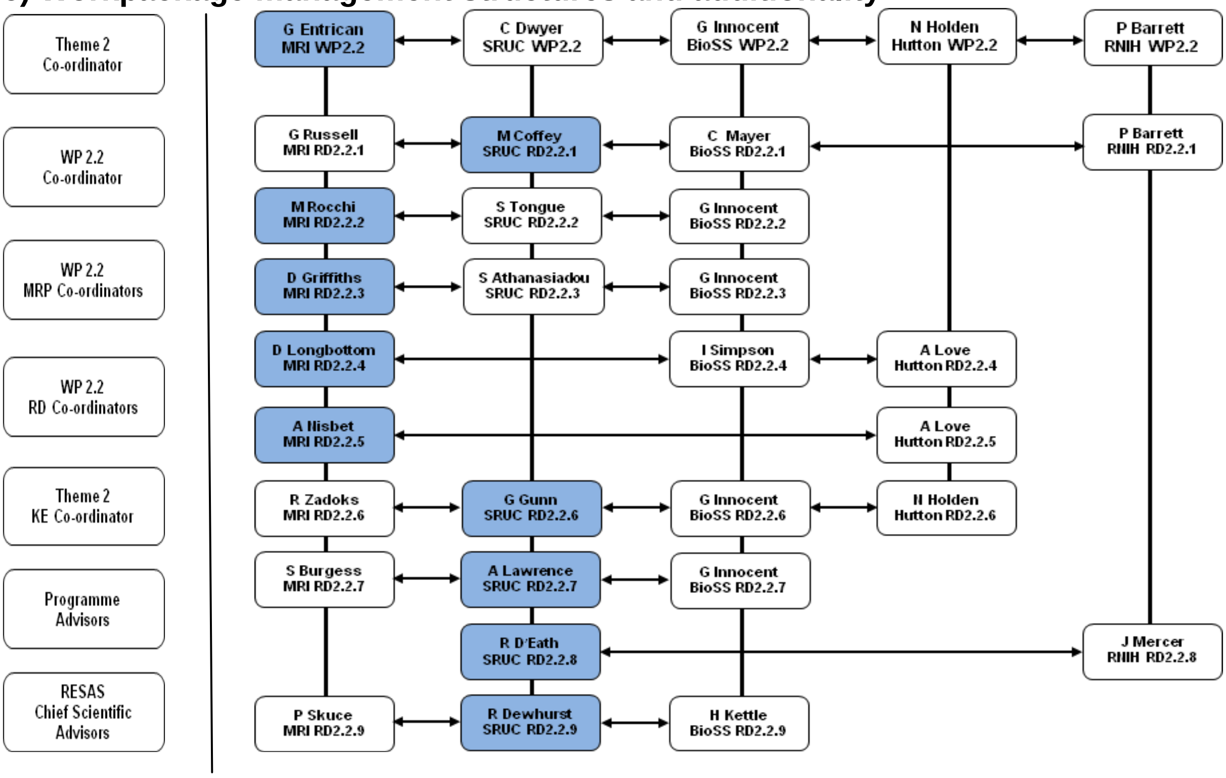
Animal health and welfare interact significantly with the potential to *reduce GHG from livestock* (RD2.2.9), which will take forward the key findings from the short-term Defra project 'Life cycle analysis (LCA) of endemic diseases on GHG emissions intensity' (AC0120) from a Scottish perspective. In particular, this will involve further scoping of the most cost-effective mitigation measures to address endemic diseases, and explore further areas of uncertainty in the LCA and Marginal Abatement Cost Curves (MACC) modelling. New experimental work will explore nutrition-related mitigation strategies, particularly related to variation with grazed herbage and feeding systems based on home-grown feeds and by/co-products from the human food and drink industry. We will also explore relationships between animal management and emissions intensity (RD2.3.1), and further investigate potential to reduce methane emissions by manipulating the rumen microbiome with links to RD2.3.6. Progress review meetings will identify additional synergies that may be achieved by collaboration between RDs within and between WPs. RD and WP Coordinators from all MRPs will collaborate deliver KE.

b) Interactions with underpinning capacity (UC)

The research within this WP is intrinsically linked to the unique resources and facilities that are available within the MRPs. This includes collections of pathogens and pests of animals and plants, samples from normal and diseased animals (including tissues, fluids and DNA), the Langhill dairy cattle datasets, pathological specimens, molecular probes and immunological reagents. The work will make use of state-of-the-art facilities for genomics, proteomics, cell culture, imaging, biological containment and animal accommodation. These resources, supported in part by UC, are managed by skilled staff and are essential for delivery of outputs from the SRP for the Scottish Government.

Funding for BioSS inputs of a collaborative or advisory nature will be provided as described above through Underpinning Capacity Function 7, "*Provision of Biomathematical & Statistical Consultancy Services*". Management level inputs will be provided through identification of a BioSS Work Package Contact, who will be invited to work package-level meetings and be involved in the preparation of annual reports and Knowledge Exchange activities. Although many interactions between staff in BioSS and the MRPs have a long history and function effectively, the nomination of such a Contact will ensure that no scientist contributing to the work package is left without a point of contact in BioSS. In addition, the Contact will be well placed to maintain a watching brief over BioSS-MRP interactions and to identify gaps in coverage or other mismatches between resource and demand which will be discussed with the BioSS Theme Contact along with other appropriate managerial staff in BioSS and the MRPs.

c) Workpackage management structures and additionality



(a) (b)

Figure 2. Chart showing (a) the WP2.2 Management Committee and (b) interactions (⟷) at WP and RD level. (a) Management meetings involving the named role-holders will be held every six months. (b) The named individuals responsible for coordination at WP and RD level within their own MRP. The filled boxes represent the overall cross-MRP Coordinators at WP and RD level respectively

The management interactions of the MRPs in WP2.2 are displayed in Figure 2. RD Coordinators will monitor progress made towards the Objectives and will provide summaries of scientific progress, key outputs and reporting of Deliverables with respect to the proposed schedule to the WP Coordinator. The WP Coordinator will supply progress narratives to the Theme Management Team, which includes the Programme Advisors and Centre for Knowledge Exchange and Impact (CKEI) Director. The WP Coordinator will collate the findings into a WP level report for compilation into Theme level reporting by the Theme Coordinator for submission to RESAS. Each MRP will follow an agreed QA system for its contributions to the reporting, with the ascending editorial responsibility of RD, WP and then Theme Coordinator. Specific timing and Programme level QA will depend upon final arrangements for Programme governance and identification of WP and Theme Coordinators, although this will likely involve close liaison with the Programme Advisor/s. The reporting system will be used to identify high impact narratives relevant to policy, industry/innovation and examples of scientific excellence, including resilience (funding), collaboration and interdisciplinary working (with MRP and/or external partners). KE activities to be led from the CKEI will be agreed by the Knowledge Planning Implementation Committee, which includes a KE lead for each Theme. The WP Coordinator will liaise closely with the Theme KE Coordinator to ensure contributions from this WP to CKEI-led activities and delivery of WP-led KE.

d) Key risks to delivery

Innovative science that is dependent on highly-skilled individuals working within specialised infrastructures inevitably carries risk. Risks will vary depending on the activity, hence a system of **Red**, **Amber** or **Green** indicator status will be used to assess and manage risks at all levels (Table 1a). The “risk register” will be a standing agenda item at our 6-monthly WP meetings where corrective action will be taken as required. New risks identified throughout the lifetime of the project will be added to the register at these meetings for future monitoring. At the outset we have identified a number of general risks to delivery (Table 1b), but would expect more specific risks to arise once the project work is underway.

Table 1. Mechanisms for management of risk within WP2.2. (a) Risks will be assessed and categorised. (b) At the WP2.2 management meetings, the WP Management Committee may decide to either: ‘tolerate’, ‘continue to monitor’, ‘take action’ or ‘escalate’ the risk based on the risk review.

Table 1 (a)

Risk Assessment	Description	Escalation
High	Showstoppers - risks that are extremely likely to occur and would have a very serious impact on delivery.	All red risks must be escalated by the Risk Owner to Programme Advisors. Programme Advisors will immediately consult with risk owner and Theme Co-ordinator and report to DEC.
Medium	Risks that could potentially become showstoppers if not effectively managed and monitored.	Responsibility of risk owner to manage and monitor these risks, providing updates to the relevant Management Committee through the highlight and exception reports. Immediate escalation drawn to attention of Programme Advisors if an amber risk is re-assessed as red.
Low	Low risk that requires minimal management, although monitoring is still required.	Responsibility of project owner to manage and monitor these risks. If reassessed as amber they must be reported to the relevant level Management Committee through the highlight and exception report.

(b)

Risk Descriptor	Risk Assessment	Impact	Controls	Risk owner	Update including recommendations for risk mitigation
Specific areas of expertise with limited staffing numbers	Medium	Some specific areas of expertise are located within a single MRP and sometimes within a single PI. Should those skills and expertise be lost, then it may be that some areas of cannot be delivered, at least in the form in which they are currently	Mapping of staff expertise within and between RDs and WPs	WP team	If there is loss of key staff then discussions would be held with RESAS to redirect the work towards areas which better suit the available expertise.

		envisaged.			
Provision and access to of private and public industry data	Medium	This WP uses both established industry links and existing data, and will seek to establish new relationships. These data are accessible only with the agreement of the data 'owners' and this could be withdrawn.	Many of these relationships are long standing and the WP team have good working relationships with data owners which will minimise this.	RD team	We will initially focus on existing data sets already in use by the MRPs, and seek to develop new collaborative relationships with industry as required.
Failure/delayed delivery of outputs due to interdisciplinary dependences.	Medium	Interdisciplinary science involving many researchers can be more risky to deliver as inevitably there are dependencies in the work.	Planned and regular meetings at the RD & WP level to l allow areas to be discussed and issues addressed.	RD & WP team	Delivery plans and Gantt charts will be reviewed regularly and dependencies noted and monitored
Significant disease outbreak	Low	A significant disease outbreak that limits or excludes access to farms (commercial or otherwise) will hinder data collection and may require redeployment of some personnel	This is of low risk but lies outside the control of the WP. Should some data collection be unable to be collected then alternative approaches will be considered	WP team	Should this become an issue then discussions will be had with RESAS to redirect the work to suit available data sources.
Data management (security, IP….)	Low	This WP is likely to generate and utilise a lot of different data sources including (i) from experiments and research platforms, (ii) mathematical/statistical modelling and simulation and (iii) public and private industry. This complexity of data and security of IP of externally sourced data is paramount to the delivery of this WP	RD teams will ensure that researchers are complying with data management plan. We will ensure that all researchers likely to be using industry wide data (public, private, pre-competitive) will establish the data transfer agreements and put in place appropriate data security measures, reviewed annually	RD lead and WP team	Review data management proactive in line with programme guidelines

3. Impact and KE

This WP will enhance the depth and level of communications with beneficiaries that have been established earlier in the development of the research plans for livestock production, health, welfare and disease. The research teams within the WP will exploit mechanisms of communication developed in the 2011-16 SRP to identify new opportunities for communication in conjunction with the three Themes of the 2016-21 SRP and the CKEI. This will include membership of advisory groups by researchers to inform on research needs through an iterative process as the SRP develops. Examples of such groups relevant to this WP are the European Food Safety Authority (EFSA), Scottish Government CAP Stakeholders Group, Scottish Biodiversity Strategy Committees and the Scottish Rural Parliament.

The planned work described in the nine RDs within WP2.2 will generate a range of tangible outputs of value to farmers in Scotland, the UK and internationally. Each RD within WP2.2 has detailed KE deliverables identified within the associated Gantt charts for the first year of the SRP and outline deliverables for 2017-18. To ensure flexibility and responsiveness to emerging needs, projected KE deliverables will be updated annually via early-stage consultation with multiple and varied stakeholders that have an interest in food security, environmental resource management, disease control in crops and animals, rural communities, healthy lives and wellbeing. The CKEI will provide the branding, design and corporate identity of the collective MRPs involved in the SRP and will utilise this branding for mass media promotion (including social media platforms) to elevate the public profile of the SRP.

Existing links will be further developed and maintained to national improvement forums (for example DairyCo GAF, Beef 2020) and the Scottish Government BES on genetic improvement for efficiency in beef systems. Sheep genomics work will complement existing activity supported by Morrison's so will ensure information is directly available to the supply chain. The generation of knowledge that translates to on-farm disease control strategies will be communicated to stakeholders through the Moredun Foundation Membership, roadshows for farmers, suitably qualified personnel and veterinary practitioners, themed workshops, newsletters, press releases, scientific publications and websites (MRPs, Knowledge Scotland, the BBSRC UK Veterinary Vaccinology Network). Partners include NFU, FSA, and NEPIC. From experience of the SRP 2011-16 it can be anticipated that this WP will work very closely with the NEPIC 2016-21 CoE and beneficiaries of the underlying research. The engagement activities of this WP are greatly informed by the identified needs of the Scottish agriculture industry and their feedback on the research set out in the tender at a consultation event with the MRPs in February 2016. Animal welfare benefits will be communicated to farmers through ongoing interactions with QMS, BPEX, EBLEX, OmsCo, DairyCo and SSPCA, as well as through participative research projects in RD2.2.7 (QBA) and RD2.2.8 (beef cattle work), specific farmer focus groups (planned in collaboration with RD2.3.12), and interactions at farmer events. Policy-relevant information will be discussed with policy colleagues within RESAS at RD/WP/Theme meetings with the involvement of the CKEI, the SRUC Rural Policy Centre and via existing interactions with EU and EFSA. Policies that have influenced and shaped this WP include the CAMERAS Monitoring Action Plans, the Scottish Biodiversity Strategy Plans, The UK Veterinary Vaccinology Strategy, CAP, The Scottish Government Strategy to mitigate Climate Change and the UK AgriTech Strategy.

Impact will be measured by capturing feedback from stakeholders, monitoring uptake of new practices, developing improved and sustainable methods of disease control, improving the efficiency of crop and livestock production, quantifying animal welfare, developing public-private partnerships and leveraging additional funding for research based on a range of high-quality scientific outputs. The outputs include the practical implementation of next generation genetic tools in genetic improvement programmes; new diagnostic tests, novel vaccines and improved knowledge of the transmission and pathogenesis of livestock diseases; outputs to provide information for developing animal welfare policy, and bringing about practical changes on-farm, and tools to rapidly assess methane emissions from livestock. This will be achieved through innovation and scientific excellence via a joined-up communication programme of KE. Predicted outcomes include developments of leading edge genomic tools, novel and sustainable strategies for disease control in livestock and novel methods to assess animal welfare, including application of results on pain and early life events. The concepts and theories addressed in the welfare work are novel and will improve our understanding of ‘positive welfare’. Collectively, the research in WP2.2 will improve animal productivity, health and welfare. The implementation of new vaccines will replace chemotherapeutics, thereby improving food safety and sustainable production in accordance with the policies for sustainable procurement. SRP-funded work will also provide leverage for more applied proposals, such as through RCUK, Innovate UK and Horizon 2020, to develop and facilitate delivery of impact. Ultimately, more efficient livestock production will reduce waste, reduce greenhouse gas emissions and improve global food security.

The Scottish Government Economic Strategy has four priority areas of investment, innovation, inclusive growth and internationalisation. Delivery of the Action Plans of the Animal Health and Welfare Strategy of Great Britain can be expected to require ongoing and improved support from the Strategic Research Programme by fostering a culture of research and development. The research teams within this WP will have ongoing interactions with Scientific Advisors within SG to guide specific outputs from the research. The work in this WP, and the translation of it into practice, is not solely dependent on the major life-science disciplines (molecular biology, bacteriology, virology, parasitology, immunology, genomics, neuroendocrinology, behavioural biology). It is multidisciplinary in nature, therefore the prioritisation of targets and the development of strategies for delivery of knowledge and products will include input from (and interactions with) mathematicians, particularly modellers, social scientists, economists and engineers. The stakeholder groups mentioned earlier rely on knowledge and information to formulate policies that improve animal health and welfare. In the design and delivery of KE, WP2.2 will keep the Theme and all KE sectorial leads informed of stakeholder feedback and will identify any opportunities for adding value by wider engagement across the SRP and stakeholder community. The CKEI will provide the strategic direction of KE to focus and deliver impacts from the research in WP2.2.

4. Quality Assurance (QA)

The MRPs are dedicated to achieving and maintaining the highest standards of quality in order to meet the requirements of their work and the needs of their customers. To achieve this they will: (1) Comply with the requirements of the BBSRC/Defra/FSA/NERC 'Joint Code of Practice for quality assurance' and the BBSRC 'Statement on Safeguarding Good Scientific Practice'; (2) Operate a quality management system that meets the requirements of the ISO 9001:2008 and which is systematically maintained, reviewed and revised for continuous improvement. The relevant Quality Management Systems in each Institute will ensure:

- o Quality performance monitoring through internal and external auditing relating to the pertaining ISO standard;
- o Understanding of specific quality objectives and targets to staff;
- o Planning and developing of standard work processes by means of Standard Operating Procedures, where required;
- o Appointment of competent personnel to co-ordinate, implement and review quality management directives [existing MRP QA managers].

(3) Ensure adequate allocation of resources to achieve quality objectives and targets; (4) Obtain and act upon feedback from key stakeholders and the Scottish Government; (5) Develop and maintain competency of all staff through the provision of tailored training and the clear communication of quality assurance requirements.

5. Ethical and regulatory issues

The proposed work will involve the use of animals, genetically modified organisms, imported biological materials and hazardous materials. These activities will be reviewed, approved and regulated in accordance with the relevant legislative and QA procedures. The use of animals for research is regulated by the Animals (Scientific Procedures) Act 1986. All animal research will be conducted under Project Licences that are issued by the Home Office after Ethical Review and due regard to the 3Rs.

GM organisms will be used in accordance with the Biological Agents and Modified Organisms (Contained Use) Regulations, the Genetically Modified Organisms (Risk Assessment) (Records and Exemptions) Regulations 1996 and the Genetically Modified Organisms (Deliberate Release and Risk Assessment – Amendment) Regulations 1997 and the Genetically Modified Organisms (Contained Use) Regulations 2014 (‘the GMO (CU) Regulations’). Use of licensed plant pathogens and of imported soils and plant materials is governed by the Plant Health (Scotland) Order 2005, regulated by SASA for the Scottish Government. Importation of animal products will be done under an Import Licence/Authorisation for Animal Products or a Licence to Import an Animal Pathogen/Carrier into Great Britain (APHA). Environmental protection is enacted through the Environmental Protection Act 1990 (and amended Scotland 2001). Methodologies for collecting data from stakeholders will be done with prior approval by the Scottish Government Survey Control Unit.

6. Contribution to the 3R's (reduction, refinement and replacement)

Reduction: Some parts of animal welfare work will be conducted on commercial farms to achieve a range of welfare conditions without the need to replicate these experimentally. Welfare and disease work in RD2.2.7 will make use animal disease models also used elsewhere in WP2.2 to reduce the need to specifically infect animals for this work. Sharing of animal experimental resources (e.g. RDs 2.2.7, 2.2.8, 2.2.9, 2.3.1 and 2.3.6) to achieve related but distinct outcomes in different RDs will also reduce the use of animals in the WP.

Refinement: Development of welfare assessment tools may lead to earlier intervention (in experimental studies as well as on farm), and better recognition of the welfare status of experimental animals. Development of improved measurement systems for determining GHG from live animals may minimise animal handling and stress associated with these procedures.

Replacement: Use of national, commercial and existing datasets and materials (e.g. video images collected in other studies) to address questions of interest without collecting de novo experimental materials. Work in RD2.2.1 makes extensive use of banked tissues or images and data sets collected via industry or in research contexts to minimise requirements for future animal usage.

7. Sustainable Development

The MRPs are committed to adopting and promoting environmental best practice in connection with their operations and in support of sustainable and safe practices. Each operates an environmental management system which is systematically maintained, reviewed and revised to ensure continuous improvement. Some operate to the ISO 14001 standard and where possible procurement is from suppliers who are also ISO 14001 registered. There is effort to ensure a year on year reduction in waste produced, especially when destined for landfill. Sustainable products, such as non-halogenated plastics, are sourced when appropriate. Energy consumption is monitored for reduction, procurement of supply is tendered on a regular basis to ensure best value for money. MRP policies promote the use of unified communications technologies (videoconferencing and VOIP telephony) where possible and practical, but where travel to meetings is essential, sustainable forms of transport are encouraged.

Name of RD: RD 2.2.1 Livestock genetic improvement tools.
Research aim and key drivers: Genetic improvement is a cost effective way to improve productivity and sustainability of livestock, as progress is permanent, sustainable and cumulative. The work proposed directly addresses aspects of the RESAS policy drivers 'Animal Health & Welfare in the Livestock Industry: Strategy 2015 to 2020' and underpins Pillar 2: Scottish Rural Development Programme (SRDP) 2014 – 2020 and proposed schemes including the Beef Efficiency Scheme (BES). In preparation of this RD, consultation on proposed objectives has been undertaken at a general stakeholder event in February, 2015 and specific discussions there after on (i) BES and cattle genetic/genomic improvement with Scottish Government (SG) Livestock and Animal Health and Welfare Policy contacts, National Farmers Union Scotland (NFUS), Quality Meat Scotland (QMS), Agricultural and Horticultural Development Board (AHDB) and agricultural industry representatives (O1&2, linking with 2.3: Agricultural Systems); (ii) sheep genomics with QMS (O3); computer tomography (CT) with AHDB, QMS and sheep industry users (O4); and (iv) new phenotyping strategies for the sheep industry for difficult to record traits with NFUS, QMS and sheep industry stakeholders (O5). Genetic improvement is estimated to have resulted in between 50-90% of the overall animal improvements seen over the last 60 years and will be a major driver for the improvements in efficiency, productivity and sustainability of Scotland's livestock sector. However, despite widespread uptake of genetic improvement tools in some sectors, such improvements have not necessarily been disseminated across the entire Scottish livestock population, particularly in the beef cattle and sheep sectors – a *key driver* for this RD. The aim of this RD is to improve livestock production, efficiency and welfare, whilst decreasing the use of resources and impact on the environment – more for less. This will be achieved using current and next generation tools, focussing on genomics and targeted gene approaches for production (growth, efficiency), maternal and health characteristics (including economically important endemic diseases). Advances include the use of genome wide selection (GWS), the application of which in some plant and livestock species shows that improvements can be substantially enhanced over and above the use of conventional genetic improvement tools, particularly for traits that are difficult to record. The new research will build on existing research and national data platforms to collect novel genotypes and phenotypes. This will include merging public and industry data and will show how our genetic improvement tools can be enhanced by sharing data across the Scottish food supply chain. Building on international collaborations we will examine the optimal way to include information from sequence in genomic breeding programmes (and manage genetic diversity, RD2.3.2).
Summary of the proposal: **O1. Industry data driving a new wave of genetic improvement for Scottish beef production.** The BES (within the SRDP) will support Scottish beef farmers to collect individual animal, and maternal, production & health performance, tie information on individual animals from birth to slaughter, promote the use of improved breeding stock and genotyping of animals. Our initial modelling of BES has shown that the proposed enhanced data capture on farm could improve the rates of genetic improvement by up to 76%. The main research providers (MRPs) lead on complementary cattle R&D projects that link industry data (public and private) to animal pedigree, through the national cattle tracing system, including carcass information, condemnation causes and tuberculosis (TB) testing. We will work alongside policy and industry stakeholders implementing BES and/or utilising the genetic improvement tools in the wider industry.

We will undertake R&D on the genetics and genomics of traits important in Scottish beef farms, including meat production and maternal traits and link it to supply chain efficiencies analysis in RD2.3.10. *Key deliverables* (Numbering system relates to Gantt chart listing Objective (O#.#), Deliverables (D#) and KE/impact events (KE#), M# Milestone, Y# Year)*:* **O1.1.** Meet regularly with BES Stakeholder and beef industry group to co-construct planned work and discuss results (**KE1**). **O1.2.** Genetic parameter and breeding value estimation for traits available from historic and/or industry data-sources (e.g., calving intervals from BCMS records, linking to Scottish abattoir records building on EBLEX carcass traits project) (**D1**) and maternal, health and welfare traits derived from data collected under BES (**D2**). **O1.3.** GWS based on Scottish industry-derived phenotypes (**D3,** Y3-4). **O1.4.** Linking national and international activities explore the genetics and genomics of BES data and linked R&D activities on genetics and genomics of novel traits (i.e., linking to feed intake recording from a Defra funded project) (**D4,** Y4+). **O1.5.** Develop broader beef breeding goals and quantify the value of incorporating industry-based data (e.g., abattoir, cattle movements, markets) into the breeding programmes (**D5,** Y4-5) and management practices.

O2: Whole genome sequence data to enhance genetic improvement tools. We will examine potential benefits of whole genome sequence data for the development and enhancement of genetic and genomic improvement programmes with target case studies discussed with an industry stakeholder group (**KE2**). We will explore how sequence data can enhance genetic improvement tools by investigating: (i) the value of including sequence data in genomic selection compared to using single nucleotide polymorphism (SNP) chips; and (ii) the benefit of including sequence data dissecting gene function of novel traits. This work will build on a more detailed modelling of the sequence data (and banked genotypes data) being generated for dairy cows from our long-term Langhill breeding experiment from external funding and thus add value to this phenotype, genotype and sequence rich SG funded resource. *Key deliverables:* Using these data we will show the added value of sequence information both for genetic evaluation (**O2.1, D6**, Y3) and discovery of functional genes (**O2.2, D7**, Y4) and generate lessons for application in other livestock populations (**KE3,** Y4+). We expect that methodologies developed using detailed genetic and phenotypic data in this dairy population can be extrapolated to beef and sheep genomic and sequence data when it becomes available (**O2.3, D8**, Y3+).

O3. Developing genomic selection tools for the improvement of the productivity and sustainability of the Scottish sheep industry. This Objective will explore how genomic information could drive next generation genetic improvement in sheep. This research will be based on data generated on externally-funded projects, where animals have been recorded for a suite of novel traits and genotyped, allowing associations between genomic and phenotypic data to be determined. Datasets (or part there of) are available, including (i) an industry collaborative project with detailed records on up to 5000 lambs from ~200 rams (genotyping funding to be secured), (ii) well-phenotyped research animals that have been biobanked, (iii) genotypes and phenotypes from 1000 commercial Texel sheep. The *key deliverables* will help underpin the implementation of GWS in sheep. **O3.1.** To achieve this, suitable training populations (see example datasets) are needed to estimate & calibrate genomic prediction “keys” for important productivity traits (e.g. carcass and meat quality – **M4, D9**) and sustainability (mastitis, footrot – **M10, D10**) traits. **O3.2.** Further work in this Objective will help to develop more cost-effective genotyping platforms, in cooperation with genotyping platform companies, to incorporate into genomic selection programmes, reducing the cost of the genotyping as a rate-limiting factor (**D11,** Y3+) and **O3.3** developing supporting imputation strategies (**D12**).

O4. Development of CT predictors of economically important traits and their implementation into breeding programs. There is a need to develop promising CT predictors of production, product quality and welfare-related traits to the point of commercial implementation to benefit the Scottish sheep sector. Product quality needs urgent improvement and recent research (e.g. in www.cost-faim.eu/) has shown how CT can predict a range of economically important traits, of which only some have been adopted into sheep genetic improvement programmes (i.e., CT predictions of carcass traits). A database of CT images has been developed (since 2000), from rams (> 6000) of substantial genetic influence in their breeds, that can be mined for new CT-derived phenotypes. This will add value to commercial CT scanning and to externally-funded projects that collect CT data e.g. the Innovate UK Agri-tech catalyst project with Morrisons (*Solutions for sustainable lamb production and breeding for more taste and less waste to increase food security in the UK and beyond*). *Key deliverables* from this work will be tools to help streamline CT- image analysis for current industry phenotypes (carcass muscle & fat weights; gigot muscularity and eye muscle area, **O4.1, D13**), enable the introduction of promising phenotypes (CT-predicted meat quality, spine characteristics) into breeding goals (moving R&D to implementation, **O4.2, D14**) and examine new CT phenotypes (e.g. predictors of lambing difficulty / methane emissions; 3D muscularity; waste traits) that could be accurately derived from CT image analysis regarding their biological and industry relevance (**O4.3, D15**). This work will be done in consultation with Signet (national body responsible for the delivery of beef and sheep genetic improvement tools, including those derived from CT images, **KE4**).

O5. Genetics of disease resistance in sheep

O5.1 Dissecting genetics of parasite resistance and immune response in selection lines of sheep. New phenotyping strategies for internal parasites in hill sheep have been implemented to test their applicability for use in sheep breeding programmes and to test if they are under genetic control. Our research shows that parasitised sheep typically have 14% higher greenhouse gas emissions compared to healthy controls. New genetic lines of sheep have been initiated in the current RESAS programme to determine if selection of sheep for higher resilience to parasites is feasible under UK farming conditions, as parasite resistance and resilience are yet to be routinely incorporated into sheep breeding goals. We will test if genomic differences exist between animals of high and low resistance to disease, test new immunological phenotyping strategies and begin to dissect the genetic architecture underpinning disease resistance in Texel (linked to **O3**) and Scottish Blackface sheep. Physiological measures developed within the MRP science base for future high-throughput health screening will be measured in sheep genetically divergent for parasite resistance from these lines. We will also investigate if selection for parasite resilience impacts on lifetime maternal performance in pure and crossbred sheep populations and quantify the genetic relationships among disease resistance and production traits. *Key deliverables* from this work will be the identification of genome markers important for disease resistance/resilience (**D16**) and genomic breeding values for disease resistance to industry (**KE5**).

O5.2. Influence of immune gene variation on health and diseases status of sheep.

Variation in immunity to disease or response to vaccination is likely to be linked to sequence variation within immune response genes. Using a candidate gene approach in resource populations of sheep representing distinct disease or immune response phenotypes could allow the development of novel tools to guide breeding efforts. *Key deliverable:* DNA samples from resource groups of sheep (RD 2.3.1) will be used in targeted sequencing approaches to identify relevant genetic markers that are enriched in more resistant animals compared to more susceptible individuals.

O5.3 Understanding the genetic basis of resistance to Johne's disease (JD) and ovine pulmonary adenocarcinoma (OPA) in Scottish sheep flocks. JD is chronic enteritis of ruminants caused by *Mycobacterium avium* subspecies *paratuberculosis* and OPA is a fatal lung cancer caused by Jaagsiekte sheep retrovirus (JSRV). Both diseases are endemic in Scotland and have significant animal health, welfare and economic implications worldwide. Sheep genomic DNA samples, each with pathology and disease phenotype data have been collected in previous programmes and represent a unique resource. We are currently investigating genetic associations with disease phenotypes. Preliminary analysis of the JD dataset identified associations with resistance and susceptibility (CWP5.3). The analysis of the OPA dataset awaits the genotyping of the final samples. (Links to RDs 2.2.1 and 2.3.2). *Key deliverable:* We aim to combine the datasets to identify markers which may be applied in selective breeding programmes and to improve our understanding of the response to infection.

Technical approach

O1. Industry data driving a new wave of genetic improvement for Scottish beef production. This Objective will link to other WPs to translate the benefits of genetic improvement to farming systems and the overall economic efficiency of beef production in Scotland (WP2.3). We will establish a stakeholder group (policy, industry and advisory representatives) to discuss approaches and results. Initial focus will be the development of the BES to help ensure the data collected are appropriate, and to maximise the potential value of the data for the purposes of the scheme: genetic improvement, benchmarking and wider industry quality assurance schemes. This includes providing help/advice in data storage to ensure maximum linkages to other key (inter)national data sources. We will undertake genetic analysis for key production traits (e.g. carcass traits, calving intervals, dam longevity) using historic industry data (abattoir, BCMS/ScotEID database) and produce initial breeding values for Scottish beef production systems. As some data on maternal performance will be collected as part of BES, in the second year we will focus on the genetic analysis of historic and newly collected data for maternal traits (e.g., calving performance, calf vigour) for Scottish beef production systems and the genetic and phenotypic relationship with production traits. In the later years of the programme we will extend the genetic analysis for traits identified by the industry as important, and where data are available, including disease/health traits (e.g., culling reasons, liver fluke) driven by industry data collection for Scottish beef production systems (Y3+). Further, BES is aiming to genotype 20% of calves participating in the scheme (60,000+) so when industry data allows (i.e., required numbers of animals genotyped with target phenotypes) we will undertake a genomic analysis for both production and maternal traits (**O1.3**, Y3+). Finally we will build a breeding goal for Scottish terminal, suckler and dairy beef systems with traditional and new traits (linked WP2.3, **O1.5,** Y4+) and quantify the economic and environmental benefit of new genetic improvement tools for Scottish beef industry.

Detailed work plan. O1.1. Y1&2: An advisory/steering group to link developments in the SRP with the roll out and delivery of BES will be established. This group, which will involve SG policy team members, ScotEID, beef industry and breed society representatives and researchers from the SRP (across Theme 2) will meet every 6-9 months to discuss progress on BES and the genetic (and genomic) analysis of the data. These meetings will be used to monitor the “usefulness” of the data being collected as part of BES for genetics analyses and wider industry benchmarking. This group will be used to highlight priorities for the R&D to support BES roll out. It is planned that this group will examine the efficacy of farmer uptake (linking to RD2.3.12) and economic and environmental benefit of the scheme (linking to relevant RDs in WP2.3 & 2.4) late in the SRP.

O1.2. Y1: As the BES scheme will only commence collecting new phenotypes (calving performance, culling reasons, stillbirth) in 2016, the first year of the SRP will focus on collating data from industry (private) and government (public) data sources for a range of breeds (and crosses) and beef systems in Scotland. Data such as dam longevity, days to slaughter and carcass performance (where data are available) will be linked to data currently available in the BCMS database. These data will be used to generate animal phenotype and pedigree files for beef (and dairy crosses) in Scotland. An aim of BES is to enhance the level of completeness of data recording (parents and phenotypes) in industry animals, so lessons learned from analysing historic data will help to inform how these systems are developed and implemented (feedback through **O1.1**). After QA of the data, we will undertake an across-breed genetic analysis of key carcass, maternal performance and lifetime efficiency (age at slaughter) traits that can be derived from industry data sources **(M1, D1)**. **Y2**: Using both BCMS and maternal/calving performance data collected in Y1 of BES we will derive maternal and calving traits such at age at first calving and calving rates for breeding cows. BCMS maternal traits will be supplemented by new maternal traits be collected under the BES scheme (e.g., calving ease, stillbirth, milk score/maternal influence on weaning weights, calf vigour). The traits will be prioritised with stakeholder group (**KE1**) and informed by our previous research (e.g., farmer-recorded calving difficulty, stillbirth, cow docility and calf vigour). We will undertake an across-breed genetic analysis of maternal traits. (**M7, D2**).

O1.3. Y1&2: BES aims to genotype 20% of the calf crop each year to allow a genomic reference population to build up over the first couple of years of the scheme. Depending on the genotyping, we may not achieve optimal population and data structure to undertake much genomic based analyses of the phenotypes in Y1. However, the Y1 genotypes will be linked to the animal records (calf, sire and dam) to identify the parts of the population with insufficient genomic coverage from the Y1 genotyping effort (**M8**). In Y2, we will take the pooled genotype and pedigree data to create a genomic pedigree matrix and analyse the key gene flows in the Scottish beef industry (**M11, M12**). This will then be further analysed for genetic and genomic diversity and inbreeding in RD2.3.2.

O2. Whole genome sequence data to enhance genetic improvement tools. We will explore the benefit of sequence data for (i) enhancing genomic selection and, (ii) genome wide association studies (GWAS, i.e., comparing the value of approximately 50,000 frequent variant genotype markers along the genome, as is current practice with the use of SNP chips, to whole genome sequence including low frequency variants).

O2.1 (Y3+) Use of Sequence in Industry (beef and dairy): GWS was introduced in April 2012 in the UK for dairy cattle for initial group of traits with estimated breeding values (EBV). Sequence-based genotypes vs SNP chip genotypes means that GWS no longer relies on linkage disequilibrium to estimate the genomic EBV (gEBV) but points to actual causative mutation(s). Benefits include (i) higher prediction accuracy of gEBV, (ii) better prediction across breeds, as we no longer have to rely on SNP-QTL associations holding across breeds, and (iii) better persistence of accuracy across generations. We aim to demonstrate that inclusion of sequence data, even for part of the population, will help improve GWS. We will test this for a moderate heritability trait that is widely available (inter)nationally (e.g., milk production) and lower heritability traits with lower volumes of data (e.g., health traits). These test cases will be agreed with genetic improvement stakeholder groups (**KE1**, M24).

O2.2 (Y4+) Biological Dissection: As next-generation sequencing costs for livestock continue to fall, many genetics researchers aim to use GWAS to identify potentially causal variants for biologically important traits. However, many of the key resource populations with requisite phenotypes are low in number with limited (and mixed) density of SNP genotyping and few individuals with a whole genome sequence. The use of SNP chips alone for dissection of some traits/genes can be limiting, as it is not possible to identify low frequency variants which affect traits of interest. Building on detailed disease phenotypes (links to RD2.3.1) we will use sequence data (actual and/or imputed) to disentangle disease-causing variants from their highly-correlated proxies within an associated region. The sequence data will allow us to include “all” common variants as well as rare variants with low minor allele frequency. In the scaling up from pedigree, to SNP, to sequence data we will account for potential issues that will arise, including multiple testing, and identify which rare variants to include.

O3 Developing genomic selection tools for the improvement of the productivity and sustainability of the Scottish sheep industry.

O3.1: GWAS will be performed on genotype/phenotype data from 1000 Texel sheep (from current RESAS programme) to identify genes or QTL relevant for key phenotypes (initially growth and carcass traits). Results can be applied directly in breeding programmes and will help develop optimised genotyping platforms (SNP chip panels). Results will inform the industry about genomic regions/ genes important for muscle growth and meat quality (Y1&2).

O3.2: SNP keys will be derived to prepare for implementation of GWS in UK sheep for production and fitness traits. Phenotypic records (incl. difficult to measure traits, like meat quality) from 1000 Texel sheep and from 5000 crossbred lambs will be related to high density SNP genotypes using GWAS to estimate and calibrate SNP keys (Y3&4).

O3.3: Imputation modelling. Cheaper low-density SNP chips will be modelled using the results of **O3.1&3.2** to test the possibilities for imputation from the low density (LD) chips genotypes to 50k SNP chips and estimate accuracies obtainable with LD chips, which could make genotyping of a larger number of animals cost effective (Y3+).

Detailed work plan

O3.1: Data on 1000 Texel ram lambs will be used in a GWAS approach to investigate associations of growth and carcass (including CT) traits with molecular polymorphisms using the Ovine 50k SNP array, with the aim to identify molecular predictors of carcass quality and productivity.**Y1**: Establish and check the dataset, derive de-regressed breeding values (EBVs, to be used as phenotypes) and analyse the data using GWAS. **Y2**: Compare results to public molecular genetic databases (e.g. http://www.animalgenome.org/cgi-bin/QTLdb/index) and other literature. Write an open access peer reviewed paper and a technical note for the Texel Sheep Breed Society regarding the practical implications of these findings.

O4. Development of CT predictors of economically important traits and their

implementation into breeding programs. CT scanning of elite commercial rams is routine for many UK sheep breeders and CT is an integral part of several SRUC sheep research projects. Potential exists for adding value to this procedure by (i) increasing throughput speed and/or (ii) making additional traits available from the same set of CT images. Identifying accurate predictor traits for additional selection goals that could be measured in top-ranking rams during routine CT scanning for carcass composition, could lead to the incorporation of these traits into a breeding programme following their genetic analyses. O4 will streamline CT image analysis for existing traits (carcass tissue weights, gigot and loin muscularity), will help take additional traits (CT-predicted meat quality; spine characteristics) to implementation into commercial breeding, and will explore novel CT-measured traits (e.g. predictors of lambing difficulty, methane emissions, waste traits) to enhance product quality, welfare and production efficiency.

Detailed work plan

O4.1: Further automation and improvement of image analysis software to increase speed and accuracy. Further development of software tools will increase the speed of data extraction from CT images for current CT-derived phenotypes (carcass muscle and fat weights, and muscularity **M5, D13**). **Y1&2:** Development, testing and implementation of new software tools for image analysis (**M6, D14**).

O4.2: From R&D to implementation into industry breeding programmes. For CT-based traits for which genetic parameters have been estimated in the current RESAS WP (meat quality, spine characteristics), work will be undertaken together with EGENES to make these traits available for commercial selection of terminal sire sheep for high productivity and product quality. **Y1:** These two additional CT traits will be made available to Signet for implementation and after year 1 will be available as part of the routine genetic evaluation (**KE4**).

O5. Genetics of disease resistance in sheep

O5.1 Breeding for disease resistance in sheep as a tool to improve livestock and the performance of livestock systems

O5.1.1 Information on faecal egg counts for a range of different internal parasite species has been collected on around 500 Blackface lambs on 3 occasions per year on a single farm since 2011. The data set currently has 4,200 individual animal records for 6 main parasitic species linked to pedigree and other performance and health data, making it a very valuable resource for this study to generate robust estimated breeding values (EBVs) and will be the focus for Y1&2.

O5.1.2 Immune measurements will be selected with no focus on specific pathogens to provide an estimate of the underlying immunological fitness of each lamb, although circulating levels of *T. circumcincta*-specific IgA, IgE and IgG will also be measured. Non-pathogen specific measurements will include serum levels of natural antibodies (NAb), pro-inflammatory cytokines and the acute phase protein, haptoglobin (data collection in Y1&2 and analysis later in the programme).

O5.1.3 The aim of this objective is to identify key genomic markers to differentiate resilient from susceptible genotypes. GWAS will be used to analyse the new data for extreme phenotypes (immunological, health and growth data) and link them to the data generated on the same animals from the Illumina 700K ovine SNP array. Key SNPs can then be included on lower density SNP arrays to be used in sheep breeding programmes.

O5.1.4 Use of crossbred progeny of known parentage will provide typical molecular architecture to that used in the Scottish sheep sector which will be used for genomic studies (GWS) and the development of cross-breed gEBVs. This will enable crossbred evaluations for maternal traits to be researched and implemented in tandem with ongoing work at EGENES and with the Texel Sheep Society (**KE5**).

Detailed plan

O5.1.1, Y1&2: Using extreme animals with high and low EBVs for live weight, we will determine if there is a difference in their parasitic burden under natural grazing conditions, as determined by faecal egg counts (FEC) and faecal soiling scores. The grazing areas used have a naturally high worm contamination and the phenotypes that exist for all animals include repeated measurements of faecal egg counts reported separately for each animal for nematode parasites (incl. *Strongyles* and *Nematodirus*) and coccidia. Individual animal egg counts for each of these main parasitic species which will enable us to determine if host resistance to one group of parasites also confers resistance to others (**M9**). Uniquely, the inclusion of coccidian counts in this data set enables us to explore the relationship between Th2 immune responses (protective for nematodes) with that of the Th1 immune response (protective for coccidia) (**M14**).

O5.2. Influence of immune gene variation on health and disease status of sheep.
Variation in disease susceptibility or immune response is likely to be linked to variation within immune genes. Using specific populations with clear differences in disease or immune response phenotype, a candidate gene approach to the identification of immune gene variation will be tested.

This objective will use lambs that are phenotypically parasite-tolerant or that require repeated treatment in a targeted selective treatment (TST) study in CWP5.3 and continuing in RD2.3.1. DNA samples from these animals will be sequenced to identify genetic variation in over 20 innate immune genes. Analysis of allele frequencies within the study animals and within control blackface and Texel sheep will determine if the approach is worthy of more in-depth study.

Further activities later in the programme include (i) defining allele frequencies at each locus to identify SNPs that may differ between the resistant and susceptible populations and (ii) cost-benefit analysis of using next-generation sequencing in larger groups of resistant /susceptible animals.

Detailed work plan

Y1 Validate protocols for analysis of innate receptor genes in sheep samples (**D15**); produce preliminary sheep receptor sequence dataset (**D16**). Submit sequences to European Nucleotide Archive (ENA) database (**KE6**). **Y2** Analyse DNA samples from resistant and susceptible animals (**D17**). Submit results for International journal publication (**KE7**).

O5.3. Understanding the genetic basis of resistance to JD and OPA in Scottish sheep flocks

Detailed work plan

Y1: (**D17**) We will increase the numbers of samples with detailed disease pathology and uninfected controls by preparing genomic DNA from animals submitted to MRI with suspected JD and OPA. (**M1, M3, D18)** We will genotype all new cases and controls using sequence based methods targeting the class II MHC-DRB1 locus by the end of year 1. **Y2:** (**D19**) In collaboration with BioSS, we will increase the depth of data analysis of individual and clusters of SNP's in cases and controls to identify associations with disease outcome. (**D20**) Complete the DRB1 analysis of the combined data set and disseminate results at a scientific conference in 2018 (**KE8**).

Staff A total of 33 technical and scientific staff (17 SRUC; 11 MRI; 4 RINH; 1 BioSS) will

be directly involved in this RD. Key cross linking staff are identified later.
Key linkages, interdisciplinarity & collaboration **Theme 2 links:** There will be collaboration with WP2.3 and WP2.4 to understand the economic benefits of improvement in beef production driven by industry data (**O1**). There is a planned complementary package of work on immune and disease traits in dairy (**O2**) and small ruminants (**O5**) in WP2.3. Further links with WP2.3 are exemplified through the development, evaluation and application of genetic improvement tools for the optimal management of genetic diversity within genomic breeding programmes. **Underpinning capacity:** Work in **O2** will use data from our long running experiment on production, feed intake, health and reproduction in the Langhill dairy herd. Collection and maintenance of these data are part funded via the SRUC Underpinning Capacity tender. Work in O4, **O5.2&5.3** will be supported by BioSS consultancy in terms of software development, input to experimental design and data analysis. **International science links**: There are ongoing connections where data on rare phenotypes (largely in research herds/flocks) and genotypes are pooled to increase the power to dissect and understand these traits and we expect that these will continue and grow. These include (i) 1000bulls.org sharing of whole genome sequence data on cattle (**O2**); (ii) international projects that pool phenotype, genotype and sequence data on efficiency traits in dairy (**O2**) and beef (**O1**) cattle; (iii) efforts to develop and deliver international genetic and genomic evaluations in sheep (**O3**). Linkages developed during the 4 years of FAIM EU COST Action to further develop CT for farm animal imaging will enable collaboration on O4. **National science links:** This work will underpin AgriTech Centres of Innovation including Agricultural Informatics and Metrics of Sustainability. Through collaboration with HEIs we will build MRP capacity on bioinformatics. As described, much of this work is linked to BBSRC, AgriTech/TSB, EU and industry funded science. **Industry/implementation links:** Strategic links will be formed to national data sources (e.g., cattle movements), industry (e.g., abattoir, supermarket) and wider national research platforms (e.g. Defra funded Beef Improvement Strategy for feed efficiency) The route to implementation for the outcomes of this RD is strengthened by the links between MRP researchers and Edinburgh Genetic Evaluation Services (EGENES, delivering industry funded routine genetic and genomic evaluations in beef, sheep and dairy). These are underpinned by a range of genetic improvement industry/expert stakeholder groups.
Added Scientific Value **O2:** This takes forward previous and ongoing detailed phenotyping undertaken jointly across MRPs and links to joint work with the UoE. This will be the largest population of well-phenotyped, genotyped and sequenced cattle in the world (by some margin). Further it will link to future developments in national and international genetic evaluations and therefore strong potential REF impact case study for the future. **O3:** As GWS is implemented already in the Dairy industry in the UK, the work on beef and sheep will benefit from this experience **O4:** This will add value to the commercial CT scanning and to projects which are underway and require substantial amounts of CT e.g. the Innovate UK Agri-tech catalyst project with Morrisons (mentioned above), which requires CT scanning of ~5000 loins and about 200 live rams.
KE, Audiences and Impact <u>Audience</u>

Policy: This work will inform Scottish Government policy within the context of the priority and focus areas of the SRDP as well as the existing “Modernising Scottish Agriculture” and “Farming for a Better Climate” agendas. Industry: Direct KE to stakeholders will be through stakeholder events, **O1 & 2:** Links have been established and general work plans discussed with SG policy teams driving BES, members of Beef 2020 group (incl. NFUS and QMS), Defra, AHDB, industry stakeholders. These will engage with this Objective and linked activities driven by beef industry data in WP2.3 &2.4 via a specialised stakeholder group (**KE1**). There will be ongoing KE with sheep breeding industry including the promotion of new CT traits to visitors to CT unit/farms; Sheep breeders round table; breed societies / Signet newsletters and websites.
Public and Professional: Through publication in high impact open access scientific journals and presentation at national and international conferences (e.g. British Society of Animal Science, *World Congress on Genetics Applied to Livestock Production*).
Impact: The outcomes of this work will have a significant impact on the rural and national economy by improving the efficiency and resilience of livestock production systems, and on industry’s and our ability to use, implement and further develop new genetic improvement tools. For example, production of genetic parameters will allow EBVs for new CT-derived traits, in collaboration with EGENES/ Signet – encouraging uptake of EBVs, improving lamb competitiveness. This combined, will have the effect of improving competitiveness of the Scottish livestock systems and breeding stock in the European and global marketplace. To ensure this impact we will engage with Policy, Public and Industry stakeholders throughout the lifetime of the programme.

RESEARCH DELIVERABLE NUMBER: RD 2.2.1 Livestock Genetic Improvement Tools

Work planning and timetable for Year 1: Major milestones (M#) for the key research objectives (O#.#) including deliverables (D#), KE/impact events (KE#), and their timing.

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1: BES Stakeholder group: Meetings and feedback with key stakeholders and BES delivery team			**KE1**									**KE1**
O1.2: Genetic parameters for BES Source and combine phenotype and pedigree data supporting BES							**M1**					**M7**
O1.3: Genomics of BES data Collate and process BES genotype and pedigree data												**M8**
O3.1: Genomic selection in sheep Collate data for sheep training population										**M4**		
O4.1: Development of new CT derived phenotypes										**M5**		
O4.2: Implementation of new CT traits with routine genetic evaluations			**KE4**							**M6**		**KE4**
O5.1: Breeding for sheep disease resistance Collate historic and collect new data on parasite burden and immune response from experimental flock												**M9**
O5.2: Immune gene variation Protocols for innate receptor amplification								**D15**				
O5.2: Immune gene variation Preliminary sheep receptor sequence dataset											**D16**	**KE6**
O5.3: Genetics of resistance to JD & OPA Genotype new cases & controls at *DRB1* locus				**M1**				**M3**				**D18**
Annual report to SG												**R1**

RESEARCH DELIVERABLE NUMBER: RD 2.2.1 Livestock Genetic Improvement Tools
Work planning and timetable for Year 2:
Major milestones (M#) for the key research objectives (O#.#) including deliverables (D#), KE/impact events (KE#), and their timing.

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1: BES Stakeholder group. Meetings with key stakeholders and BES delivery team						KE1						KE1
O1.2: Genetic parameters for BES Industry available data (D1) &BES collected data (D2)						D1						D2
O1.3: Genomics of BES data Process Y2 BES genotypes and link to pedigree and phenotypes								M11				M12
O2.1: Benefit of whole genome sequence data in breeding programmes: Linking sequence and genotype data												M13
O2.2: Ruminant genetic improvement stakeholders meeting												KE2
O3.1: Genomic selection in sheep GWAS for production traits						D9						
O3.1: Genomic selection in sheep Initial GWAS for fitness traits in sheep						M10						D10
O4.1: Establish systems for rapid CT image analysis			D13					D14				
O4.2: Implementation of new CT traits with routine genetic evaluations												KE4
O5.1: Breeding for sheep disease resistance Analyse Th2 immune response data from high:low animals												M14
O5.2: Immune gene variation Analyse DNA samples from resistant/ susceptible animals and prepare deliverable											D17	KE7

report.												
O5.3: Genetics of resistance to JD & OPA Increase the depth of data analysis of individual SNP's and clusters of SNPs								**D19**				
O5.3: Genetics of resistance to JD & OPA Complete the MHC class II *DRB1* analysis of the combined data set										**D20**	**KE8**	
Annual report to SG												**R2**

Name of RD: 2.2.2 Evaluation of livestock health

Research aim and key drivers

Disease has a detrimental effect on animal health and welfare and causes losses in production. In order to assess the effectiveness of control measures and determine their economic impact, a quantification of the level of disease and/or health status is needed. This research deliverable aims to provide improved baseline measurements of disease and health status (current and future) as well as cost-effective biosecurity management tools.

The **key drivers** are:

- Improved estimates of health status and disease frequency are required for a number of purposes, including: accurate evaluation of the economic impact of endemic disease, their contribution to greenhouse gas emissions, implementation of effective disease control strategies and the maintenance of trade. Improved estimates will be achieved by broadening the data sources used, adding new information (from industry, government-led schemes, multi-centre collaborations etc) and extending current surveillance activities. The information will be used to inform and support current Scottish Government (SG) policy and its development in areas that include: enhanced surveillance, improved use of data for targeted advice and control measures in the end stages of the BVD eradication scheme and the promotion of the positive health status of Scottish livestock. The information will also be used to encourage industry-led activities.
- The need for cost-effective biosecurity measures. Optimal biosecurity measures often are too expensive or challenging for the farming industry. Recommendations for workable and financially viable biosecurity measures or management plans will be prepared by combining improved health status estimates with socioeconomic analysis. This will translate into novel approaches that are more acceptable to the livestock sector.

The RD partners have used existing industry sector stakeholder interface groups from CWP6.1/6.2, MRP engagement workshops, interactions with SG scientific advisory and policy colleagues to identify the requirements to meet these needs and the endemic diseases to be prioritised for each species: maedi-visna (MV), Tick-borne diseases (TBDs); benzimidazole (BZM) resistance in *Nematodirus battus* and liver fluke in sheep, paratuberculosis (paraTB) and Bovine Virus Diarrhoea (BVD) in cattle; antimicrobial use (in pigs and cattle); as well as biosecurity in small scale poultry enterprises (SSPE) (i.e. medium to small commercial and back-yard flocks). Livestock Scotland (Nigel Miller) has re-iterated the importance of paraTB for the cattle sector.

Summary of the proposal:

Within the broad aim of providing improved measurements of disease and health status as well as cost-effective biosecurity recommendations we have identified three overarching key deliverables (KD) comprising five Objectives (O) organised (Y1-2) into 17 individual sub-objectives [OX.x], deliverables (D), milestones (M) and KE components (KE) as set out in the Gantt charts.

KD1: provision of improved estimates of health status and disease prevalence through two approaches: the use of available data (O1) and the application of improved diagnostic strategies (O2).

KD2: understanding the possible **change of health status and disease prevalence** within the Scottish livestock population if targets for reduction of antimicrobial use are implemented (O3).

KD3: the assessment of the economic impact of priority endemic diseases and

conditions (eg. liver fluke and paraTB) (O4) and the cost-effectiveness **of biosecurity recommendations,** with an initial focus on SSPE (O5).

Accurate estimates of the frequency of disease occurrence are necessary to effectively evaluate livestock health. O1 will investigate the use of statistical methods to derive better estimates from existing data sources, while O2 explores better estimates from novel diagnostic tests. Outcomes from these objectives, (plus O3.2.3), will facilitate the design of new livestock surveillance system components. From baseline estimates, the impact of disease can be quantified to understand whether the instigation of control measures is economically worthwhile (O4). However, to achieve real change, control measures also have to be feasible, adopted and implemented; these socio-economic aspects will be explored in O5 (biosecurity as an exemplar). Changes in disease frequency, measured using the tools developed in O1 & 2, may be due to many factors. A major current policy influence is the pressure to reduce antimicrobial use (AMU) in the face of antimicrobial resistance (AMR); this may lead to a reduction in the health status of livestock. Conversely, by implementing disease control strategies, the consequent improvement in health status may lead to a reduction in AMU, in accordance with SG policy. There is anecdotal evidence for both these scenarios occurring: we seek quantitative evidence in O3.

The work proposed in O1 builds upon work completed in CWP6.1. The generic framework (InteGrated framewORk, IGOR developed with AHDB Pork funding) has been adapted for endemic diseases and Scottish livestock sectors. C(Current)EPIC work has contributed by addition of demographic data sources; N(New)EPIC (Topic 3: surveillance) will adapt IGORs within the context of exotic disease, while endemic analyses in both NEPIC and the NSRP will be informed by outputs from O1; thus, opportunities identified via CWP6.1 IGORs will be realised. CEPIC identified MV as priority No. 3 for the sheep sector (behind scab and foot-rot); data sources for this analysis are available for Scotland. CWP6.1 work on ovine fallen stock data has demonstrated some potential to contribute to surveillance intelligence; expansion to cattle data will complement C & NEPIC work with demographic data. These analyses will act as exemplars. If value is demonstrated then they will direct Y3-5 research to enable appropriately designed, targeted, surveillance activities for other priority endemic diseases. Anthelmintic resistance (O2, prioritised through sector-specific stakeholder engagement) is one of few issues that can single-handedly result in a non-viable sheep enterprise. Lack of diagnostic tests for TBD in ruminants affects publicly funded surveillance programs (Tri-Partite Surveillance [TPS] agreement) and investigations of environmental change. O4 addresses a priority condition for each of the two predominant Scottish livestock sectors (cattle & sheep), while O5's focus on the SSPE is in response to a need identified in a recent EPIC GAP analysis (CEPIC M1 GAP analysis). It builds on work in CWP6.1 with small-scale pig producers (QMS & SFC provided additional funding) and will also provide essential information for the development of avian disease spread models in NEPIC.

Objective 1: Improved estimates (of health status and disease prevalence) by optimising the use of available data. A generic framework, (IGOR) that facilitates the identification of existing data sources, enables evaluation of their utility and optimises their use for baseline measurement and ongoing monitoring of priority endemic diseases is being developed and used (CWP6.1) to visualise the possibilities for Scottish livestock populations. In conjunction with BioSS colleagues and data providers, the completed frameworks will be used to target the application of statistical methods (some of which are novel to the animal health field) to produce better estimates of health status and disease prevalence. **Timed deliverables:** Y1-2**,** a prioritised list (justified) of diseases for data exploration per livestock industry sector; improved understanding of within herd BVD status; an improved estimate of the prevalence of MV in the Scottish sheep flock; an assessment of the utility of cattle fallen stock data. Y3-5: a framework for estimating underlying disease status in those diseases where direct measurement is technically difficult or expensive, and design and development of surveillance components to fill gaps identified in the system, e.g. for active surveillance of prioritised endemic diseases in sheep.

Objective 2: application of improved diagnostic strategies. Estimates of health status and disease prevalence are difficult to achieve when specific diagnostic tests are not available. Novel diagnostic strategies will be applied to two areas: emergence of BZM resistance in *N. battus* in Scottish sheep and prevalence of tick borne fever (TBF) and other TBDs in ruminants. Samples will be obtained through collaborations with industry and governmental bodies such as EBLEX (English beef and sheep industry body) APHA, SRUC, Moredun Foundation and publicly funded surveillance programs (TPS agreement). **Timed deliverables**: Y1-2, investigation of the prevalence of TBF and mixed TBD infections in samples from the SG-funded TPS agreement using molecular and serological tests under development in CWP6.2. Initial investigation into prevalence of *N. battus* BZM resistance. Y3-5: dissemination of information on BZM resistance and TBDs prevalence to stakeholders and the re-evaluation of biosecurity measures targeting movement of animals from disease-free to endemic areas.

Objective 3: How to achieve sustainable livestock production and mitigate disease while reducing antimicrobial (AM) use. The challenge of AMR is the driving force behind pressure on the livestock industries to reduce AM use. However, AM use, health status and disease prevalence have a complex and intricate relationship. The current contribution of AM use to animal health will be determined by investigations into 1) how AM use can be measured 2) how other disease control policies may influence AM use and how 3) targets for reduction might affect behaviours and productivity. This builds on AM use and AMR work within CWP6.1 and expected outputs (2016) from an APHA-SRUC study (VMD-funded, VM0526) that utilises samples from FSA-funded work (FS101055). **Timed deliverables**: Y1-2, a report on recording methods of AM usage in the pig industry; estimates of the consequence of disease (BVD) control on AM use; evidence-based recommendations (VMD/FSA study) as to whether further work on baseline estimates of AMR is required, Y3-5: possible extension of disease/AM use work to other diseases and sectors; a report on disease consequences (including socio-economic) of reduced AM use in Scottish livestock sectors.

Objective 4: Assessing the economic impact of priority endemic disease and conditions: liver fluke in sheep and paraTB in cattle. Sheep and cattle industries are under increasing pressure to increase efficiency in response to demands for improved animal health and welfare, greater food security and lower environmental footprints. Endemic diseases impose costs on farmers. Although on-farm control measures may improve productivity, their cost needs to be balanced against their effectiveness. Bio-economic modelling frameworks developed within CWP4.1 and refined in RD 2.4.2 combined with input from BBSRC-funded work (economics of liver fluke in cattle), will be used to address paraTB in cattle and liver fluke in sheep. **Deliverables** (expected in Y3-5, due to linked work being developed in RD 2.4.2)**:** economic assessments of the cost of paraTB in cattle and liver fluke in sheep and cost-benefit analyses of alternative control strategies at both farm and sector levels.

Objective 5: Is “biosecurity” worthwhile for smaller-scale producers? Smaller-scale enterprises are a neglected part of livestock production in Scotland. They can be involved in transmission of endemic and exotic disease and their contribution to the success (or not) of disease control initiatives is often questioned by the major commercial livestock keepers. Biosecurity data for this group are scarce; the barriers and incentives for the uptake of best practices may differ between them and the major commercial producers. The successful small-scale pig producers' (SSPP) questionnaire survey (CWP6.1 & QMS) will be used as a template to address this knowledge gap in other livestock sectors, starting with poultry small enterprises (as discussed with SG). **Timed deliverables:** Y1-2, a policy brief; knowledge transfer and exchange with poultry SSPE. Y3-5: a final report summarising the main messages of the survey and identifying the most effective approaches to improve biosecurity by SSPEs. This work will later be integrated with outputs from RD 2.3.12 (best practice), where biosecurity practices on commercial farms will be investigated, to provide recommendations to improve biosecurity in livestock production systems.

Technical approach

No animal work requiring HO licences is currently planned for this RD; should this change, this will be approved by the respective MRPs ethics committee.

Objective 1: provision of improved current estimates of health status and disease prevalence through the use of available data

Technical approach

The IGOR frameworks will be applied to chosen diseases/health conditions per species. Stakeholder interface meetings (with industry and EPIC), effectively used in CWP6.1 to identify current industry priorities, will continue on a regular basis to confirm priorities and disseminate outputs. Similarly, meetings with SG will ensure their priorities and questions are identified. Priorities will be iteratively reconfirmed and future ones determined. Additional statistical methods will be identified and trialled (e.g. parallel spatio-temporal analysis of data, capture-recapture methods (CRC) and latent class variable (LCV) modelling). Known current priorities informed the proposed activities for Y1-2. These are: 1) Improved prevalence estimates for MV in Scottish sheep by applying CRC methods to data from historic statutory *B. melitensis* surveys, SAC CVS diagnostic data, Sheep & Goat Health Schemes data and abattoir data from the same time period; 2) LCV modelling applied to a) existing BVD data (ScotEID-BVD) to examine if it i) enables the use of epidemiological proxy measures (e.g. antibodies in blood, or milk) instead of key disease status measures, and ii) provides a framework for estimating underlying disease status to assist accurate identification of problem herds in the final stages of SG's BVD eradication programme; b) PARABAN data (from nine, mostly Scottish cattle farms, longitudinal data 2007-2014) to obtain a better picture of how paraTB diagnostic test results relate to actual disease status; 3) build on CWP6.1 work with sheep fallen stock data to a) explore the utility of statistical aberration detection methods to detect unusual peaks in mortality in cattle fallen stock data and b) to develop an indicator of mortality as inverse estimates for 'health status', when combined with data from CTS (Cattle Tracing System). Over the course of this programme (by end of Y5) the frameworks and analyses will be used, with emerging methodologies (e.g. from the EU RISKSUR project), to identify gaps in the surveillance system; to design components for effective targeted animal health surveillance of prioritised endemic diseases in Scottish livestock sectors, and assess the cost-effectiveness of their implementation. Resultant estimates of health and disease status will be used to estimate the economic impact (O4).

Detailed work plan

Year 1: stakeholder meetings with all five industry groups (cattle (dairy & beef), sheep, pigs and poultry) [D1 beef & sheep by end Aug 2016; D2 pigs & dairy & poultry by end of Dec 2016] and the questions to be answered (e.g. should we measure disease incidence or prevalence?) [O1.1 continuous across period to end Dec 2016]. Discussion with SG will follow these meetings [KE1 depends on (d.o.) and will be after D1: end Sept 2016; KE2 d.o. and after D2: end Feb 2017]. Data sources for the planned analyses will be acquired and prepared (M1, end July 2016), and the analyses initiated (M2 d.o. M1, end March 2017): MV, CRC methods; BVD, LCVM application; fallen stock data, cattle, spatio-temporal analyses [O1.2].

Year 2: finalise and report [D8, d.o. O1.2, end Nov 2017] on the initial analyses above [O1.3, continuous process], while identifying subsequent possibilities and priorities, including initial application of LCVM to paraTB data [O1.4, d.o. O1.2, end March 2018, M8]; identify and assess where gaps in the frameworks exist for priority diseases and conditions [O1.5, d.o. D1 & D2, end March 2018, M9]. Later work will include: continued stakeholder interface meeting as an iterative process, probably on a once every two years basis, plus development of a framework for estimating underlying disease status in those diseases where direct measurement is not feasible and the design of surveillance components to fill any gaps identified and for active surveillance of prioritised endemic diseases in sheep.

Objective 2: application of innovative diagnostic strategies to estimates of animal health

Technical approach

To employ innovative diagnostic approaches currently under development (AHDB studentship and SG-TPS to estimate prevalence of two conditions (BZM resistance and TBDs) in Scottish sheep populations. To date, specific high-throughput assays for these conditions are not available or at the early stages of validation therefore their prevalence is unknown. Using DNA based approaches (e.g. pyrosequencing and/or isothermal loop-mediated PCR) we will investigate emergence of BZM resistance in field populations of *N. battus,* by examining single nucleotide polymorphisms (SNPs) at codon 200 within isotype 1 of the β-tubulin gene. Streamlining the process will allow rapid assessment of the genotype of parasite populations from egg DNA. This will be integrated with work proposed within NEPIC to develop a better understanding of the potential risk factors (eg. demographics, management practices and treatment strategies) associated with the development of resistance and to target treatment strategies for areas where multiple treatments are essential to control *N. battus* infection. Meanwhile, samples collected through the TPS scheme for Louping ill will be subjected to additional investigations to identify potential concurrent TBDs (initially TBF, with the option of incorporating *Borrelia burgdoferi* and *Coxiella burnetii* later in the programme). This RD will build on the current development and validation of molecular and a serological TBF diagnostics and, if successful, will extend to other diseases, through molecular or serological multiplexing of assays in the late years. KE will be delivered mainly in Y3-5 through the dissemination of information on BZM resistance and TBDs prevalence to stakeholders and the re-evaluation of biosecurity measures targeting movement of animals from disease-free to endemic areas.

Detailed work plan ***Year 1:*** Collection of parasite material from farms throughout Scotland, in collaboration with stakeholders and SRUC [O2.1, M3 & D3, end May and Nov 2016]. Serum samples and buffy coats of ticks-exposed animals already at Moredun will be identified [M4, end Sep 2016] and supplemented by exploiting louping ill submissions from SAC CVS [O2.2]. Nucleic acids and serum banks will be prepared and consolidated [D4, end Mar 2017]. ***Year 2:*** Completion of sample collection [M10 & D9, end May 2017 & Jan 2018] [O2.1 ctd, d.o. M3 & D3], and completion of P200 SNP analysis of *N. battus* populations for BZM resistance genes identification [O2.3, d.o. O2.1, M11, end Sep 2017], followed by publication of the results [KE4, by Dec 2017] and information dissemination to stakeholders through KE events such as North/Scot sheep, the Royal Highland Show and farming press articles [KE5, by Mar 2018]. Testing of the samples collected through the TPS surveillance by PCR or ELISA [O2.4, d.o. O2.2, M12 & M13, by Aug 2017 & Feb 2018] to investigate TBF prevalence within tick–exposed flocks, dissemination of results at stakeholder meetings and farming events [KE6]. Further activities (Y3-5) will include the addition of *Borrelia burgdoferi* and *Coxiella burnetii* to the test portfolio. If appropriate, methods developed under O1 will be applied to the outputs of the diagnostic testing work performed in O2 to attempt to generate improved population estimates of disease prevalence from the sample prevalence generated (Y5). The sample estimates produced will provide input to sample size calculations to inform the design of surveillance system components.

Objective 3: How do we achieve sustainable livestock production and mitigate disease while reducing antimicrobial (AM) use?

Technical approach

1. Sustainable reduction of AM use - directly: the current dialogue with the pig industry will be continued to contribute expertise, exchange knowledge and develop practical methods of recording AM usage, to meet any proposed targets for reduction of use (from EU and/or UK legislation or from the industry itself). 2. *Reduction of AM use – indirectly through other disease control initiatives:* a temporal analysis to investigate if AM usage varies with changes in BVD status (ScotEID database), using veterinary practice records from a population of Scottish dairy farms (approx. 30 herds, mostly from SW Scotland) that have been actively encouraged to eradicate BVD. Later this work may be extended to include investigation of the economic effects; effects on other diseases, production parameters and changes in biosecurity practices. 3. *Evaluation of available data:* further analysis of the data from 20 Scottish farms in VM0526 to determine the current baseline of AMR estimate for Scottish cattle destined for the food chain. The outputs will help to determine whether there is a need to test additional archived samples, or to run a new survey (RD 2.2.6) and if so, what the sample size and strategy should be i.e. will inform the study design for active surveillance of AMR in cattle in Scotland (RD 2.2.6) and other sampling strategies (e.g. RDs 2.2.6 & 3.1.3 mutual sample use for AMR investigations).

Detailed work plan: ***Year 1:*** development of new methods of recording AM use for the pig industry [O3.1, KE3] with short update on progress reports to SG at 6 (D5, end Aug 2016) & 12 months (D6, end March 2017); determine a suitable measure of AM use for the BVD/AM use work [O3.2, D7 end Sept 2016] and acquire and prepare the data for this analysis [O3.3, M5 end of March 2017].***Year 2:*** work with the pig industry (adoption phase) [O3.1, M14], report progress to SG end Dec 2017 [D10]; analyse the cattle data [O3.4 end Dec 2017, d.o. O3.2 & O3.3] [M15] and report on the BVD/AM use analysis [D11 end March 2018]. Analyse the Scottish data (from VM0526) [O3.5, end August 2017] [M16] and consider in the light of emerging outputs from D11 (d.o. O3.4 & D11). The outcomes will be reported back to industry stakeholders (via O1.1) and Scottish Government [KE7]. Y 3-5: dependent outcomes of Y1-2 deliverables, plus SG and stakeholder requirements.

Objective 4: Assessing the economic impact of priority endemic disease and conditions - liver fluke in sheep and paraTB in cattle

Technical approach

Bio-economic models, that combine epidemiological and economic concepts to integrate animal health into whole-farm business management, are used to explore optimum on-farm control strategies. Existing models will be further developed and refined in RD 2.4.2 and then applied to assess both the economic impact of these two endemic diseases and the relative contribution that their management and control strategies could make to whole-farm profitability and sustainability in the sheep and cattle sectors, respectively.

<u>Detailed work plan:</u>

This work will occur from Y3 onwards (requires early Y1-2 outputs from 2.4.2).

Objective 5: Is "biosecurity" worthwhile for smaller-scale producers?

<u>Technical approach</u>

A network of producers' associations (SSPP CWP6.1 & 6.5) will be used to identify our target population and the best methodology for the survey; the SSPP questionnaire will be adapted, piloted and distributed. The target population are Scottish backyard and small and medium poultry enterprises approx. 380-400 completed questionnaires (to be confirmed in design stage). After analysis and reporting these data would be used for simulation models that incorporate biosecurity parameters and additional analyses. Outputs will include: a) dissemination at regional and national meetings b) production of articles for small-holders' magazines; c) ad-hoc meetings in areas not covered by a); d) presentation at national and international scientific meetings. Focus groups will be held at the knowledge exchange meetings to explore why SSPE apply specific biosecurity measures. Recommendations will be made on the most effective approaches to improve the biosecurity for SSPEs.

<u>Detailed work plan:</u>

Year 1: Develop (M6 May-Aug 2016, d.o NEPIC ST2.4), pilot and initiate the SSPE survey (M7 Sept-Nov 2016, d.o. M6) [O5.1]. Initiate data collection [O5.2] Year 2: Complete data collection (M17 Oct 2016 to end May 2017, d.o O5.1), analyse (M18, d.o M17, June – Sept 2017) [O5.2]; policy brief with initial survey results (D12 Nov 2017, d.o O5.3 & M18), [O5.2] plan and hold knowledge exchange meetings and focus groups (O5.3 Sept 2017 – March 2018, d.o M18) [O5.3, KE8]. Y3-5 Report on analysis of KE & focus groups (end June 2018, d.o. O5.3). Planned extension to other livestock sectors (sheep, cattle) in Y3-5 will be dependent on SG and stakeholder requirements.

Expertise

This section has been removed from the post-peer review version of this proposal to provide space for response to points raised. However, the response to a specific query, related to of microbiological expertise is as follows: Moredun has a long term interest and expertise in specialised livestock diagnostic of bacterial, viral and parasitic diseases, with the RD investigators also leading the Virus Surveillance Unit and the GE parasitology labs. Regarding the work planned by SRUC, the microbiological expertise will reside in the RD in which the actual diagnostic work is occurring, eg for AMR, RD 2.2.6, or will take advantage of external collaborations (APHA VM0526).

Key linkages, interdisciplinarity & collaboration

Work in this RD will bring together epidemiologists, experts in diagnostic and best practice management, statisticians and socio-economists allowing an integrated approach to the problems identified. The principal key linkages are with other RDs in Theme 2 and the new EPIC COE. For example: the stakeholders meetings in O1 will be held in collaboration with requirements for NEPIC ST4.1; while other O1 outputs (improved disease frequency estimates) will contribute to NEPIC Topic 3 Surveillance, particularly ST3.1. They will also provide input estimates, where relevant, for incidence and consequences work in RD 2.2.9 and inform the analysis of the impact of disease on greenhouse gas emissions in RD 2.3.6; in O2 where relevant data is generated in 2.3.3, it will be used to inform the analysis for TBDs work, whereas field application of

diagnostic assays (TBD pathogens) links RDs 2.2.2, 2.3.3 & 2.2.4. Once validated, those assays will be used to study the epidemiology of TBD, specifically its role in livestock abortion in 2.2.6. Using existing questionnaire data, risk factors for the latter will be identified; work in O3 will be informed by any improvements in measuring AMR that arise from O4 RD 2.2.6 (analysis of existing large datasets). Reciprocally, work in O3 will contribute to the AMR work planned in RD 2.2.6, in conjunction with RD 3.1.3, through both the design of suitable sampling strategies and improved estimates of AM use, which may contribute to later RD 2.2.6 work on clinical outcome. Work from O5 will contribute to RD 2.3.12. A link to RD 2.4.2 (Economic Adaptation) will enable bio-economic models developed there to be used for economic analyses in O4. Relevant data on paraTB generated in 2.3.3 will also contribute to O4. Work from NEPIC Topic 2 (ST2.4) will inform the design of the survey in O5. The Y2 focus groups will be joint events between researchers from NEPIC ST2.4 and O5 (KE8, Mar 2018). Links will be managed through data exchange, six-monthly review meetings, e-mails and video or teleconferences, promoting inter-MRP dialogue and strengthening collaborations. Links with NEPIC will be maintained by the researchers within RD 2.2.2 who are also participants in NEPIC COE. Collective outputs will be collated and presented at KE events identified later in this document, to relevant stakeholders and submitted for publication.
Added Scientific Value This RD will make a significant contribution to scientific understanding of how to bring together existing information and innovative ways to collect and utilise new data (e.g. sheep surveillance). In O1 data generated in other projects (PARABAN and PARABAN Reloaded) will be used to examine the potential of LCV modelling to provide information about the value that can be obtained from the use of different diagnostic tests for paraTB. In O2, the research will utilise techniques developed through an AHDB levy board studentship, a BBSRC Lola and collaborations with other MRPs and Universities to gain a wider picture of the prevalence of resistance gene frequencies within populations of *N. battus*. Additional TBD surveillance will foster closer collaboration within organisations (MRI and SRUC) and deliver a broader understanding of TBDs prevalence in Scotland and the emergence of co-infections in relation to climate change. In O3, the data generated by a VMD-funded APHA/ERU study, based on samples from FSA-funded work, will be employed to determine the current baseline estimate for AMR in Scottish cattle destined for the food chain. The close collaboration of SRUC with the pig industry in projects such as Wholesome Pigs Scotland will allow sharing of expertise and knowledge exchange in terms of practical methods of recording antibiotic usage. BBSRC-funded work on the economics of liver fluke in cattle will inform the work of O4 as it is extended to encompass the dual issues of paraTB in cattle and liver fluke in sheep. Proposals on aspects of surveillance and improved estimates of health status and disease prevalence are and will continue to be submitted to appropriate funders (e.g. FSA, BBSRC, Innovate UK, ANIWHA, Industry bodies).
KE, Audiences and Impact **KE:** Specific KE outputs have been incorporated in all objectives covered by this RD and can be found in the attached Gantt chart with indicated timelines. They will encompass a broad spectrum of activities, such as stakeholders and SG [KE1-2] and policy events [KE7, D12] farm and roadshows [KE6], educational seminars to industry [KE3], peer-reviewed publications [KE4], work with schools (ad hoc) and provision of advice [continuous, across the programme]. Six-monthly and annual report from this RD will be collated and submitted to the program management team [KE9, 10, 11 &12].

Audience: A broad range of audiences will be targeted e.g. farmers, industry groups, veterinary and policy advisors, public, agricultural associations and charities. Industry interface meetings as per Gantt chart (O1) will promote KE with farmers, industry groups and advisors in relation to changes in disease priorities and new/emerging diseases. Disease awareness (O2) will be increased by participation at roadshows (every Oct/Nov), farmer's meetings and specialist livestock events (e.g. RHS, every June) to which policy advisors (SG/UK) will also be invited. SRUC's Advisory and Consultancy networks will be used to inform farmers of the consequences of reduced antimicrobial usage (O3) as well as the economic impact of liver fluke and paraTB (O4) in years 3-5. Smaller-scale producers will be targeted for KE relating to O5 at events such as the Scottish Smallholder and Grower Festival (every Sept) and biannual rare breed sales. SG advisors will receive quarterly updates to support their work in the context of the BVD eradication programme, animal health surveillance, new Animal Health and Welfare EU Regulation and revised EU legislation on medicines use. Policy briefs will be prepared where relevant e.g. on major developments in diagnostic capabilities and/or disease trends (especially for TBDs). Public and potential smallholders will be reached by articles in general and specialised press and human health practitioners will be targeted for the AMR and late-stage TBD work (Y3-5).

Impact: The impact from RD2.2.2 will arise from providing improved information on where and when priority animal diseases occur and how they can be controlled to support evidence–based policy decisions. As the KE activities outlined in the Gannt chart are delivered, the impacts described will be realised incrementally and the benefits for stakeholders are expected to continue beyond 2021. Impact will be primarily economic, through more cost-effective strategies to measure (O1) and control (O4) disease and greater industry competitiveness due to improved animal health. Demonstrable high health status (O1 and O2) and low levels of AMR (O3) are likely to increase domestic consumer confidence and food security, and develop overseas markets for Scottish livestock and animal products, contributing to economic growth. Similarly, application of innovative diagnostic methods (O2) will deliver commercial benefits and enhance Scotland's reputation as a world leader in biosciences. The proposed outputs on BVD (O1 & O3) in years 1 and 2 will contribute to policy development in the final stages of the Scottish BVD Eradication Scheme to minimise the time and resources required to achieve a BVD-free Scotland. The work with SSPEs (O5) will reduce disease through improved biosecurity by creating a community of practice for a marginalised group of livestock keepers.

RESEARCH DELIVERABLE NUMBER: 2.2.2

Work planning and timetable for Year 1: Please include major milestones [M] (key sub-objectives [OX.x], deliverables [D], KE/impact events [KE]) and their timing.

Year 1: 2016/17	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
O1 Optimise use of existing data												
O1.1 Stakeholders meetings						KE1					KE2	
D1 Meeting with beef and sheep industry groups					D1							
D2 Meeting with dairy, pigs and poultry industry groups									D2			
O1.2 Preparation/analysis of surveillance data												
M1 Acquisition and preparation of data				M1								
M2 Commencement of data analysis												M2
O2 Application of improved diagnostic strategies												
O2.1 Collection of parasite material for P200 analysis												
M3 Initiate sample collection from selected farms		M3										
D3 Report on number of samples collected								D3				
O2.2 Establish serum and buffy coat TBD sample archive												
M4 Archived sample identification and retrieval						M4						
D4 Consolidation of serum and nucleic acid banks												D4
O3 Impact on livestock health status												
O3.1 Recording AM use in the pig industry			KE3						KE3			
D5 and D6 update on progress to SG						D5						D6
O3.2 Determine a suitable measure of AM use for BVD/AM						D7						
O3.3 Acquire and prepare BVD/AM data												M5
O4 the economic impact of priority endemic disease	**Please note no Y1-Y2 work is planned for this objective**											
O5 Cost-effectiveness of biosecurity												
O5.1 Develop, pilot and initiate SSPE survey												
M6 Develop SSPE survey					M6							
M7 Pilot and initiate SSPE survey								M7				
O5.2 Initiate data collection for analysis												
Annual progress report												R1

RESEARCH DELIVERABLE NUMBER: 2.2.2
Work planning and timetable for Year 2: Please include major milestones [M], (key sub-objectives [OX.x], deliverables [D], KE/impact events [KE]) and their timing.

Year 2: 2017/18	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
O1 Optimise use of existing data												
O.1.3 Completion of surveillance analysis								D9				
O1.4 Identification of subsequent possibilities and priorities												M8
O1.5 Identify gaps in the frameworks for priority diseases												M9
O2 Application of improved diagnostic strategies												
O2.1 ctd Collection of parasite material for P200 analysis												
M9 complete collection of parasite material		M10										
D10 All parasite material cultured to L3										D9		
02.3 P200 SNP analysis												
M11 Completion of N. battus P200 analysis						M11						
KE4 & KE5 publication and dissemination of findings									KE4			KE5
O2.4 investigation of TBF prevalence in exposed flock						KE6						KE6
M12 complete PCR testing of surveillance samples					M12							
M13 complete ELISA testing of surveillance samples											M13	
O3 Impact on livestock health status												
O3.1 ctd Recording AM use in the pig industry												
M14 Adoption phase with the pig industry							M14					
D10 Progress report to SG									D10			
O3.4 Analysis of cattle data and report on BDV/AM use												
M15 Complete analysis of the cattle data									M15			
D11 Report on BDV/AM use analysis												D11
O3.5 Analyse Scottish data (from VM0526)												
M16 Complete data analysis					M16							
KE7 Report findings to stakeholders and SG												KE7
O4 the economic impact of priority endemic disease	**Please note no Y1-Y2 work is planned for this objective**											

O5 Cost-effectiveness of biosecurity												
O5.2 ctd Complete data collection, analyse and plan KE												
M17 Complete data collection		M17										
M18 Complete data analysis						M18						
D12 Policy brief with initial survey results								D12				
O5.3 Plan and hold KE meetings and focus groups												KE8
Annual progress report												R2

Name of RD: 2.2.3 Disease Mechanisms
Research aim and key drivers: The aim of this RD is to provide new knowledge relating to the pathogenic mechanisms that underlie livestock diseases. A broad range of questions will be addressed that examine the interaction of pathogens (viruses, bacteria and parasites) with their host, with a particular focus on the role of the host immune system in the disease process. The key driver for this research is the current lack of reliable control methods for the diseases under study, which result in substantial economic losses to Scottish and UK farming and are a serious concern for animal welfare. This research will address this issue by providing new information that can be translated into practical and affordable diagnostic tools and vaccines for use by farmers, veterinarians and other stakeholders to reduce the economic and welfare impact of these important enzootic diseases. Reducing the impact of livestock disease will improve the efficiency and sustainability of Scottish and UK farming and strengthen the viability of rural communities. This benefits the wider public through increased food security and safety. The proposed research focuses on selected important enzootic diseases of livestock caused by a range of pathogens, including some that also cause disease in humans. These examples have been prioritised for research on the basis of ongoing discussions with a number of stakeholder groups including Scottish Government Animal Health and Welfare Stakeholder Group, industry-led Livestock Health Scotland, SAC Consulting, NSA, NFUS, SVS, QMS, EBLEX, HCC, Moredun Foundation and sheep breed societies as well as individual livestock producers through discussion at Animal Health events.
Summary of the proposal: The research proposed in this RD represents a broad programme of work that addresses a number of important diseases of importance to livestock production in Scotland and at UK and EU level. As set out below and in the attached Gantt Charts, the work is organised across 12 Objectives (O) and the overarching Key Deliverables are: • Characterisation of bacterial, viral and parasite components involved in disease pathogenesis and exploitation of these components as targets for vaccines and diagnostics (O1, O3-O10), including studies to optimize vaccine usage on farms (O12). • Determination of the role of host innate and adaptive immunity in pathogenesis, in response to infection and in the response to vaccination (O1-O10, O12). • Improved understanding of pathogen spread within the host and transmission between hosts (O3-7, O9-O11). This work builds on previous RESAS-funded research on disease mechanisms, including studies from Programme funding (O1-O9) and specific work strands from SPASE on *Campylobacter* and Disease Modelling (O10-O11). **Objective (O)1. Immunological characterisation of chlamydial antigens for the development of DIVA vaccines to protect against ovine enzootic abortion (OEA).** OEA, caused by *Chlamydia abortus*, is responsible for approximately 45% of cases of abortion in ewes in the UK and has a significant financial impact on sheep production and health. Current vaccines for OEA are effective at reducing clinical disease and shedding but do not elicit sterile immunity or allow the differentiation of vaccinated from infected animals (DIVA). Given the persistent nature of the infection, a DIVA approach, coupled with the recently commercialised *C. abortus*-specific ELISA (MVD-Enfer; developed under the current SG Programme and released Apr 2015), would be advantageous for integrated control strategies. The proposed research will identify and characterise novel candidate bacterial genes and antigens that are involved in disease

pathogenesis and protection in order to assess their utility as vaccine targets.

O2. The effect of concurrent nematode infection in sheep on vaccine response. Studies in humans and rodents demonstrate that nematode parasites can suppress host immunity to enable survival within the host. The suppression of host immune competence may also result in a reduced ability of the host to respond to concurrent infections or vaccination. Curative anthelmintic treatment can restore normal immunological function *in vivo*. Comparable data is limited in livestock species, and does not exist for small ruminants. This RD will determine whether concurrent nematode infections affect the ability of sheep to respond to commonly used vaccines, and whether clearance of parasites via anthelmintic treatment prior to vaccination enhances vaccine-induced immune responses that correlate with protection (e.g. *C. abortus*). This will provide detailed mechanistic information on how nematodes affect the immune response to an important sheep pathogen and its impact on protection against abortion.

O3. Knock-out mutants of *Mycobacterium avium* subsp. paratuberculosis (Map) as live attenuated vaccines for Johne's disease (JD). Current vaccines for JD are killed vaccines that reduce the severity of disease and faecal shedding of Map but do not prevent infection. Vaccine research on tuberculosis has shown that live attenuated vaccines afford greater protection against mycobacterial infections than killed or subunit vaccines. In the current SRP Map knockout mutants were constructed, including mutants with a Green Fluorescent Protein (GFP) marker, which provide a means for monitoring viability and tracking infections within cells. This will permit studies on their interactions with host cells and indicate the suitability of these mutants to be live vaccine candidates. This RD will determine whether they retain the ability to infect the host and have the potential to induce a protective immune response without causing disease.

O4. Host pathogen interactions in single and co-infections in bovine respiratory disease complex (BRDC). An estimated 1.9 million cattle are affected by BRDC each year in the UK with annual costs estimated at around £60 million despite the availability of a number of BRDC vaccines. Several viral and bacterial pathogens are involved in BRDC, which complicates understanding of pathogenic mechanisms. In addition, conventional techniques to detect the pathogens responsible for specific outbreaks can be time consuming or lack sensitivity. In this RD, *ex vivo* lung culture models will be used to elucidate the early host responses to BRDC pathogens that determine whether the animal progresses to recovery or disease. This will guide the development of improved vaccines to pathogens in BRDC and may suggest alternative ways to reduce the pathology associated with BRDC and reduce antibiotic usage based on a greater understanding of the host cellular responses to infection. In addition, multiplex diagnostic methods for pathogen detection in BRDC will be expanded.

O5. Cell tropism of jaagsiekte sheep retrovirus (JSRV) and host innate immune response. Ovine pulmonary adenocarcinoma (OPA) is an important enzootic disease of sheep caused by JSRV. The development of control strategies for OPA has been difficult due to the limited immune response to viral antigens in infected sheep and the low level of virus in peripheral blood. Recently, progress has been made in identifying diagnostic markers for OPA and these will be exploited in work proposed under RD2.2.4. This RD will extend work begun under the current RESAS Programme to understand JSRV cell tropism in sheep with OPA and to characterise the innate immune response to JSRV infection. This will provide additional knowledge on OPA pathogenesis that can be used in diagnostic development and/or vaccine design.

O6. Host-pathogen interactions in bovine cryptosporidiosis. Cryptosporidium parasites are a major cause of enteric disease in farmed livestock worldwide and are also a leading cause of infant diarrhoea in humans. There are no safe and effective treatments or vaccines currently available. Neonatal calves are particularly vulnerable to infection, which can result in significant morbidity due to severe diarrhoea and dehydration and cryptosporidiosis has emerged as a significant cause of calf mortality in beef suckler units. Here, host-pathogen interactions will be studied to increase understanding of host factors that determine disease outcome, a phenomenon that is linked to age. Identification of host factors that are linked to disease or disease-resistance will provide a platform of knowledge to enable future development of vaccines to aid disease prevention.

O7. Immune responses in ovine mastitis. Mastitis or inflammation of the mammary gland represents one of the most costly diseases of sheep farming. Clinical mastitis is a significant health and welfare issue while sub-clinical mastitis causes reductions in milk quality and quantity which impacts lamb growth. Despite its importance the nature of the response to infection in sheep is poorly understood and effective strategies for disease control are lacking. In the current RESAS programme infection models for each of the three principal mastitis pathogens of sheep in Scotland, *Mannheimia haemolytica*, *Staphylococcus aureus* and *Streptococcus uberis*, were successfully developed using locally sourced isolates. The proposed research will exploit these systems to characterise the immune responses in mastitis and their role in pathogenesis.

O8. Disease and immune mechanisms in ovine responses to vaccination against Teladorsagiosis. *Teladorsagia circumcincta* is the primary cause of parasitic gastroenteritis in sheep in temperate areas. Through previous RESAS funding, a prototype recombinant vaccine against *T. circumcincta* was developed. This prototype vaccine comprises 8 proteins and induces significant protection against challenge in 6-7 month old lambs, with vaccinated animals harbouring up to 75% fewer worms compared to controls. Based on these results, this vaccine holds great promise as a future control option for farmers in tackling teladorsagiosis in Scotland and other countries. This RD will attempt to establish correlates of immunity and pathogenesis in sheep vaccinated with this, and a simplified prototype, vaccine for *T. circumcincta* with the aim of improving efficacy of the vaccine.

O9. The impact of sheep scab vaccines on host:parasite population dynamics. Infestation with the sheep scab mite (*Psoroptes ovis*) represents a major animal welfare concern and a significant economic burden on the sheep and cattle industries, in Scotland and worldwide. The concept of controlling sheep scab by vaccination is supported by the demonstration of a degree of protective immunity in sheep following previous infestation with *P. ovis*. Using a rational approach to antigen identification a suite of seven recombinant proteins was previously identified which, when administered to sheep as a vaccine cocktail, results in >50% reductions in lesion size and mite numbers following challenge in protection trials. Here, host and parasite transcriptomes will be examined following vaccination to provide a better understanding of the influence that vaccination may have on both host and parasite populations.

O10. Interaction between *Campylobacter* and host species and the basis of persistence, pathogenesis and protection. *Campylobacter* species are estimated to cause 685,000 cases of acute diarrhoeal illness in people in the UK each year at a high recurring cost to society and the economy. They occupy the intestinal tracts of a wide range of livestock species often in the absence of overt disease yet infections in humans typically result in severe disease sometimes with life-threatening and long-term consequences. In this RD, a combination of activities is proposed in which bacterial and host factors will be defined and validated to contribute to the outcome of colonisation and infection. Principal focus will be placed on the determinants of host response to infection *in vivo* in both reservoir hosts and models of disease. Innate and adaptive immune responses and their contribution to protection will be examined and the impact of genetic variation, whether in the pathogen or avian host, on the outcome of infection investigated. These aspects offer potential as targets for development of interventions.

O11. Inferring genetic and other individual variation in population and dynamic models. This RD will develop and deploy sophisticated inference tools to quantify disease mechanisms at field scales by extracting maximum value from genetic, epidemiological and other data on agricultural and ecological systems of importance across the RESAS portfolio. ***This objective links with HEI bid 4: 'Inferring genetic and other individual variation in population and dynamic models'***. In collaboration with RD2.3.3, RD2.2.6 and NEPIC it will help to address major issues in Scottish livestock production by providing necessary analytical tools to derive effective long-term disease prevention strategies; *e.g.*, via estimation of between host transmission and disease progression within hosts (a key goal of RD2.2.3) in both livestock and wildlife. The inference methods developed will also be applied to invasive non-natives (RD1.3.3) and animal movement data (RD2.3.10). The project will act as a 'hub' to ensure that key *additional applications* and collaborations are identified during the course of the project, *e.g.*, from the Centre of Expertise on Plant and Tree Health and aquaculture, ensuring benefits are realised across the RESAS portfolio.

O12 Incorporating vaccines into best practice methods for controlling gastrointestinal nematode parasites of sheep. A novel vaccine for *Haemonchus* has recently been commercialised by MRI and another for *Teladorsagia* is under development. Vaccines offer a new approach to controlling these parasites but the optimal way of integrating them into existing control methods has still to be elucidated. This RD will use the *Haemonchus* vaccine as a model to address this for nematode vaccines in general.

Technical approach and Detailed work plan

Objective (O)1. Immunological characterisation of chlamydial antigens for the development of DIVA vaccines to protect against OEA. In years 1 and 2 of the programme, chlamydial antigens identified by proteomic analysis will be assessed in T-cell assays to identify those eliciting the required protective immune response (a Th1-biased cellular response characterised primarily by IFN-gamma production). This work will include protein refolding studies of the *C. abortus* major outer membrane protein (MOMP), a major candidate protective antigen, in an attempt to improve its protective efficacy. In years 3-5, candidate antigens will be formulated into subunit vaccine preparations and their protective efficacy assessed in pregnant sheep (RD2.2.5). In parallel, recently developed techniques for plasmid transformation of *Chlamydia trachomatis* will be applied to other chlamydial animal pathogens, providing opportunities to investigate gene function and generate knockout mutants through additional funding applications.

<u>Detailed work plan:</u> Year 1-2: Produce candidate recombinant *C. abortus* antigens for novel subunit vaccine, including cysteine-less chlamydial MOMP for protein refolding studies (**O1.1**). Evaluate cellular responses to recombinant chlamydial antigens using T-cells derived from immune sheep that produce IFN-gamma as an immune correlate of protection (**O1.2**). Develop methods for the transformation of non-plasmid bearing species/strains of *Chlamydia* (**O1.3**).

O2. The effect of concurrent nematode infection in sheep on vaccine response. This RD will determine whether clearance of gastro-intestinal nematodes (GIN) by anthelmintic drug treatments enhances the immune response to a commercial live attenuated *C. abortus* vaccine (CEVAC Chlamydia). If there are clear differences in how treated vs. non-treated ewes respond immunologically to the vaccine, then protection trials will be performed (in parallel with those conducted in RD2.2.5) in which the effects of deliberate GIN infection of ewes at the time of vaccination on protection against subsequent experimental *C. abortus* infection will be determined. Vaccine responses will be determined using established immunological techniques and data analysed using appropriate statistical approaches. Faecal egg counts will be used to monitor parasite burdens and to confirm the successful removal of GIN parasites by anthelmintic treatment. As experiments will be performed on a flock of conventionally reared and common breed of ewes, and with a commercial vaccine, the results of this study are expected to be transferable to other Scottish sheep flocks. Advice on best practice will be disseminated to relevant stakeholders in year 2.

Detailed work plan: Year 1: Optimise assays for assessment of immune responses to *C. abortus* vaccine (CEVAC Chlamydia, Ceva Animal Health Ltd) using cellular (IFN-γ and IL-4 production) and serological assays (ELISA) in order to establish the quantitative and qualitative immune profile that correlates with vaccine-induced protection (**O2.1**). Year 2: Determine whether prior treatment with an anthelmintic affects the ability of sheep to respond to CEVAC Chlamydia (**O2.2**). Breeding ewes will be divided into two groups (n=30) with identical median GIN egg counts. One group will be treated with anthelmintic 2 weeks prior to vaccination; the other group will be left untreated. Blood and faecal samples will be collected prior to treatment and at 2 week intervals for up to 12 weeks post-vaccination. Vaccine-specific cellular and antibody immune response in blood will be measured using the optimised assays developed in A4.

O3. Knock-out mutants of Map as live attenuated vaccines for JD. This RD will characterise the Map mutants and compare their properties with wild-type Map with respect to their growth kinetics and ability to infect and survive within macrophages (years 1-2). The ability of the Map mutants to induce a pro-inflammatory or anti-inflammatory phenotype on infection relative to wild-type Map will then be determined. Initially, experiments will be carried out *in vitro* using bovine monocyte derived macrophages (years 1-3). If the mutants demonstrate an ability to infect macrophages and induce the appropriate immune responses, their attenuation will be investigated using the MRI mouse model of infection where the readout will be colonisation and granuloma formation in the liver (years 3-4). If the mutants are attenuated in the mouse model, a mutant will be selected for further evaluation in the MRI calf model of infection to determine the ability of the selected mutant to elicit a pro-inflammatory immune response relative to wild-type Map (years 4-5). Attenuated mutants found to elicit the appropriate immune responses will be taken forward in a future programme for validation as potential vaccine candidates.

Detailed work plan: Year 1-2: Characterise the Map mutants and compare their properties with wild-type Map (**O3.1**). Determine if the Map mutants induce a pro-inflammatory or anti-inflammatory phenotype in macrophages (**O3.2**). For O3.1 and O3.2, one mutant will be examined in year 1 and another in year 2. Based on the data obtained, we will consider full transcriptomic analyses in year 3.

O4. Host pathogen interactions in single and co-infections in BRDC. *Ex vivo* lung culture systems (lung parenchyma, bronchial epithelium and macrophages) will be used as infection models to investigate the innate immune responses to individual, concurrent or consecutive respiratory infections (years 1-3), focussing initially on bovine respiratory syncytial virus (BRSV), bovine herpesvirus-1 (BHV-1) and *Pasteurella multocida.* RT-qPCR will be used to determine changes in expression of target genes involved in innate immune responses and in driving Th1 or Th2 adaptive immune responses. ELISAs and immunohistochemistry will be used to investigate changes in expression of relevant host proteins following infection. The findings from the *ex vivo* lung infection

models will be assessed for reproducibility and validated on samples obtained from natural or experimentally-induced BRDC, employing archived material which already exists from previous work at Moredun. If a new experimental infection is required, this will be conducted in year 4/5. In parallel, additional assays will be developed to extend the capability of the existing multiplex-PCR for bovine viral respiratory pathogens (parainfluenza-3 virus, BRSV and BHV-1), developed in the current SRP. Preliminary studies have shown that bovine coronavirus is frequently present in diagnostic material in cases of BRDC and its significance is currently under evaluation. In addition, BHV-1 diagnosis can be confounded by prior vaccination and a test able to detect the gE-deleted vaccine strain would also improve the diagnostic test currently available.
Detailed work plan: Year 1: Establish *ex vivo* bovine lung infection models (**O4.1**). Addition and validation of bovine coronavirus screening to current respiratory virus multiplex PCR (**O4.2**). Year 2: Validation and multiplexing of gE-deleted BHV-1 PCR (**O4.3**). Year 2+: Optimise co-infection protocols and determine innate immune responses to viral and bacterial co-infections (**O4.4**). Requirements for respiratory bacterial pathogens qPCRs (and alternative methods) for diagnosis in Scotland will be reviewed in consultation with SG-funded field veterinary surveillance staff.
O5. Cell tropism of JSRV and host innate immune response. This RD will utilise a recently-developed fluorescently-tagged JSRV strain and an *ex vivo* ovine lung culture model to study the cell tropism of JSRV *in vitro* and *in vivo* and to determine the local innate immune response to JSRV infection. Replication of JSRV-GFP and wild-type (untagged) JSRV will be examined in primary cell culture and in *ex vivo* ovine lung culture and cytokine production measured in response to infection (years 1-2). Subsequently, experimental infection of lambs will be performed with JSRV-GFP and compared to the *in vitro* findings (years 3-4). The use of the GFP-tagged virus will facilitate the identification of infected cells within the lung and in secondary lymphoid tissues. Together, this information will expand understanding of JSRV tropism and host immunity. This knowledge will guide future diagnostic development (linking to RD2.2.4) and may identify new opportunities for vaccines against OPA.
Detailed work plan: Year 1: Analysis of JSRV replication in primary ovine cell cultures (**O5.1**). Previous studies reported that JSRV replication in cell lines *in vitro* occurs at very low efficiency. Using JSRV-GFP, some primary ovine cell types (including epithelial cells and fibroblasts) have been identified that support its replication. JSRV and JSRV-GFP replication will be studied in these cells and the production of a panel of cytokines previously identified to be activated following JSRV infection *in vivo* will be measured. Year 2: Replication of JSRV in ovine lung slices (**O5.2**). Ovine lung tissue will be exposed to JSRV and JSRV-GFP and cytokine responses measured as for cell lines.
O6. Host-pathogen interactions in bovine cryptosporidiosis. This RD will include *in vivo* and *in vitro* studies to examine host-parasite interactions during acute infection and recovery in experimentally and naturally infected cattle to determine the key innate and adaptive immune responses induced following infection with *C. parvum*. The *in vivo* cellular host response in the ileum will be characterised during the phases of parasite host cell invasion, acute infection and recovery, where ileum samples will be collected from experimentally infected calves at different stages of infection. These tissue samples will be fixed and analysed for different immune components at the site of infection. This will generate a better understanding of how the innate and adaptive immune responses act specifically at the site of infection, whether they are responsible for the clinical signs of disease and which responses are associated with clearing the infection. Studies will also be conducted using short-term cultures of primary epithelial cells from neonatal ileum to enable molecular immunology analysis of host genes and

their expression following invasion and early parasite intracellular development. Establishment of a robust culture system for Cryptosporidium would also allow *in vitro* drug efficacy testing before conducting *in vivo* trials.

Detailed work plan: Year 1: Conduct experimental infections of neonatal calves with *Cryptosporidium* oocysts and monitor immunopathology over the course of a primary infection to determine the mechanism of disease pathogenesis (**O6.1**). Year 1-2: Establish bovine ileum primary cell cultures and assess their capacity to be infected by *Cryptosporidium* sporozoites, excysted from oocysts (**O6.2**). Activation of host genes will be assessed during the early stages of infection using molecular immunology.

O7. Immune responses in ovine mastitis. Previous studies have developed infection models for each of the three principal mastitis pathogens of sheep in Scotland, *Mannheimia haemolytica*, *Staph. aureus* and *Strepto. uberis*, using locally sourced isolates. Using these systems, this RD will characterise the cellular immune response in sheep challenged with each of the three major sheep mastitis pathogens and determine whether lymphocytes from the milk or draining lymph nodes of recovered/immunised animals respond to bacterial antigens (years 1-2). Subsequently, the role of the mammary epithelium in the induction of the intra-mammary immune response will be determined. Together with complementary work on epidemiology (RD2.2.6), this will improve our understanding of the immune response to infection, which will underpin the future development of vaccines and diagnostic tools.

Detailed work plan: Year 1: Intra-mammary challenge with *M. haemolytica* (**O7.1**). Year 2: Intra-mammary challenge *S. aureus* and *S. uberis* (**O7.2**). The cellular output of the milk, draining lymph nodes and peripheral blood will be archived over the course of these infections, providing resources for comparative phenotypic, functional and molecular analyses in years 3-4.

O8. Disease and immune mechanisms in ovine responses to vaccination against Teladorsagiosis. In work proposed under RD2.2.5, the efficacy of a simplified novel prototype vaccine composed of 4 immunomodulatory proteins derived from *T. circumcincta* will be compared with that of the original 8-antigen prototype to establish if the simplified vaccine has equivalent, or enhanced, ability to control *T. circumcincta*. In this RD samples of serum and abomasal tissue from that vaccine trial will be examined to attempt to establish correlates of immunity and pathogenesis in the vaccinated and challenged sheep (years 2+). This will be followed in years 3-5 with additional studies to characterise and optimise anti-parasite immune responses.

Detailed work plan: Year 1-2: Produce 4 new *T. circumcincta* recombinant proteins for novel vaccine (**O8.1**, see RD 2.2.5). Year 2+: Compare efficacy of original and novel prototype vaccine against *T. circumcincta* challenge in lambs >6 months old (see RD2.2.5) (**O8.2**). Characterise local anti-parasite immune responses in vaccinated and control lambs from O8.2 (**O8.3**).

O9 The impact of sheep scab vaccines on host:parasite population dynamics.

This RD will compare host (sheep) cutaneous transcriptional responses following primary and secondary (challenge) infestation with *P. ovis* to identify host pathways involved in the development of natural protective immunity. In addition, transcriptomic and proteomic responses involved in the parasite response and survival in the face of a vaccine-induced immune response will be assessed in *P. ovis* mites. This work will exploit an existing microarray dataset that assessed host (ovine) cutaneous responses to infestation with *P. ovis* over a 24-hour time course (years 1-2). This study investigated responses in both naïve sheep and in sheep undergoing a challenge infestation following previous exposure and treatment. In years 3-5, we will identify *P. ovis* proteins involved in survival in the face of a vaccine-induced host protective immune response.

Detailed work plan: Year 1-2: Perform detailed pathway analysis of the existing transcriptomic dataset to identify host pathways and signalling events associated with the development of natural protective immunity (**O9.1**).

O10. Interaction between Campylobacter and host species and the basis of persistence, pathogenesis and protection. The mechanisms by which *C. jejuni* infects multiple hosts and causes disease in only some species are largely unknown. Procedures and reagents developed under SPASE will be used to analyse the interactions between *C. jejuni* and host tissues and cell populations that differ in resistance to colonisation. ***This work links with HEI bid 3: 'A systems-wide approach to the control of Campylobacter in the food chain: exploiting genetic variation'***. The HEI project will define the impact of genetic variation, whether in the pathogen or avian host, on the outcome of infection. This will involve the use of inbred chicken lines exhibiting heritable differences in resistance to *C. jejuni*, including analysis of their gene expression and interactions of isolated explants and immune cells with *C. jejuni ex vivo*. During years 1 and 2, SRUC will contribute in the design of *in vitro* and *in vivo* experiments and interpretation of outcomes. In year 3, SRUC will organise animal studies in a simulated field context and will contribute to the dissemination of results. Material generated through these experiments will be archived and processed at MRI for bacterial transcriptome and proteome analysis. Network modelling will be used to assign the major host response processes that characterise the intestinal response to *C. jejuni* infection. This will exploit the transcriptome data generated here and in the piglet infection model (SPASE). Through informatics, pathological and bacteriological perspectives, target genes and proteins will be selected and their expression verified using RT-qPCR, proteomics and immunohistochemistry. Confirmation of the involvement of the targets prioritised will define key mechanisms of disease.

Detailed work plan: Year 1: Define whether differential resistance to *Campylobacter* is related to innate immune responses *in vitro* (**O10.1**). Years 1-2: Perform challenge experiments to test the impact of host genotype on resistance to *Campylobacter* (**O10.2**). This will involve infecting chickens differing in susceptibility with *Campylobacter* and measuring transcriptome expression (**O10.3**) and immune responses (**O10.4**).

O11. Inferring genetic and other individual variation in population and dynamic models. Tools will be developed to enable Bayesian inference for Markov and semi-Markov processes to be applied to larger more complex models and datasets than currently possible. This builds on SPASE work that significantly enhances state of the art Markov chain Monte Carlo (MCMC) and Particle (P)-MCMC techniques. Such tools enable disease and other mechanisms, difficult, costly or impractical to measure directly, to be quantified using noisy incomplete data and inform study design by assessing what and how much data are needed for accurate inference. Our innovations, *e.g.,* model-based proposal (MBP)-MCMC, can be applied to a large class of important problems; we will develop efficient algorithms for phylogenetic analysis, and to quantify genetic influences on disease spread combining epidemiological and genomic data.

Detailed work plan: Year 1: Develop novel Markov process inference techniques and apply to first exemplar data set (**O11.1**); *e.g.*, on bTB (RD2.3.3), IPN, AGD, JD (RD2.2.6), PRRS, invasive non-natives (RD1.3.3). Year 2: Develop novel MBP-MCMC/P-MCMC techniques; apply to second exemplar data set (**O11.2**). Produce prototype software tools (**O11.3**).

O12 Incorporating vaccines into best practice methods for controlling gastrointestinal nematode parasites of sheep. As the *Haemonchus* vaccine is pathogen-specific, it will need to be used with minimal anthelmintic in order to control non-targeted genera; *e.g.*, *Trichostrongylus*. Other factors that need to be considered for optimal efficiency include integration with grazing management strategies, minimising the number of vaccinations and timing them so that vaccine induced immunity coincides with the period of highest exposure. The performance of the vaccine will be monitored using worm egg counts from private farms. This will identify the best performing premises and when coupled with a detailed history of when and how often the vaccine was administered, the number and timing of drenches and whether grazing management was employed, the most efficient control strategy will be identified.

Detailed work plan: Year 1 & 2: Collect data on egg counts, vaccine, drench and grazing management history from 30 farms during January to April, the high risk season and analyse data (**O12.1**; **O12.2**).

Use of underpinning capacity: The work proposed here would not be possible without RESAS funding for underpinning capacity. Each Objective exploits animal disease models, pathogen reference strains and archived tissue and serum collections developed previously and maintained through capacity funding. This work is critically dependent on facilities for animal housing and pathogen containment and on the state-of-the-art infrastructure for genetic, transcriptomic, proteomic and bioinformatics analyses that is maintained through continued Underpinning Capacity support.

Statistical approaches, animal subject numbers and ethical considerations: *In vitro* and *in vivo* studies will be planned and data analysed in consultation with BioSS. Statistical models will be fitted as appropriate. Power calculations have been or will be performed to establish animal numbers for all experiments. In the first 2 years of the programme the number of animals required specifically for this RD is estimated to be 20 sheep (O1), 5 cattle (O3), 8 neonatal calves (O6), 24 neonatal lambs (O6), 12 lactating ewes (O7) and 260 chickens (O10). In addition, blood samples will be taken from sheep in the MRI flock for O2. Animal usage in years 3-5 cannot be predicted at this time but is likely to continue at a similar level. All animal experiments will be performed under the regulations of a UK Home Office Project Licence. Experimental design will be overseen and approved by SRUC or MRI's Experiments and Ethics Review Committees.

Key linkages, interdisciplinarity & collaboration: Research performed in all of the objectives will provide new knowledge that will guide ongoing and future development of new diagnostics (RD2.2.4) and vaccines (RD2.2.5) for livestock disease. In turn, these new tools will support future epidemiological studies (RD2.2.6). Selected examples are:

- Work planned in O4 is closely linked to the SG-funded surveillance scheme and industry-related partnership (Zoetis-Edinburgh Emerging Infectious Disease Activity (ZEIDA)). The MRP collaboration (MRI/SRUC) will enable access to a larger sample set to enable the field validation of the BHV-1-gE test in collaboration with SAC Consulting and industry partners. This will allow exchange of information and improve surveillance in real time, and will also enable research in vaccine breakdowns.
- Work on *Campylobacter* (O10) is the continuation of ongoing work funded via SPASE and is linked to a number of projects on gut health in chickens funded by Biosciences KTN, Zoetis and Aviagen. The outputs generated here will underpin and complement research in RDs 2.2.4, 2.2.5, and 3.1.3 (food safety).
- Work on optimising the expression and refolding of protective membrane components of *C. abortus* (O1) will be assessed for protective efficacy in RD2.2.5, allowing correlates of immunity to be defined. The research in both deliverables are linked and supported through an industrial collaboration with a UK-based vaccine company.
- The inference methods developed in O11 will be widely applied; *e.g.*, to invasive non-natives (RD1.3.3), wildlife disease systems (RD2.3.3), livestock epidemiology (RD2.3.3, RD2.2.6 and NEPIC) and plant disease (Centre of Expertise on Plant and Tree Health).

Added Scientific Value: Many of the contributors to this RD currently hold other

internationally-competitive research funding (*e.g.*, from BBSRC, EU, Defra) that supports research into the underlying pathology of the diseases studied here and that complements the work proposed here. For example, work on *T. circumcincta* vaccines (O8) will draw on parallel studies in RD2.2.5 as well as complementary studies funded (2015-18) by the BBSRC Animal Health Research Club (AHRC) to investigate age-dependent vaccine efficacy in sheep. Similarly, work on bovine cryptosporidiosis (O6) complements AHRC funding looking at resistance to *C. parvum* infection in cattle and work on OPA (O5) complements transcriptomic studies funded by BBSRC. Research on vaccines for sheep endo- and ectoparasites will complement projects currently funded by the EU (PARAGONE (Horizon 2020, 2015-19)) and BBSRC AHRC (2015-18).
KE, Audience: KE will be coordinated through the CKEI to target a broad range of audiences, including government (Scottish, UK and EU), industry groups (QMS, EBLEX, HCC), livestock producers (directly and through NFUS, NSA and breed associations) and the wider public. KE activities will be linked to other activities across WP2.2 and particularly to those of RD2.2.4, RD2.2.5 and RD2.2.6. These will include a range of broad interest events, such as Royal Highland Show (June 16, 17 (K2, K6)), Animal Health Roadshows (Oct 16, 17 (K3, K7) and Edinburgh International Science Festival (April 16, 17) (K1, K5), through to more focussed stakeholder and policy activities, farm meetings and specialist livestock events; *e.g.*, farm meetings are planned to discuss management of Cryptosporidiosis in neonatal calves (O6) (Nov 16, 17 (K4, K8) and to disseminate advice on best practice for nematode vaccine usage (K9, Nov 17). We will continue to engage with the public through websites, newssheets and press articles. **Impact:** The outputs of this work will be new information that will drive the next generation of vaccines and diagnostic tests for controlling livestock diseases. This will be directly relevant to several other RDs, in particular RD2.2.4, RD2.2.5 and RD2.2.6. The outputs will also guide strategies by government, policymakers and livestock producers to control animal disease. Improved animal health and welfare will result in more efficient livestock production, contributing to greater food security and safety.

RESEARCH DELIVERABLE NUMBER: RD2.2.3
Work planning and timetable for Year 1: Milestones (M), KE and impact events (K), reporting (R).

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 *C. abortus* recombinant protein production. Express and purify recombinant antigens.						**M2**						
O1.1 *C. abortus* recombinant protein production. Produce mutant cys-less MOMP construct.												**M16**
O1.2 *C. abortus* cellular immunity assays. Compare recombinant antigens with chlamydial EBs for ability to induce IFN-γ production by T cells.												**M17**
O1.3 Plasmid of Chlamydia species. Produce plasmid vector.												**M18**
O2.1 Assays for immune response to *C. abortus* vaccine. Develop methods for evaluating ovine IFN-γ and IL-4 expression at single-cell level.						**M3**						
O2.1 Assays for immune response to *C. abortus* vaccine. Compare cellular and humoral responses to generate a profile of vaccine-induced protective immunity.												**M19**
O3.1 Characterise growth of Map mutants *in vitro*. Optimise growth conditions for Map ArgG knockout mutant.						**M4**						

O3.1 Characterise growth of Map mutants *in vitro*. Confirm mutation by RT-PCR and sequence analyses.												**M20**
O3.2 Determine immune phenotype of Map mutants. Determine cytokine responses to ArgG mutant in MDMs using bioassays.						**M5**						
O3.2 Determine immune phenotype of Map mutants. Determine immune response to ArgG mutant in MDMs using gene expression assays.												**M21**
O4.1 Establish *ex vivo* bovine lung infection models. Optimise 3 combinations of in vitro system and pathogen infection.						**M6**						
O4.1 Establish *ex vivo* bovine lung infection models. Determine innate immune responses to 3 individual pathogens.												**M22**
O4.2 Addition of bovine coronavirus to multiplex PCR. Development and validation of uniplex PCR.						**M7**						
O4.2 Addition of bovine coronavirus to multiplex PCR. Multiplexing, validation and sensitivity testing.												**M23**
O5.1 JSRV replication in primary ovine cell cultures. Optimise JSRV infection protocols.						**M8**						
O5.1 JSRV replication in primary ovine cell cultures.												**M24**

Perform cytokine assays.												
O6.1 Animal infections with *Cryptosporidium.* Complete infection studies in neonatal calves.						**M9**						
O6.2 Cell culture studies with *Cryptosporidium.* Optimise infection protocol for HCT-8 cells.												**M25**
O7.1 Intra-mammary challenge with *M.haemolytica.* Selection of animals.			**M1**									
O7.1 Intra-mammary challenge with *M. haemolytica.* Intra-mammary challenge with M. haemolytica.						**M10**						
O8.1 Produce novel *T. circumcincta* recombinant proteins. Finalise expression constructs.						**M11**						
O8.1 Produce novel *T. circumcincta* recombinant proteins. Confirm protein expression.												**M26**
O9.1 Pathway analysis of ovine transcriptomic data. Collate transcriptomic data, perform QC analysis and normalise across study.						**M12**						
O9.1 Pathway analysis of ovine transcriptomic data. Perform statistical analysis and identify differentially expressed genes.												**M27**
O10.1 Role of innate immunity in resistance to *C. jejuni.* *In vitro*						**M13**						

studies in avian bone-marrow derived cells.												
O10.1 Role of innate immunity in resistance to *C. jejuni.* *In situ* studies in avian intestinal tissue explants.												**M28**
O10.2 Challenge infections with *C. jejuni* in broilers. Perform challenge experiment with resistant and susceptible birds.												**M29**
O10.2 Challenge infections with *C. jejuni* in broilers. Archive material and appraisal of transcriptomic and proteomic methodologies.												**M30**
O11.1 Novel applications of Markov process inference. Develop Markov process inference techniques.							**M15**					
O11.1 Novel applications of Markov process inference. Apply inference techniques exemplar data 1.												**M31**
O12.1 Evaluate *Haemonchus* vaccine - 1st trial. Collect data on egg counts, vaccine, drench etc.						**M14**						
O12.1 Evaluate *Haemonchus* vaccine - 1st trial. Complete data analysis.												**M32**
K1 Edinburgh International Science Festival April 2016	**K1**											
K2 Royal Highland show June 2016			**K2**									
K3 Animal health roadshow Oct-Nov 2016								**K3**				

K4 Farm meeting: Cryptosporidium management								K4				
R1 Year 1 Report to RESAS												R1

RESEARCH DELIVERABLE NUMBER: RD2.2.3
Work planning and timetable for Year 2: Milestones (M), KE and impact events (K), reporting (R).

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 *C. abortus* recombinant protein production. Express and purify recombinant cys-less MOMP.						M34						
O1.1 *C. abortus* recombinant protein production. Attempt renaturation of cys-less MOMP.												M52
O1.2 *C. abortus* recomb. protein cellular immunity. Determine the quality of recall responses to recombinant chlamydial antigens.						M35						
O1.3 Plasmid transformation of *Chlamydia* species. Optimise protocols for plasmid transformation.						M36						
O1.3 Plasmid transformation of *Chlamydia* species. Compare and evaluate transformation efficiency**.**												M53
O2.2 Effect of anthelmintics on *C. abortus* vaccine. Identify sheep with identical egg counts, treat and immunise.						M37						
O2.2 Effect of anthelmintics on *C. abortus* vaccine. Analyse immune responses in treated sheep and												M54

compare with data from O2.1(M19).												
O3.1 Characterise growth of Map mutants *in vitro*. Optimise growth conditions for Map ClpB knockout mutant.						**M38**						
O3.1 Characterise growth of Map mutants *in vitro*. Confirm mutation by RT-PCR and sequence analyses.												**M55**
O3.2 Determine immune phenotype of Map mutants. Determine cytokine responses to ClpB mutant in MDMs using bioassays.						**M39**						
O3.2 Determine immune phenotype of Map mutants. Determine immune response to ClpB mutant in MDMs using gene expression assays.												**M56**
O4.3 Validation/multiplexing of gE-deleted BHV-1 PCR. Sourcing and collection of clinical samples.						**M40**						
O4.3 Validation/multiplexing of gE-deleted BHV-1 PCR. Development of triplex gE deleted PCR.												**M57**
O4.4 Infection models and innate immunity in BRDC. One co-infection model optimized and innate immune responses determined.						**M41**						
O4.4 Infection models and innate immunity in BRDC. Second co-infection model												**M58**

optimized and innate immune responses determined.												
O5.2 Replication of JSRV in ovine lung slice culture. Optimise infection conditions for lung slices.						**M42**						
O5.2 Replication of JSRV in ovine lung slice culture. Complete cytokine assays.												**M59**
O6.2 Cell culture studies with *Cryptosporidium.* Evaluate bovine gut organoid cultures.									**M49**			
O7.2 Intra-mammary challenge with *S. aureus and S. uberis.* Animal selection.			**M33**									
O7.2 Intra-mammary challenge with *S. aureus and S. uberis.* Challenge with *S.aureus* and *S. uberis.*						**M43**						
O8.1 Produce novel *T. circumcincta* recombinant proteins. Proteins produced in scale for ELISA.						**M44**						
O8.2 Compare original and novel *T. circumcincta* vaccines. Assessment of serology underway.											**M51**	
O8.3 Local immune responses in vaccinated lambs. Characterise anti-parasite immune responses.												**M60**
O9.1 Pathway analysis of ovine transcriptomic data. Perform pathway analysis						**M45**						
O9.1 Pathway analysis of ovine transcriptomic data.												**M61**

Validate candidate genes and identify pathways												
O10.3 Transcriptome analysis of caecal mucosa of chickens that differ in their susceptibility to *Campylobacter*. Perform transcriptomic analysis.						M46						
O10.3 Transcriptome analysis of caecal mucosa of chickens that differ in their susceptibility to *Campylobacter.* Selection of candidates for validation.												M62
O10.4 Measure immune responses to *Campylobacter*. Quantify host immune responses.												M63
O11.2 Develop MBP-MCMC/P-MCMC techniques. Develop novel MBP-MCMC/P-MCMC methods.							M48					
O11.2 Develop MBP-MCMC/P-MCMC techniques. Apply inference techniques exemplar data 2.									M50			
O11.3 Produce prototype software tools*.* Produce prototype software tools.												M64
O12.2 Evaluate Haemonchus vaccine - 2nd trial*.* Collect data on egg counts, vaccine, drench etc.						M47						
O12.2 Evaluate Haemonchus vaccine - 2nd trial. Complete data analysis.												M65
K5 Edinburgh International Science Festival	K5											
K6 Royal Highland show			K6									

K7 Animal Health Roadshows								**K7**				
K8 Farm meeting: Cryptosporidiosis in calves Nov 17.								**K8**				
K9 Farm meeting: Disseminate best practice advice on vaccine usage.								**K9**				
R2 Year 2 Report to RESAS												**R2**

Name of RD: 2.2.4 Novel Diagnostic Tools
Research aim and key drivers The aim is to develop novel tools and approaches to improve diagnosis of the most economically important endemic diseases of livestock in Scotland and the UK. The key drivers of the research involve: (1) addressing issues with regard to accuracy and specificity of current disease diagnostics; (2) the development of novel diagnostic platforms; (3) horizon scanning for new and/or emerging infections; and (4) developing tools to detect resistance to drugs used in the control of parasitic worms. The information generated will be used to develop practical and affordable tools and tests that will be of commercial interest to the animal health industry and of direct benefit to farmers, veterinarians and other animal practitioners and stakeholders. Improvements in the detection and diagnosis of infection and disease will enable the implementation of appropriate control measures and management strategies to limit impact on animal health and welfare, reduce environmental contamination and risks for transmission to naïve animals. This will increase the productivity, efficiency and economic impact of livestock production that will in turn impact on the sustainability of the Scottish and UK livestock sector, as well as agricultural industries throughout the world. It will also be of direct benefit to the wider public through increased future food safety and security. The proposed research focuses on important endemic diseases of livestock that result from infection with bacteria, viruses and parasites, some of which can also cause infection in humans. The proposal has been developed following discussions with key stakeholder groups, such as Scottish Sheep Scab Industry Working Group, NFUS, NSA, SVS, QMS, EBLEX and sheep breed societies. Opinion has also been sought directly from farmers, veterinarians and producers through the Moredun Foundation, animal practitioner surveys and at agricultural events/shows in the UK. Priority areas have also been determined following interaction with Animal Health companies, some of which are involved in the proposed research. The work follows on from current Scottish Government (SG) funding in association with stakeholders in SPASE and EPIC and is matched to the expertise, skills-base and existing work programmes within the MRPs, maximising scientific success, value and impact. It also takes into account SG policy priority areas and is informed by Scottish Rural Development Programme 2014-20 pillar 2 priorities to enhance and support rural communities, businesses and economies, as well as protecting the environment and addressing the impact of climate change.
Summary of the proposal The research described here will address a number of overarching key deliverables leading to: (1) the development of new and more versatile technologies for the accurate diagnosis of infectious disease (O2) and interrogation of complex disease syndromes (O1, O2), which will help to determine the interaction between microbial populations and host response and effects of therapeutic intervention on population dynamics; (2) the monitoring and differentiation of endemic and emerging pathogens and strains in surveillance (O2, O3, O5) and eradication programmes (O3); (3) the identification of infections in vaccinated animals (O4) and of subclinical infections and infestations (O6, O8); and (4) the development of tools for detecting drug resistance to parasitic worms (O7). The work builds on current work programme funding on diagnostics (O3-O8), as well as from SPASE (O7) and EPIC (O3), as well as new areas of technological development (O1, O2). **Objective (O) 1. Development of computational and analytical metagenomic pipelines for analysing microbial populations in bovine respiratory disease**

(BRD). An open-source bioinformatic platform (e.g. 'Galaxy') will be implemented in a series of modules and workflows to enable the processing, storage and statistical analysis of complex metagenomic and metatranscriptomic data using high throughput sequencing technologies (Deliverable (D) 1). This technology will facilitate interrogation of microbial populations and host response in relation to different disease syndromes (such as respiratory, reproductive disease) or in disease vectors (midges, ticks, mosquitoes) and changes in populations under different conditions (stress, co-infections, vaccination, climate, drug treatment). Initial exploratory analyses will be conducted to define the lung microbiome of cattle with BRD, the single most common cause of death and poor performance in young cattle, estimated to cost £60M pa to the UK cattle industry. These initial studies will enable future investigations to determine the causes of suspected adverse reactions following vaccination against BRD and to interrogate other biological systems, with the potential identification of novel or emerging pathogens.

O2. Investigation of new technologies applied to diagnostic surveillance and emerging disease. New, faster and more versatile technologies are constantly being developed for the diagnosis of infectious diseases and/or syndromes. The aim is to evaluate these technologies for their applicability to current endemic disease diagnostics, as well as to horizon-scanning surveillance of emerging diseases. Such technologies include Luminex-based molecular multiplexing and loop-mediated isothermal amplification (LAMP). As part of the evaluation, an assessment of Luminex capabilities for serological and molecular applications will be conducted, including a review of associated costs (D2).

O3. Development of tools to analyse bovine viral diarrhoea (**BVD) virus (BVDV) variation and chains of infection.** BVD is an endemic disease with a significant impact on cattle production and health due to the abortifacient and immunosuppressive effects of infection. Maintenance in the UK herd is driven by persistently infected (PI) animals that tolerate infection and shed virus continuously. Scotland has a BVD eradication programme based on the identification, restriction of sale and movement of PI cattle. However, illegal and cross-border movement of PI cattle and potential spread from wildlife may impact Scotland's ability to become and remain BVD-free. MRI performs sequence-based genotyping of BVD in serum samples within EPIC. In this programme we will develop enhanced high throughput genotyping methods for BVDV strain analysis (D3) to support detailed epidemiological surveillance and the identification of sources of disease in collaboration with colleagues in EPIC and to support the Scottish BVDV eradication campaign.

O4. Genome analyses of *Mycobacterium avium* subsp. *paratuberculosis* (*Map*) strains to identify antigens for DIVA diagnostics and vaccines. Commercial Johne's vaccines are based on killed attenuated *Map* strain 316F. Although the vaccines reduce clinical disease and shedding, they do not prevent infection so a vaccinated animal can still be a source of infection. Current diagnostic tests cannot differentiate infected from vaccinated animals (DIVA). Genomes of 150 *Map* strains, including 4 vaccine strains, have been sequenced in collaboration with the Sanger Institute, which, together with publicly available *Map* sequences, provides a powerful resource to define differences between attenuated vaccine strains and *Map* field strains. A comparison of these genome sequences will be made to identify genes in field strains that are absent or highly divergent in vaccine strains, which could be exploited in a DIVA diagnostic test (D4). We will also attempt to determine the genetic basis for attenuation, which will offer rational approaches towards targeted attenuation strategies and potential for optimising vaccine efficacy.

O5. Specific tools for the diagnosis of protozoan infection/abortions in ruminants. Although abortion is a major problem for livestock operations and welfare worldwide, the identification of a specific cause is difficult and only achievable in <50% of cases, even in well-established diagnostic laboratories. Of this percentage, most losses are due to infectious reproductive diseases. Bovine neosporosis is a recently diagnosed disease, which is recognised as a major cause of abortion and neonatal loss in cattle worldwide, resulting in significant economic losses to the dairy and beef industries. The causative agent, *Neospora caninum* is an intracellular, cyst-forming, coccidian protozoal parasite in the family Sarcocystidae (Phylum Apicomplexa), which also includes *Toxoplasma gondii* (major cause of abortion in sheep) and *Sarcocystis* spp. Current antisera that are used in immunohistochemistry to distinguish/identify *Neospora*, *Toxoplasma* and *Sarcocystis* as possible causes of ruminant abortion may cross-react, making species identification difficult or impossible. Therefore, in this programme species-specific serological and molecular diagnostic tools will be developed based on recombinant antigens and genes to distinguish between *Neospora*, *Toxoplasma* and *Sarcocystis* (D5).

O6. Novel diagnostic tests for ovine pulmonary adenocarcinoma (OPA). OPA is an important respiratory disease of sheep caused by jaagsiekte sheep retrovirus (JSRV). The disease is of increasing concern to Scottish and UK farmers as there is no vaccine and no reliable ante-mortem diagnostic test to detect infection in live sheep during the long subclinical phase of infection. Recent progress on detecting neutralising antibodies in OPA-affected sheep will be extended (D6) towards developing a test that can identify JSRV infection before the onset of clinical disease. Research will continue on the identification of tumour biomarkers for their potential as diagnostic markers in OPA, which links to a current BBSRC-funded project (BB/L009129/1) providing comprehensive RNA-Seq and microRNA-Seq data. These analyses will identify lead diagnostic targets/assays for subclinical JSRV infection that will be evaluated further using prospective samples collected during the programme and which will assist in flock management strategies to decrease the risk of future infections. Another approach for diagnosing subclinical OPA involves the use of trans-thoracic ultrasound scanning, which will also be assessed on-farm.

O7. Phenotypic and genotypic tools for investigating the development and dissemination of anthelmintic resistance in gastro-intestinal nematodes (GINs). GINs are a major global constraint on efficient livestock production. Three of the five available classes of anthelmintics for controlling GINs in sheep have major resistance issues. Two new compounds have been recently brought to the market, namely Zolvix® (MPTL, monepantel) and Startect® (derquantel+abamectin). Thus, it is imperative to have the capability to detect changes in parasite population sensitivities to these compounds as early as possible. Understanding how anthelmintic resistance develops and how parasites evolve in the face of anthelmintic selection is key to developing strategies to preserve their efficacy. Sensitive detection will enable early detection of resistance, enable the monitoring of prevalence and spread of resistance, allow assessment of the impact of traditional (whole flock/herd) and newer (targeted) treatment strategies on resistance development and dissemination. This objective links directly to inform improvements in livestock as outlined in RD2.3.1. The proposed research will develop molecular tools (D7) and investigate mechanisms and markers of anthelmintic resistance with particular reference to MPTL and Startect® (D8) using phenotypic and genotypic approaches.

O8. Further development of diagnostic tools for the diagnosis and control of sheep scab. Infestation with sheep scab mite *Psoroptes ovis*, represents a major animal welfare concern and significant economic burden on sheep and cattle industries worldwide. Diagnosis is achieved through observation of clinical signs e.g. itching, pruritus, wool loss and ultimately through the detection of mites in skin scrapings. However, early stages of infestation are difficult to diagnose and sub-clinical animals represent a major risk factor in disease spread. The research proposed will develop (D9) and evaluate a paper-based 3D microfluidic point-of care (PoC) device incorporating previously identified and validated antigens Pso o 2 (detects subclinical disease) and Pso-EIP-1 (produced in plant cells for optimal yields and has utility in a DIVA test (D10)), as well as selected biomarkers that differentiate current from recently resolved infestations. This PoC test will allow serological distinction between vaccinated and *P. ovis* infested animals and permit early detection of disease; thus reducing risks of developing clinical disease and limiting spread.

Technical approach and detailed work plans

O1. Development of computational and analytical metagenomic pipelines for analysing microbial populations in bovine respiratory disease (BRD). BRD is defined as a disease complex as it is usually caused by multiple pathogens (viral and bacterial), that interact to produce disease. Due to the complicated multi-pathogen nature of BRD, both the viral and bacterial populations of the upper and lower bovine respiratory tract will be defined using both metagenomic (DNA-seq) and metatranscriptomic (RNA-seq) approaches, allowing identification of both DNA and RNA viruses in addition to bacteria. Nasal pharyngeal (NP) swabs and bronchoalveolar lavage (BAL) samples will be obtained from 4 month old calves (n=10) obtained from different commercially run farms. DNA and RNA samples will be isolated and prepared for next-generation paired-end shotgun sequencing. Consistent data processing, storage and statistical methods will be implemented using an open-source bioinformatic platform in a series of modules and workflows that will provide a user friendly resource for this project and the wider community. Utilising archived samples from the MRI Virus Surveillance Unit (VSU), we will investigate the diversity of bacteria and viruses within the diseased bovine lung. The BAL and NP swab samples have been obtained from cattle with suspected BRD obtained through routine surveillance and pharmacovigilence programs. We will prepare DNA and RNA from NP swabs and BAL samples obtained from cases of BRD for analysis by DNA-seq and RNA-seq. The established analytical pipelines and sequence depth will be used to analyse the microbiomes of BRD cases and the effect of disease on the healthy lung microbiome. To quantitatively assess the presence of specific pathogens associated with BRD, specific identified targets will be analysed by qPCR and RT-qPCR.

Detailed work plan

Year 1+: O1.1 Establish analytical bioinformatic pipelines (D1) for analysing high-throughput sequencing data. Year 2+: O1.2 Sampling of the upper and lower respiratory tracts of 4 month old calves for DNA and RNA; O1.3 Conduct metagenomic and metatranscriptomic analysis to define the microbiome of the normal bovine respiratory tract of healthy calves; O1.4 Conduct metagenomic and metatranscriptomic analysis to define the microbiome of calves with BRD. Future sub-objectives include a comparative and quantitative assessment of the specific pathogens associated with BRD.

O2. Investigation of new technologies applied to diagnostic surveillance and emerging disease. The proposed work within the MRI VSU will compare novel diagnostic techniques (eg Luminex-based molecular multiplexing, isothermal amplification) with those that are currently employed in routine diagnostics (mainly classical serology and real-time PCR). Depending on the outcome of these evaluations, new tests will replace older techniques with faster, less expensive and more versatile assays. The diagnostic service provided by the VSU is underpinned by specialist knowledge that could be quickly exploited in the event of an outbreak of a novel disease.

Detailed work plan

Year 1+: O2.1 Conduct an assessment of Luminex capabilities for serological and molecular applications and conduct cost review (D2); O2.2 Diagnostic test comparison of current multiplex PCR with the Luminex system. Future sub-objectives include a validation study with field and reference samples; development and validation of an isothermal amplification system (or alternative emerging rapid technologies) using multiplex respiratory PCR as test case; comparison of isothermal amplification system (or alternative emerging rapid technologies) with classical multiplex PCR and/or Luminex diagnostics.

O3. Development of tools to analyse bovine viral diarrhoea (BVD) virus (BVDV) variation and chains of infection. The proposed research will develop high throughput genotyping methods for additional BVDV genes (Npro and E2), use sequence data from one or both of these loci in the phylodynamic analysis of BVDV infection and evaluate the potential of PCR methods to generate complete BVD genome sequence data from small samples. Virus sequence and phylogeny data will be translated into high quality policy-relevant advice for the BVD eradication team and high impact publications in collaboration with colleagues in EPIC.

Detailed work plan

Year 1+: O3.1 Test high throughput methods (D3) for PCR and sequencing of additional BVDV genes; O3.2 Develop strategy for amplification of BVDV genome from serum samples and test using sequenced BVDV isolate. Year 2+: O3.3 Use data from A7 for phylodynamic analysis to define potential chains of infection linking samples from different UK locations.

O4. Genome analyses of *Mycobacterium avium* subsp. *paratuberculosis* (*Map*) strains to identify antigens for DIVA diagnostics and vaccines. The existing in-house genome sequence dataset includes representatives of current Map vaccine strains plus a substantial global panel of field isolates from different mammalian host species. The complete genomes of vaccine strains will be aligned with a representative subset of field isolates using a range of genome comparison tools. Initial analyses will focus on defining genes that are absent in vaccine strains but present in field strains and vice versa. Since Mycobacterium species are highly clonal, inter-strain differences may take the form of divergent genes and/or genomic regions and searches will account for these potential polymorphisms. Detailed comparison will also be made of candidates identified through preceding work. The shortlisted candidates will form the basis for a decision to proceed to the next phase of analysis. To date, characterization of protein antigens/immunogens of mycobacteria has been limited. The candidate list identified above will be further examined in detail using recently-developed bioinformatics tools for prediction of potential B-cell and T-cell epitopes as potential targets for antibody and cell-mediated immune responses. This approach has been very successfully used by others for identifying exploitable proteins of several other bacterial species. This epitope selection process will further reduce the candidate panel to potentially useful target proteins and will be a further decision point for progression into validation as serodiagnostic tools via generation of recombinant proteins and screening of retrospective serum samples from animals of known Johne's disease status.

Detailed work plan

Year 1: O4.1 Identification of Map genes that could be exploited for a DIVA diagnostic for current Johne's vaccines. Year 2: O4.2 In silico prediction of immunogenicity of the encoded Map proteins (D4) for validation as DIVA diagnostic candidates.

O5. Specific tools for the diagnosis of protozoan infection/abortions in ruminants. This objective will produce *recombinant* proteins for the generation of genus specific antisera that can be utilised in IHC to aid diagnosis of *N. caninum*, *T. gondii* and *Sarcocystis* spp in ruminant abortion cases. It will also lead to the development of a species-specific PCR that can detect and distinguish common protozoan abortifacients of ruminants.

Detailed work plan

Year 1+: O5.1 Identification of genus specific antigens and genes (D5) to distinguish between cases of *Neospora*, *Toxoplasma* and *Sarcocystis*; O5.2 Expression and purification of recombinant antigens for generating antisera specific to *Neospora*, *Toxoplasma* and *Sarcocystis. Year 2+: O5.3* Raise antisera against the genus specific recombinant antigens produced for *Toxoplasma*, *Neospora* or *Sarcocystis*. Future sub-objectives include the validation of the specificities of the sera for each of pathogens and development of species-specific PCRs.

O6. Novel diagnostic tests for ovine pulmonary adenocarcinoma (OPA). The optimised OPA neutralisation assay will be used to test archived sera from Scottish farms that were previously tested for JSRV by PCR. Data will be analysed with reference to the results of PCR testing for these farms (already completed) and the history of OPA within those flocks. ELISAs, RT-qPCR and immunoblotting approaches will be used to test sera and nasal swabs from OPA-affected sheep and negative controls for the presence of selected candidate tumour markers. The specific markers to be tested will be shortlisted from the list of ovine genes that are upregulated in OPA (some already known, others arising from ongoing studies funded through BBSRC grant BB/L009129/1). Up to 10 markers (protein or microRNA) will be studied in total. Trans-thoracic ultrasound scanning will be used to scan sheep on farms with an on-going problem with OPA to select for cull those sheep with detectable disease. Studies will investigate whether such an approach is helpful in reducing disease incidence and the efficacy of this method for screening bought-in animals for OPA.

Detailed work plan

Year 1+: O6.1 Evaluation of neutralising antibodies (D6) to JSRV in OPA-affected and non-affected sheep; O6.2 Evaluation of OPA tumour biomarkers in archived sera; O6.3 Evaluation of trans-thoracic ultrasound scanning on farms. Future sub-objectives include trial of evaluated diagnostic tests in field conditions on Scottish farms.

O7. Phenotypic and genotypic tools for investigating the development and dissemination of anthelmintic resistance in gastro-intestinal (GI) nematodes. Rapid detection and species identification of GI nematodes in livestock is a pre-requisite for proposed resistance work and epidemiological applications in the field. DNA based methods such as multiple tandem parallelplex PCR (MT-PCR), LAMP and meta-barcoding or similar technologies offer significant potential for high-throughput and/or pen-side diagnosis of GI nematodes. In pilot studies, LAMP has proven highly sensitive, specific and robust for detection of GI nematode DNA derived from faecal samples. As well as detection of GI nematodes in host animals, the proposed research aims to further develop these testing platforms for the detection of the larval stages of these parasites in the environment e.g. species profiling of pasture larval counts. This will allow us to investigate, for example, the role of *refugia* in the development of anthelmintic resistance and aspects of the epidemiology of GI nematodes in relation to on-farm risk analysis and the role of wildlife reservoirs [links to RD2.2.6 and RD2.3.1].

The proposed resistance work will focus on the new actives, MPTL and derquantel. Genotypic characterisation of MPTL action on *Haemonchus contortus* has shown that the compound targets the DEG-3 family of acetylcholine receptors, which carry key mutations in laboratory-selected resistant lines. It is not known whether this same mechanism of resistance is found in other parasitic species or in resistant populations selected in the host animal. Three MPTL-resistant *Teladorsagia circumcincta* isolates have been selected during the current work programme. We will continue the fruitful collaboration with HEI GUVS (University of Glasgow Vet School) (**HEI bid 5**) to (a) determine whether mutations in *T. circumcincta deg-3* receptors underlie the resistance phenotype in this parasite, as in *H. contortus*; (b) determine whether other genetic changes contribute to resistance; (c) develop genetic markers for early diagnosis of MPTL resistance; (d) determine whether the genetic basis of the fitness benefit apparent in MPTL-resistant worms can be elucidated. With derquantel much less work has been conducted to date. Its mode of action is believed to involve different acetylcholine receptors but its mechanism of resistance is not understood. We will generate the biological resources required to investigate both phenotypic and genotypic changes associated with resistance selection in the natural host.

Detailed work plan

Year 1+: O7.1 Assess analytical sensitivity and specificity of MT-PCR and real-time LAMP platforms for detection of GI nematodes and define suitable primers for metabarcoding; O7.2 Examine MPTL resistant isolates for presence or absence of mutations within MPTL-1 gene; O7.3 Selection of Startect® resistant *T. circumcincta* isolate(s); O7.4 Evaluate and compare (D7) MT-PCR and real-time LAMP methodologies for use on nematode field material. Year 2+: O7.5 Optimise in vitro bioassay (D8) for detection of MPTL and/or Startect® resistance; O7.6 Investigate role of non-specific mechanisms of resistance, using optimised in vitro bioassay for detection of MPTL.

O8. Further development of diagnostic tools for the diagnosis and control of sheep scab. This objective will further develop novel diagnostic tools for the pen-side diagnosis of sheep scab and differentiate between infested and vaccinated animals.

Detailed work plan

Year 1+: O8.1 A paper-based 3D microfluidic device (D9) incorporating the existing (ELISA-based) individual assays (Pso o 2 and selected BMs) will be developed into a single multiplexed PoC platform; O8.2 Individual assays will be incorporated into the multiplexed format and the platform validated with serum from animals with known and varying degrees of pathology; O8.3 An additional novel diagnostic antigen, Pso-EIP-1, which is difficult to produce in conventional systems, will be fused to functional tags such as GST (to improve stability and isolation) and expressed in plant systems to obtain the highest yields necessary for future testing as a diagnostic component.

Year 2+: O8.4 PoC tests suffer from reduced sensitivity compared to equivalent lab-based tests. To further enhance the performance of the PoC assay we will array Pso-EIP-1 onto the surface of nanocarriers, for improved stability, functional orientation and reactivity. Tags on Pso-EIP-1 will permit oriented capture of Pso-EIP-1 onto the surface of tag-antibody functionalized nanocarriers (such as poly(D, L-lactide-co-glycolide), or non-infectious virus-like particles (VLPs) or gold nanospheres); leading to effective surface display of the Pso-EIP-1. As an alternative approach Pso-EIP-1 will be directly linked to VLPs or nanoparticles using covalent linker chemistries. The most effective display strategy will be identified using ELISA (D10). The optimal surface display approach identified in this activity may also be of use to later stages of RD2.2.5; O8.5 A Pre-filtering step will be introduced for the removal of erythrocytes from whole blood based on inert separation to allow the use of whole blood at PoC. Future sub-objectives include incorporating the arrayed Pso-EIP-1 particles into the paper-based PoC platform and further validation and optimisation of Pso-EIP-1 within the novel PoC platform using existing sample archives. If successful with Pso-EIP-1, the arraying techniques used may be applied to Pso o 2 for further optimisation.

Use of underpinning capacity: Each aspect of the work conducted within this RD will be dependent on protein and genomic databases, pathogen and strain collections, archived tissue and serum collections and knowledge generated under the current work package. It will be dependent on utilising the proteomic facilities, animal housing, pathogen containment and isolation, and cell culture facilities at MRI and plant production facilities at Hutton, supported through Underpinning Capacity. The analysis of large and complex high-throughput metagenomics and metatranscriptomic sequencing datasets and proteomic data is dependent on the use of high power servers and associated fast access storage to handle the intense processing demands as well as network attached storage devices for storing and protecting archived data.

Statistical approaches, animal subject numbers and ethical considerations: Statistical support will be provided for all analyses and the design of animal experiments through consultancy with Biomathematics and Statistics Scotland (BioSS). BioSS delivers statistical and mathematical modelling consultancy to various organisations, including all of the SG MRPs and aims to improve the usefulness of statistical methods through the development of novel methodologies in the context of specific scientific applications. Statistical models (e.g. mixed model and repeated measures analyses) will be fitted to data as appropriate. Power calculations have been performed to establish animal numbers for proposed animal experiments (10 calves will be required in O1), based on replicate numbers from previous studies. Animal experiments will be performed under the regulations of a UK Home Office Project Licence; experimental and statistical design will be subject to approval by MRI's Experiments and Ethics Committee.

Expertise: The scientists involved have internationally-recognised track records in their various fields of expertise for high quality research on: animal (MRI) and plant (Hutton) disease and control of infection, including development of novel diagnostics and vaccines; animal disease surveillance (MRI); management of drug resistance in nematodes (MRI); and the application of statistical and mathematical modelling to biological science (BioSS). All groups have existing collaborative links with MRPs, HEIs (including Edinburgh, Glasgow and Heriot-Watt Universities) and industry. These collaborations bring together complementary skills, expert knowledge and capability in a wide range of disciplines, including bacteriology, microbiology, virology, parasitology, molecular biology, immunology, pathology, proteomics, genomics, bioinformatics and statistical analyses, enabling the commercial development of novel tools for diagnosing endemic diseases of high importance to the Scottish economy and livestock sectors worldwide.

Key linkages, interdisciplinarity & collaboration

Research performed within this deliverable links directly with outcomes on disease mechanisms (RD2.2.3), and will impact and guide future objectives towards vaccine development (RD2.2.5) that will in combination be key to improving the management, diagnosis and control of livestock disease and lead to commercial development opportunities. These new tools will also support future epidemiological studies (RD2.2.6). To monitor progress and maximise KE outputs, collaborations/linkages will be managed through regular project-specific meetings, progress reviews and a review workshop in year 3 of the programme. Five key linkages:

1. Work on the development of computational and analytical pipelines for analysing complex high throughput sequencing datasets (O1) will draw on samples obtained from naturally and experimentally-induced BRD in RD2.2.3 and collaborative links with researchers in School of Informatics, University of Edinburgh where overlapping novel computational and statistical methodology development provides the potential for joint funding applications to both Innovate UK and BBSRC Tools & Resources funds. 2. The outputs for the work on development of BVDV genotyping tools (O3) will allow chains of infection to be traced, linking with NEPIC colleagues at the University of Glasgow (animal movements) and University of Edinburgh (phylodynamics). This work benefits from collaborative links with the diagnostic laboratories of SAC Consulting and Biobest (part of Westpoint Veterinary Group). 3. The work on OPA (O6) links to BBSRC-funded transcriptomic studies that will identify targets for the development of novel diagnostics and provide gene expression data for OPA tumour cells, supporting studies on disease mechanisms (RD2.2.3). The work also links to RD2.2.6 to study the epidemiology of respiratory disease through application of developed diagnostic assays and exploiting data and samples collected in a previous RESAS flexible fund project. 4. The work on anthelmintic resistance in GI nematodes (O7) builds on current work in SPASE and work being planned by GUVS, MRI and others as part of a BBSRC's LoLa (BB/M003949/1)-funded project investigating mechanisms and markers of anthelmintic resistance. The molecular tools developed as part of this objective will be used to analyse nematode species composition and anthelmintic resistance status from field trials, thus informing animal disease epidemiology (RD2.2.6) and improvement of livestock (RD2.3.1). 5. The development of a PoC diagnostic platform for sheep scab (O8) represents a highly interdisciplinary project, which involves close collaboration between MRI & Hutton. Research outputs will feed directly into RD2.2.5, informing on the use of surface display technologies for improved delivery of novel vaccines, while the plant-based expression of diagnostic antigens will exploit the findings of RD 2.1.3 which will use novel approaches to drive the expression of foreign proteins from virus vectors.
Added Scientific Value Scientists involved in this research deliverable currently hold internationally-competitive research grants that complement and provide added value to the work proposed here. The application of additional respiratory diagnostics to surveillance samples (O1 & O2) will deliver a broader understanding of the Scottish situation for BRD prevalence and foster closer collaboration within MRPs (MRI and SRUC). The use of multiplex diagnostics (O2) will also promote a better understanding of the spread of multiple diseases in relation to climate change. The BBSRC-funded (BB/L009129/1; 2014-17) OPA transcriptomic project, in collaboration with Edinburgh Genomics (University of Edinburgh) will identify targets for the development of the novel diagnostics (O6). The BBSRC sLoLa (BB/M003949/1) will provide *H. contortus* genomic resources to develop novel interventions to control endemic GI parasites (O7). The development of sheep scab penside and DIVA diagnostics (O8) and work to develop a sheep scab vaccine (DEFRA; 2013-16) are important elements of an integrated control strategy.
KE, <u>Audience:</u> KE will be coordinated within the RD, across the WP and through the theme which will liaise with and contribute to the Centre for Knowledge Exchange and Impact (CKEI) to help target a broad range of audiences, including farmers, veterinarians, livestock producers, agricultural/levy bodies, government, policy and regional advisors, charities, public (e.g. schools, Science Festival), Pharma, SMEs and scientists. These will be targeted through: (1) open access peer-reviewed publications

and conference presentations; (2) ad-hoc events, such as meetings, workshops and press events; and (3) industry-focussed publications, such as policy briefs, fact/news sheets, farming press, MRP websites, the Moredun magazine (12,000 Moredun Foundation members) and press releases. Scientists will directly interact with industry stakeholders through annual regional agricultural shows (May & August; K1, K5), annual Royal Highland Show (June; K2, K6), annual Moredun roadshows (November; K3, K7) and annual Moredun Press Day (December; K4) [KE deliverables are mapped on the GANTT charts]. A stakeholder workshop on progress and outputs will be organised in year 3 of the programme. Outputs will be disseminated through publication in relevant peer-reviewed journals, and by participation at national and international conferences and workshops. The research will inform Scottish Government policy within the context of the priority and focus areas of the SRDP as well as the existing “Modernising Scottish Agriculture” and “Farming for a Better Climate” agendas. Policy relevant outputs will also be generated within the context of the SG Animal Health and Welfare in the Livestock Industry Strategy 2015-2020.

Impact: The development of novel diagnostic tests and platforms will inform SG policy on disease control and have a significant impact on food safety and security, as well as on the national economy through improving livestock health and welfare, productivity and reducing environmental contamination and risks to human health. Meta-genomic profiling is rapidly being adopted in assays of biodiversity in the environment and to monitor effectiveness of land-management practices by monitoring changes in biodiversity using sequencing methods. As such the computational and statistical components of this should have more widely applicable benefits both to research in this area in Scotland and the wider community. These benefits will lead to increased global competitiveness and sustainability for the Scottish food industry. Scottish, and international, industry will benefit from exploitation of IP arising from the delivered research outputs, in the form of commercial diagnostic technologies and tests. Impact will be delivered through engagement with Policy, Public and Industry stakeholders throughout the 5 year programme with timelines as described above under Audience.

RESEARCH DELIVERABLE NUMBER: 2.2.4

Work planning and timetable for Year 1: Key sub-objectives (O), milestones (M), deliverables (D), KE & Impact Events (K)

Year 1: 2016/17	**Period 1 (Apr-Jul)**				**Period 2 (Aug-Nov)**				**Period 3 (Dec-Mar)**			
O1 Develop metagenomics pipelines for investigating microbial populations associated with BRD												
O1.1 Analysis of high-throughput sequencing data												
M1 Requirements analysis & testing completed						M1						
M2 Data infrastructure implemented & populated on server												M2
O2 New technologies for diagnostic surveillance and emerging disease												
O2.1 Assessment & cost review of Luminex technology			K2									D2
M3 Report on technology suitability and cost review						M3						
O2.2 Comparison of multiplex PCR with the Luminex system												
M4 Develop initial assay design with vendor												M4
O3 Tools for analysing BDVD variation and infection												
O3.1 Methods for PCR and sequencing of BVDV genes												K4
M5 Design novel primer sets for BVDV Npro and E2 genes						M5						
M6 Validate Npro, E2 primer sets with selected samples												M6
O3.2 Amplification of BVDV genome from serum samples												
O4 Identify *Map* antigens for DIVA diagnostics & vaccines												
O4.1 *Identification of Map genes for DIVA diagnostic*			K2					K3				
M7 Identify bioinformatics tools and select optimal pipelines for comparative sequence analysis						M7						
M8 Identify sequence differences between field isolates and vaccine strains												M8
O5 Tools for diagnosing protozoan infection in ruminants												
O5.1 Identify antigens to distinguish Neo, Toxo & Sarcocystis								K3	D5			
M9 Literature and database search for suitable antigens						M9						
O5.2 Express recombinant antigens specific for Neo, Toxo & Sarcocystis			K2					K3				

O6 Novel diagnostic tests for OPA												
O6.1 Evaluation of neutralising antibodies to JSRV			K2									D6
M10 Test archived sera from 15 farms						M10						
O6.2 Evaluation of OPA tumour biomarkers in archived sera												
M11 RT-qPCR for serum miRNAs (up to 5)						M11						
M12 Assess 1-2 serum protein biomarkers												M12
O6.3 Evaluation of trans-thoracic ultrasound scanning on farms												
M13 Complete scanning and necropsies from 3 farms						M13						
M14 Complete scanning and necropsies from 3 additional farms												M14
O7 Tools for investigating anthelmintic resistance in nematodes												
O7.1 Assess MT-PCR and real-time LAMP platforms and define primers for metabarcoding			K2					K3				
M15 Screen samples of known GIN species composition						M15						
O7.2 Examine MPTL resistant isolates for MPTL-1 gene SNP			K2					K3				
M16 Sequence comparison of parental and resistant isolates									M16			
O7.3 Selection of Startect® resistant *T. circumcincta* isolate(s)		K1			K1							
M17 Report Startect® dose that selected population survives						M17						
O7.4 Evaluate MT-PCR and real-time LAMP on field material		K1			K1							K4
O8 Tools for diagnosis and control of sheep scab												
O8.1 Develop paper-based 3D microfluidic multiplex									D9			
M18 Demonstration of 3D paper microfluidic capability						M18						
O8.2 *Validate multiplexed platform with standardised sera*			K2									
O8.3 Express Pso-EIP-1 using a plant expression platform												
M19 Codon optimized clones of Pso-EIP-1 produced						M19						
M20 Pso-EIP-1 expressed in plants												M20
R1 Year 1 Report to RESAS												R1

RESEARCH DELIVERABLE NUMBER: 2.2.4

Work planning and timetable for Year 2: Key sub-objectives (O), milestones (M), deliverables (D), KE & Impact Events (K)

Year 2: 2017/18	**Period 1 (Apr-Jul)**				**Period 2 (Aug-Nov)**				**Period 3 (Dec-Mar)**			
O1 Develop metagenomic pipelines for investigating microbial populations associated with BRD												
O1.1 Analysis of high-throughput sequencing data												D1
M21 Core analytical modules implemented on server						M21						
O1.2 Respiratory tract sampling of calves for DNA & RNA			K6									
M22 Source and obtain calves for sampling										M22		
O1.3 Define microbiome of healthy bovine respiratory tract			K6					K7				
M23 Process samples for DNA and RNA												M23
O1.4 Define microbiome of calves with BRD								K7				
M24 Process samples for DNA and RNA												M24
O2 New technologies for diagnostic surveillance and emerging disease												
O2.2 Comparison of mPCR with the Luminex system			K6									
M25 Development of at least 1 molecular assay						M25						
M26 Sensivity/specificity comparison with mPCR												M26
O3 Tools for analysing BDVD variation and infection												
O3.1 Methods for PCR and sequencing of BVDV genes				D3								
O3.2 Amplification of BVDV genome from serum samples			K6									
M27 Design overlapping primer sets for BVDV genome			M27									
M28 Validate primer sets by sequencing two genomes									M28			
O3.3 Phylogenetic/phylodynamic analysis of BVDV infection												
M29 Test primer sets for direct amplification from serum									M2			

									9			
O4 Identify *Map* antigens for DIVA diagnostics & vaccines												
O4.2 *In silico prediction of antigens for DIVA diagnostics*			K6									D4
M30 Assess tools for the identification of MAP antigens						M3 0						
O5 Tools for diagnosing protozoan infection in ruminants												
O5.2 Express recombinant Ags for Neo, Toxo & Sarco			K6									
M31 Generation of expression clones			M3 1									
M32 Test expression of expression clones									M3 2			
O5.3 Generate antisera to Neo, Toxo & Sarco antigens												
O6 Novel diagnostic tests for OPA												
O6.2 Evaluation of tumour biomarkers in archived sera								K7				
M33 RT-qPCR further serum miRNAs (up to 5)						M3 3						
M34 Assess 1-3 further serum protein biomarkers												M34
O6.3 Evaluation of trans-thoracic ultrasound scanning			K6									
M35 Re-scan 3 flocks from yr 1						M3 5						
M36 Re-scan additional 3 flocks from yr 1												M36
O7 Tools for investigating anthelmintic resistance in nematodes												
O7.4 Evaluate MT-PCR and real-time LAMP		K5			K5			K7	D7			
M37 Applicability to field-derived GIN eggs/larvae tested			M3 7									
O7.5 Optimise bioassay for detecting MPTL/Startect resistance		K5			K5							D8
M38 Suitability of bioassays determined						M3 8						

O7.6 Investigate role of non-specific mechanisms of resistance								K7				
M39 Optimised bioassay used with xenobiotic pumps											M39	
O8 Tools for diagnosis and control of sheep scab												
O8.2 Validate multiplexed platform with standardised sera			K6									
M40 Identify and collate sera sets for validation			M40									
O8.4 Optimise Pso-EIP-1 surface display on nanocarriers												D10
M41 Methods for linkage of Pso-EIP-1 to nanoparticles developed						M41						
O8.5 Introduce pre-filtering step for using whole blood												
R2 Year 2 Report to RESAS												R2

Name of RD: 2.2.5 Novel Vaccines
Research aim and key drivers The aim of this RD is to develop highly effective, optimised, safe, novel vaccines for the control of the most production- and welfare-limiting endemic diseases of Scottish livestock. The key drivers for this research are: • The limitations of the current chemotherapeutics, such as reduced efficacy (anthelmintic and antibiotic resistance) and the effects of residues on environmental, operator and food safety; • The potential for vaccines to overcome these limitations and to provide increased productivity and efficiency in livestock production with the economic, food security and environmental benefits which accrue from that. In the development of this research proposal, we have taken into account the views of key stakeholders; e.g. Scottish Sheep Scab Industry Group (includes NFUS; Sheep Veterinary Society; National Sheep Association; Convention of Scottish Local Authorities; SEPA; AHVLA; BVA; SSPCA; National Office of Animal Health; Institute of Appraisers and Auctioneers; QMS and the Scottish Organic Producers Association). We have sought opinion directly from farmers and producers from within the Moredun Foundation and from SRUC-published data on disease prioritisation in Scottish livestock. Scottish Government policy priority areas have also informed this proposal, specifically through the Pillar 2 key priority areas identified in the Scottish Rural Development Programme (SRDP) 2014-2020 (innovation in agriculture, animal welfare and risk management in agriculture, resilient economy in agriculture, food and forestry sectors). Importantly, we have sought the opinions of multiple Animal Health companies involved in vaccine manufacture.
Summary of the proposal: This RD is committed to the development of vaccines, their optimisation and their application to control diseases which have been identified by livestock keepers as amongst the most important endemic diseases affecting Scottish livestock production and welfare. The objectives are therefore to further develop vaccines to control the major endemic endo- and ectoparasites of sheep (*Teladorsagia circumcincta*, *Psoroptes ovis* and *Fasciola hepatica*) and cattle (*Ostertagia ostertagi*) and to further develop vaccines to control major bacterial diseases affecting production in lambs (*Mannheimia haemolytica* and *Chlamydia abortus*) and, crucially, to develop platforms for vaccine production and delivery to assist in bringing effective vaccines to commercial reality. Through previous RESAS funding, a prototype recombinant vaccine against T. circumcincta, the primary cause of parasitic gastroenteritis (PGE) in sheep in temperate areas, was successfully developed. This vaccine comprises 8 proteins and induces significant (up to 75% reduction in worm numbers) protection against challenge and holds great promise as a future control option for farmers in tackling teladorsagiosis in Scotland and other countries. However, this novel, pre-competitive, prototype cocktail vaccine contains multiple antigens produced in one of two different expression systems (*Pichia pastoris* and *Escherichia coli*), making commercial development costs high. The work proposed here addresses this issue through simplifying both the antigen cocktail and the expression system used for the vaccine. In previous RESAS-funded work, calves immunised with the *T. circumcincta* vaccine

were also protected against infection with the closely-related parasite, *O. ostertagi,* the most economically-important parasitic nematode of cattle in temperate regions; however levels of protection were variable. The objectives here are therefore to further optimise the current prototype vaccine to provide greater and more consistent protection against *O. ostertagi* infection in cattle.

Infestation of the skin with *P. ovis* (sheep scab mite) represents a major animal welfare and economic burden on the sheep industry. A prototype vaccine composed of 7 recombinant proteins gave highly significant reductions in lesion size and mite numbers (>50% reduction in each) following challenge in protection trials but this vaccine contains multiple antigens produced in different expression systems. Thus, a key objective here is to optimise and simplify the expression of the recombinant sheep scab vaccine antigens in a co-expression system to enhance acceptability for commercial production.

As a result of climatic conditions, the emergence of drug resistance and other environmental factors, liver fluke has become a significant threat to Scottish livestock recently. There is, therefore, an urgent industry need for a liver fluke vaccine to protect livestock, especially sheep, from infection. Despite a considerable international research effort over many years, there is still no immediate prospect of a commercial liver fluke vaccine. Sheep and cattle mount a notoriously poor, or non-existent, protective response to fluke infection but vaccine candidates identified to date have typically been excreted/secreted antigens, which are exposed to the host immune response during natural infection. In contrast to previous vaccine studies, we propose to evaluate the ‘hidden’ or ‘gut’ antigen approach to vaccination, taking advantage of the fluke’s natural blood-feeding habit. This approach has led to the successful commercialisation of TickGard® and Barbervax® vaccines, both of which target blood-feeding parasites. A small-scale pilot trial of this approach produced a reduction in adult fluke burden and reduced liver pathology in sheep vaccinated with a crude detergent-soluble fluke extract. The objectives here are therefore to repeat and refine this hidden-antigen approach for vaccine development.

Vaccines to control two of the major bacterial pathogens affecting lamb production (*M. haemolytica* and *C. abortus*) will also be further developed in this RD. Mastitis, or inflammation of the mammary gland, represents one of the most costly diseases of sheep farming. Clinical mastitis is a significant health and welfare issue, while sub-clinical mastitis causes reductions in milk quality and quantity which impacts lamb growth. Despite its importance, the nature of the response to infection in sheep is poorly understood and effective strategies for disease control are lacking. In the current RESAS-funded research programme (2011-16), we successfully developed an infection model for *M. haemolytica* in sheep mammary glands. This, taken together with the fact that vaccines against *M. haemolytica* have previously been developed at MRI to protect against respiratory disease in cattle and sheep, has led to the development of a programme of research to address sheep mastitis. Here, protection against *M. haemolytica*-induced mastitis will be assessed using the mammary gland model.

Ovine enzootic abortion, which is caused by the obligate intracellular Gram-negative bacterium *C. abortus*, is one of the most common diagnosed infectious causes of lamb loss in ewes worldwide. The organism is zoonotic and can cause devastating spontaneous abortion in pregnant women in whom the disease can also be fatal. Although there exist commercial vaccines to protect against this disease, these are not only expensive to generate, but the vaccines themselves have been shown to cause abortion in sheep and appear not to eliminate shedding of the organisms at lambing, leading to safety concerns for the sheep and, importantly, their handlers. There are also stability issues and, in recent years, these vaccines have suffered from production problems. The current vaccines do not allow differentiation of vaccinated animals from those infected with wild-type strains (DIVA), and therefore interfere with accurate disease diagnosis and control. For these reasons, there is commercial interest in developing next generation vaccines that are efficacious, cheap to produce, safe, stable, do not cause disease and adhere to DIVA principles. Previous RESAS-funded studies using a subcellular C. abortus-derived vaccine formulation in pregnant sheep have shown protection in ewes during experimental challenge with the organism and led to reduced shedding of infectious organisms at parturition and induction of T-cell driven cytokine responses that can be correlated with protection. The key objectives for developing this vaccine here are to titrate the vaccine further in challenge studies to determine the lowest single shot dose required to elicit a protective immune response and to investigate whether vaccine efficacy can be improved by utilising other adjuvants and/or delivery systems, including a recombinant antigen subunit vaccine approach (see RD 2.2.3). Improvements in the production of the vaccine will be investigated in this pre-competitive phase in order to increase its future commercial viability.

Having developed prototype multi-antigen recombinant subunit vaccines for the pathogens specified in this RD, the critical next steps to increase their economic viability and efficacy (and thus commercial uptake) will be to develop optimised co-expression and/or multi-expression systems and delivery methods with the most suitable adjuvants. We will therefore produce selected multi-component recombinant cocktail vaccines in optimised co-expression and/or multi-expression systems and test their efficacy in pen-trials. As an initial example of this approach, the 7 P. ovis vaccine antigens will be co-expressed in planta to simplify production. In addition, to enhance vaccine efficacy and simplification, we will continue to develop ruminant viruses as novel delivery systems. Specifically, we will continue work on vectors derived from the MCF virus alcelaphine herpesvirus-1 (AlHV-1), ovine lentivirus (oLV) and Orf virus. These derivative vectors have been selected as they are conducive to stable expression of heterologous antigens, and, moreover, like their parent viruses, they induce strong humoral and cellular responses and/or promote efficient targeting to antigen presenting cells, properties which make these vectors valid candidates for antigen delivery of antigens. Finally, vaccine delivery through a pulse-release device and/or alternative adjuvants will be compared to standard delivery via the non-depot saponin adjuvant used in many of the ruminant trials, above. The recently commercialised vaccine for Haemonchus contortus, Barbervax®, will be exploited to achieve these comparisons. This is an ideal system as the current adjuvant used in Barbervax® is saponin-based and the correlation between antibody levels and protection for this vaccine are well-understood. The objective is to use an effective vaccine with a known correlate of protection in conjunction with novel adjuvants/pulse release device to attempt to reduce frequency of immunisation and prolong duration of immunity – attributes that translate to the ultimate commercial uptake of all the vaccines described in this RD.

Key overarching deliverables within the 5-year programme are therefore:

1. Elucidation of the protective capacity of simplified optimised vaccines for the control of teladorsagiosis, ostertagiosis, psoroptic mange, fasciolosis and enzootic abortion in the definitive ruminant host.
2. Assessment of a novel application for an existing vaccine against M. haemolytica through immunisation and challenge models in sheep.

Technical approach and Detailed work plans

Objective (O) 1. Further development of a vaccine to control Teladorsagiosis in sheep

O1 Two approaches will be taken to address the issues of complexity in the current prototype vaccine for *T. circumcincta*:

i) Determine the efficacy of a second, simpler, prototype vaccine for *T. circumcincta* in sheep, using 4 alternative, putative immunoregulatory, antigens identified through work in the current RESAS-funded (2011-16) programme. If effective this will halve the number of expressions, purifications and greatly impact the costs of vaccine production;

ii) Optimise and simplify the expression system for the best recombinant cocktail vaccine (see O6 below). The resulting simplified, optimised vaccine will be tested in pen and field trials and efficacy assessed by reduction in faecal egg count (FEC) and worm burden.

Detailed work plan

Year 1: Determine full coding sequences of, and produce, 4 novel *T. circumcincta* recombinant proteins in either *E. coli* or *P. pastoris* for novel prototype vaccine [Sub-objective 1 (O1.1)].

Year 2: Pen trials to compare efficacy of current and novel prototype vaccines through challenge in lambs (O1.2). Completion of analyses is Deliverable 1 (D1).

Further work in years 3-5 will use novel expression systems to optimise antigen production and presentation (see O6) and, through field trials on plots seeded with nematodes (see RD2.3.1), the ability of the prototype vaccine to break the parasite life cycle and prevent pasture contamination by ewes/lambs and its effect on anthelmintic demand to maintain lamb performance will be determined (O1.3).

O2. Further development of a vaccine to control Ostertagiosis in cattle

O2 To give greater and more consistent protection in calves, *O. ostertagi* antigens specifically targeted by the *T. circumcincta* vaccine will be identified using two approaches:

(1) *in silico* sequence analysis to identify *O. ostertagi* orthologues of the *T. circumcincta* antigens;

(2) screening of native *O. ostertagi* antigen preparations with serum from immunised, protected calves to identify antigens recognised by *T. circumcincta* vaccine-induced antibodies. Proteomics will be performed to identify the antigens, which will then be cloned, expressed and used as antigens in *in vivo* vaccine trials.

Detailed work plan

Year 1: Identify *O. ostertagi* antigens targeted by the *T. circumcincta* vaccine (O2.1). Sequences of *T. circumcincta* antigens will be compared to *O. ostertagi* databases (e.g. Nembase4). Also, 2D Western blotting will be used to identify native *O. ostertagi* antigens bound by antibodies from vaccinated, protected calves. Identities of immune-reactive proteins will be determined by mass-spectrometry.

Year 1 and 2: O2.2. Production of *O. ostertagi* antigens identified in O2.1. Coding sequences for the antigens will be determined and recombinant versions expressed using *E. coli* and/or *P. pastoris* (D2).

Year 2+: O2.3. Perform *in vivo* protection trial using novel *O. ostertagi* antigens generated in O2.2: Antigens generated in O2.2 will be used to immunise groups of calves. Protection against a bolus parasite challenge will be determined; (completion

December 2018). In Years 3-5, additional protection trials will be performed using a trickle parasite challenge model.

O3 Development of a vaccine to control Fasciolosis

O3 The approach to hidden-antigen vaccine development will be refined by testing selected detergent-soluble fluke fractions and lectin-binding sub-fractions derived from them in vaccine trials, monitoring FEC, coproantigen ELISA, serology and liver examination at post mortem.

Detailed work plan

Year 1: O3.1. Preparation and characterisation of detergent-soluble liver fluke extracts; O3.2. Vaccine trial in sheep with selected extracts using a triclabendazole-resistant liver fluke isolate challenge; completion represents D3.

Year 2: O3.3. Preparation and characterisation of selected lectin-binding sub-fractions; O3.4. Vaccine trial in sheep with selected sub-fractions using triclabendazole-resistant liver fluke isolate; completion September 2018.

O4 Efficacy testing of an anti-mastitis vaccine in sheep

O4 Here, the capacity of the M. haemolytica respiratory disease vaccine to induce protection against intra-mammary challenge in a sheep model will be assessed.

Detailed work plan

Year 2+. O4.1. Groups of sheep will be immunised at appropriate sites prior to intra-mammary challenge and responses compared with those in unvaccinated controls; completion September 2018.

O5 Development of next-generation subcellular vaccine and towards a novel recombinant based DIVA vaccine against ovine enzootic abortion

O5 A novel prototype subcellular vaccine recently demonstrated 100% protection against an experimental *C. abortus* challenge. Work here will develop the studies on this next generation prototype to further define the lowest protective dose and determine whether efficacy at lower doses can be improved through the use of different adjuvants to drive the immune response towards that required for protection. The vaccine potential of recombinant forms of the components of the prototype subcellular vaccine, identified through proteomic analyses (see RD2.2.3), will be assessed.

Detailed work plan

Year 1: O5.1 Evaluation of the efficacy of different doses of the new prototype vaccine in pregnant sheep. Completion represents D4. O5.2 Characterise the immune response in vaccinated and control animals from O5.1; completion December 2016.

Year 2+: O5.3 Develop methods for growing *C. abortus* using non-adherent cell culture techniques to high titres for preparation of the new prototype vaccine; completion October 2018 O5.4; Evaluate the effect of different adjuvants on the protective efficacy of the vaccine in pregnant sheep; completion December 2018.

O5.5: Characterise the immune response in vaccinated and control animals from O5.4; completion December 2018.

Further activities later in the programme include investigation of the protective efficacy of recombinant subunit vaccine formulations in pregnant sheep (April 2019-December 2020) and characterisation of the immune response in vaccinated and control animals from this study (April 2020-December 2020).

O6 Vaccine production and delivery strategies to improve efficacy and economic viability

O6 To improve their economic viability and efficacy, selected multi-component recombinant cocktail vaccines required for control of parasites of ruminants will be expressed in optimised co-expression and/or multi-expression systems and tested in pen trials. In addition, optimal adjuvant and vaccine-delivery methodology will be informed through the use of a "gold-standard" comparative approach using a defined commercially exploited anti-nematode vaccine:

SO6.1: As an initial example of optimised co-expression, the 7 *Psoroptes ovis* vaccine antigens will be codon optimised for plant expression and cloned into plant virus-based expression vectors, which will be transformed into Agrobacterium and subsequently injected into tobacco plants for transient expression. Expression will be improved, if required, by blocking different aspects of the gene silencing machinery and/or by the use of modified Agrobacteria with an optimised expression cassette delivery system. After expression, the proteins will be isolated from plants and used in a vaccine trial. Dependent on efficacy, the vaccine antigens will be arrayed on safe biodegradable nanoparticles to further improve vaccine performance.

Detailed work plan

Year 1 O6.1i: Codon optimisation of P. ovis vaccine antigen sequences and cloning into expression vectors.

Years 1 and 2 O6.1ii: In planta co-/multi-expression and isolation of sheep scab mite vaccine antigens; completion March 2018. Completion represents D5.

Year 2+ O6.1iii: Plant co-/multi-expressed vaccine tested in sheep in pen-trials to determine effects on parasite load and pathology, and immune correlates of protection where possible; completion December 2018.

Dependent on the outcomes of these trials, surface display of *P. ovis* vaccine antigen sequences on nanoparticles will be performed to determine any enhancement effect of this delivery on vaccine efficacy in Years 3 and 4. Additional pathogens may also be targeted dependent on the success of this approach.

SO6.2: As an additional approach, ruminant viruses will continue to be developed as novel vaccine delivery systems. Specifically, work on vectors derived from the MCF virus alcelaphine herpesvirus-1 (AlHV-1), ovine lentivirus (oLV) and Orf will be continued. To establish proof of principle that these vectors can elicit protective immune responses, pathogens that have a single or small number of defined protective antigens and where an established disease model is available in sheep and/or cattle will be focussed on. Initially, 4 pathogens will be considered; (i) Louping ill virus capsid and envelope proteins will be inserted into vectors derived from AlHV-1, oLV and/or Orf (linking to RD2.3.3) as will antigens from;(ii) *T. circumcincta* (8 antigen vaccine, see O1); (iii) *P. ovis* (synthetic antigen comprising concatenated B-cell epitopes from 7 antigens; (iv) *C. abortus* (outer membrane protein). This represents a range of pathogen types that require different protective immune mechanisms and therefore provides a balanced range of diseases to test the novel vectors. This work will be performed in parallel to other studies on these targets under this RD, allowing comparison with non-viral delivery methods.

Recombinant viral vaccines will be constructed and their function evaluated *in vitro* using cell lines and primary antigen-presenting cells from sheep and cattle, prior to proof of principle experiments *in vivo*. Animal experiments will be performed in the relevant species and will determine; (i) whether an immune response is generated by the viral vector and (ii) whether this response is protective. Where possible, *in vivo* studies with viral vectors will be timed to coincide with ongoing trials of vaccines against the relevant pathogen; for example, vaccination against *T. circumcincta* in Year

2. This will allow direct comparison of virally-delivered vaccines with other vaccine formulations and reduce the number of animals required as control groups will not need to be repeated.

Detailed work plan

In the first two years, *in vitro* studies will be performed to construct and test vaccine strains of virus vectors, followed by *in vivo* testing in Years 3-5.

Year 1: O6.2i - Assess expression of an epitope tagged recombinant virus glycoprotein in co-infected AlHV-1. O6.2ii - Demonstrate recombinant AlHV-1 attenuated vaccine virus in bacterial vector.

Year 2: O6.2iii - Construct lentiviral vectors encoding pathogen antigens and demonstrate expression in ovine and bovine cells *in vitro*. O6.2iv - Produce constructs for construction of viruses expressing test antigens (e.g. Louping ill virus capsid and envelope proteins). O6.2v - Determine the effect of incorporating lentiviral accessory proteins on efficiency of vector production and delivery.

In subsequent years, the viral-vectored vaccines will be tested in *in vivo* challenge experiments alongside the plant co-/multi-expressed vaccines where appropriate (e.g. for *P. ovis*) and development of the oLV vector to improve the safety profile and enhance expression of target proteins in antigen presenting cells performed.

SO6.3 To determine the effects of alternative antigen release and adjuvant systems on improved vaccine performance (fewer immunisations, prolonged protective antibody levels), the serological responses of lambs administered with Barbervax® using different adjuvants/pulse release substances provided by collaborating pharmaceutical companies will be monitored. If serological response of a group proves superior to that of saponin (the present adjuvant), then those animals will be challenged to check that protection had been conferred.

Detailed work plan

Year 1. O6.3i: Lambs will be immunised with Haemonchus vaccine formulated either in standard saponin adjuvant or a novel adjuvant, following a standard immunisation schedule. Serological responses, which reflect vaccine efficacy accurately for this species, will be monitored and assessed for both magnitude and longevity. Completion March 2017.

Year 2. O6.3ii: The above procedure will be repeated to compare standard saponin with a pulse-release formulation. Completion March 2018.

Year 2+ Dependent on the outcomes of O6.3i and O6.3ii, a protection trial will be performed using the optimised adjuvant/delivery system compared to the current formulation.

Use of underpinning capacity:

Underpinning capacity is critical to the success of each of the aspects of this work as we will use the clinical research, animal containment and pathogen collection facilities at MRI and the plant-production facilities at Hutton, supported by Underpinning Capacity. In addition, we will employ many reagents and knowledge generated under the current RESAS Programme here.

Statistical Approaches, Animal Subject Numbers and Ethical Considerations:

Power calculations have been/will be performed to establish animal numbers for all experiments, based on replicate numbers and vaccine efficacy response parameters in previous analyses. For longitudinal parasitological analyses, a generalised additive mixed model (GAMM) model [for example on log(FWEC+1)] will be specified. Antibody responses will be modelled using linear mixed models (LMMs) (group as fixed effect, animal as random effect). For repeated measures over time, data will be modelled by random intercept and slope LMMs, including time and its interaction with group as fixed effect. Total estimated numbers of sheep specific to this RD (2.2.5) will be 72 lambs (O1), 192 breeding ewes and their lambs (O1,) the majority (~80%) of which will be re-use animals from RD 2.3.1), 120 lambs (SO6.3) 40 sheep (O4), 48 sheep (O3) and 320 ewes (O5). Total estimated numbers of calves will be 70 (O2). All experiments will be performed under the regulations of a UK Home Office Project Licence; experimental design will be ratified by MRI's Experiments and Ethics Committee

Expertise

Scientists from MRI contribute skill, knowledge, capability and capacity for innovative development of novel vaccines and vaccination strategies for endemic diseases of high commercial importance in the Scottish livestock sector. Through the burgeoning relationship with innovative molecular and plant scientists at Hutton, the MRI scientists are developing novel platforms for vaccine production and delivery to make these vaccines successful and ultimately available to Scottish farmers. Support staff and associated expertise from Underpinning Capacity at both institutes are vital to the success of the science proposed here.

Key linkages, interdisciplinarity & collaboration

- RD2.2.5 O1 is linked directly with RD2.2.3 and RD2.3.1. Work in RD2.2.3 will characterise the local anti-parasite immune response in lambs vaccinated with the optimised vaccine produced in RD2.2.5, allowing correlates of immunity to be established while work in RD2.3.1 will provide field conditions for the testing of the optimized vaccine.
- Several objectives in RD2.2.5, (but principally O6.1) are linked with RD2.2.6 and NEPIC, in which disease transmission and effects on parasite species composition (RD2.2.6), and the impacts of vaccination and vaccine efficacy against sheep scab (NEPIC), will be determined.
- RD2.2.5 O5 is linked directly with RD2.2.3. Work in RD2.2.3 will optimise the expression and refolding of known components of the protective membrane fraction that has been identified in the current programme and will be assessed for protective efficacy in RD2.2.5, allowing correlates of immunity to be defined.
- The research in RD2.2.3 and RD2.2.5 O5 is linked with an industrial collaboration with a UK-based vaccine company.
- The research in RD2.2.5, O66.2iv in particular, links to RD2.3.3 through use of a viral vaccine delivery mechanism to control a tick-borne virus.
- Plant-based expression of vaccine antigens in RD2.2.5 will exploit the findings of RD2.1.3 which will use novel approaches to drive the expression of foreign proteins from virus vectors.
- Outputs from surface-display of antigens for *P. ovis* diagnosis in RD2.2.4 will be used to inform surface-display of vaccine antigens in SO6.1 in RD2.2.5.

These key linkages will enhance the KE value of the work by allowing explanation of vaccine efficacy and optimal use, as well as critical data for vaccine commercialisation and registration in future.

Added Scientific Value

Members of this RD currently hold competitive research grants to explore aspects of immunoprophylaxis of endo and ecto-parasites including:

Defra funding for sheep scab vaccine development (2013-2016) from which O6.1 is a logical progression; PARAGONE (Horizon 2020 EU funding 2015-2019) which will examine the optimisation of prototype vaccines for *T. circumcincta*, *P. ovis* and/or *F.*

hepatica through detailed examination of the mechanisms of vaccine action and therefore optimal delivery, adding value to O1,2,3,6.1 and 6.2; BBSRC AHRC funding (2015-2018) to investigate age-dependent vaccine efficacy in sheep, adding value to O1, in particular.

KE, Audiences and Impact

Audiences:

Policy: This work will inform Scottish Government policy within the context of the priority and focus areas of the SRDP, as well as the existing “Modernising Scottish Agriculture” and “Farming for a Better Climate” agendas. In addition, policy relevant outputs will be generated within the context of the imminent Scottish Animal Health and Welfare in the Livestock Industry Strategy, 2015-2020. Appropriate outputs will be directed through Policy Briefs and direct interaction with the relevant policy leads.

Industry: Direct KE to stakeholders will be through stakeholder events, in particular at the Royal Highland Show (June 2016, 2017; KE1 and KE2) and through annual Moredun Foundation road shows in October/November 2016 and 2017 (KE3 and KE4), and articles in the farming press (via Moredun’s Annual Press Day in December 2016 and 2017 (KE5, KE6)). Factsheets and news-sheets (4 annually to 12,000 UK stakeholders) will be produced as demand from our regional advisors demands.

Public and Professional: Through publication in high impact open access scientific journals and presentation at national and international conferences annually (e.g. BSP 2016, 2017, WAAVP 2017). In addition, KE and policy outputs will be unified through publication of key results on appropriate websites and disseminated to wider audiences and venues through the CKEI.

Impact:

The outcomes of this work will have a significant impact on food security and on the rural and national economy by improving livestock productivity and welfare as well as having impact on operator safety and reduction of residues in foodstuffs. These factors combined will have the effect of improving competitiveness and sustainability of the Scottish food industry in the global marketplace, contributing to greater food security and will inform future Government policy on disease control. Scottish, and international, industry will benefit by the exploitation of IP arising from the project (i.e. vaccines, novel therapeutics). To ensure this impact, we will engage with Policy, Public and Industry stakeholders throughout the programme with timelines as described in the KE audiences section above.

Research Deliverable 2.2.5 Work planning and timetable for years 1 and 2 are shown below: Showing the initiation of key research objectives (O); Milestones (M); Deliverables (D); KE events (KE) and their timing (shaded). M1 = Coding sequences of antigens finalised; M2 = in silico antigen analysis complete; M3 = detergent-soluble liver fluke extracts prepared; M4 = dose response animal trial completed; M5 = interferon-gamma responses determined following challenge; M6 = Codon optimized *Psoroptes* antigens cloned; M7 = express tagged viral glycoprotein; M8 = make GFP-Neo targeting vector; M9 = vaccine formulation in novel adjuvant complete; M10= novel adjuvant trial completed; M11 = expression constructs complete; M12 = selected lectin-binding sub-fractions prepared; M13 = appropriate cell lines identified; M14 = animals sourced for adjuvant trial; M15 = post-vaccination immune responses determined; M16 = Antigens expressed in plants; M17 = Optimized methods for isolation of *Psoroptes* antigens from plant material; M18 = T circ antigen expression in oLV vectors in vitro; M19 = LIV antigen expression in oLV vectors in vitro; M20 =

vectors for Louping–ill antigens; M21 = Lentiviral accessory protein expression plasmids constructed; M22 = Effect of accessory proteins on vector production and expression determined; M23 = pulse release adjuvant formulated; M24 = pulse release adjuvant trial completed

RESEARCH DELIVERABLE NUMBER: 2.2.5
Work planning and timetable for Year 1:

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 Further development of a vaccine to control Teladorsagiosis in sheep **O1.1***Teladorsagia* recombinant antigen production						M1						
O2 Further development of a vaccine to control Ostertagiosis in cattle **O2.1** *Ostertagia* antigen identification **O2.2** *Ostertagia* recombinant antigen production						M2						
O3 Development of a vaccine to control Fasciolosis **O3.1** Produce *Fasciola* vaccine antigens 1 **O3.2** *Fasciola* vaccine antigens 1 protection trial						M3						D3
O5 Novel vaccines against enzootic abortion **O5.1** Dosage efficacy of *Chlamydia* EAE vaccine **O5.2** Characterise immune response to *Chlamydia* EAE vaccine **O5.3** *Chlamydia* cell culture development						M4 M5			D4			
O6 Vaccine production and delivery strategies to improve efficacy and economic viability **O6.1i** *Psoroptes* antigen cloning **O6.1ii** *In planta* expression of *P. ovis* antigens **O6.2i** Virus glycoprotein expression in AIHV-1 **O6A.2ii** Recombinant AIHV-1 in bacterial vector **O6.3i** *Haemonchus* adjuvant trial 1						M6 M7 M8 M9						M 10
KE Events: Royal Highland Show				KE 1								
KE Events: Moredun Foundation Roadshows								KE 3				

KE Events: Moredun Annual Press Day									KE 5			
Annual Report (Year 1)												R1

Work planning and timetable for Year 2:

Year 2: 2017/18	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
O1 A vaccine to control Teladorsagiosis in sheep **O1.2** *Teladorsagia* vaccine pen trial												D1
O2 A vaccine to control Ostertagiosis in cattle **O2.2** *Ostertagia* recombinant antigen production			M 11						D2			
O2.3 *Ostertagia* recombinant vaccine trial												
O3 Development of a vaccine to control Fasciolosis **O3.3** Produce *Fasciola* vaccine antigens 2						M 12						
O3.4 *Fasciola* vaccine antigens 2 protection trial												
O4 An anti-mastitis vaccine in sheep **O4.1** *Mannheimia* vaccine trial												
O5 Novel vaccines against enzootic abortion **O5.3** *Chlamydia* cell culture development		M 13										
O5.4*Chlamydia* EAE adjuvant evaluation						M 14						
O5.5 Immune responses to EAE vaccine										M 15		
O6 Vaccine production and delivery strategies to improve efficacy and economic viability **O6.1ii** *In planta* expression of *P. ovis* antigens			M 16						M 17			D5
O6.1iii *Psoroptes* recombinant vaccine trial												
O6.2iii Construct lentiviral vectors						M						M

O6.2iv Constructs for pathogen antigens **O6.2v** Lentiviral accessory protein incorporation **O6.3ii** *Haemonchus* adjuvant trial 2						18 M 21 M 23		M 20				19 M 22 M 24
KE Events: Royal Highland Show				KE 2								
KE Events: Moredun Foundation Roadshows								KE 4				
KE Events: Moredun Annual Press Day									KE 6			
Annual Report (Year 2)												R2

Name of RD: 2.2.6 Animal disease epidemiology
Research aim and key drivers Epidemiology is the study of the occurrence of diseases, or health-related events, within populations, the risk factors for disease and the application of this knowledge to the control of that disease or event. Work on occurrence, or frequency, of disease and economic impacts occurs in RD2.2.2. In RD2.2.6 the *aim* is to advance knowledge and provide improved ways to control key diseases. Better control can be achieved by detecting the presence of disease faster, or more accurately; by preventing its occurrence; or, by applying measures to control its spread when it occurs. However, other factors - such as socio-economic issues - contribute to disease transmission and the success of control strategies; these will be integrated into the epidemiological work. The *key driver* is the policy need for "…the development of improved knowledge of the epidemiology of key livestock infections". This will be achieved through five linked research areas (Objectives). The focus is on infections that have a big impact on livestock production, or have the potential to cause human disease (known as zoonoses) and on antimicrobial resistance (AMR), which affects animals as well as humans and is highly topical. This collaborative research proposed builds on previous experience and research funded by RESAS. It closely matches research requirements described in the ITGF and optimises the use of the high quality skills, knowledge, facilities and expertise available across the MRPs. The range of approaches, methods and diseases presented has been influenced by ongoing discussion with RESAS and a range of industry stakeholders occurring within a number of recent stakeholder events. Existing large datasets will be used to facilitate the detection and control of disease; new statistical models and approaches will be applied; advances will be achieved through the development of new control strategies, incorporating socio-economic aspects, and by pioneering new tools in the field. Key endemic diseases and issues considered will initially be those of ruminants (sheep and cattle) including: liver fluke, Bovine Virus Diarrhoea (BVD), paratuberculosis (paraTB), sheep scab, nematode populations, tickborne diseases (TBD) and ovine pulmonary adenocarcinoma (OPA). Key zoonoses will include verocytotoxigenic *E.coli* O157:H7 (VTEC); *Cryptosporidium* spp. Salmonellosis in pigs, and AMR. Improved control will reduce the impacts of zoonotic threats, so helping to safeguard public health and promote the safety of Scottish food.
Summary of the proposal: Within the broad aim of providing improved ways to control key diseases, five objectives (O) have been identified, organised into a number of sub-objectives. The individual research activities with related deliverables (D), milestones (M) and KE components (KE) are set out below and in the Gantt charts (year Y). **Objective 1: Analyses of existing large datasets.** This work focuses on the use of a range of existing large datasets (eg ScotEID) to improve disease control measures. O1.1. Improved methods for detection of livestock disease O1.1.1. Statistical and mathematical methods will be applied to existing datasets to improve disease detection, focussing initially on endemic diseases. This builds upon work within current programme (WP6.1), EPIC (CoE on Epidemiology, Population health and Infectious disease Control), and previous work on scrapie, to develop targeted surveillance strategies for

key endemic diseases in sheep, with liver fluke and the abattoir network as the first example. O1.1.2 An extensive combined data resource, from multiple historic projects (Wellcome, FSA) on VTEC distribution and prevalence, will be exploited to facilitate detection and contribute to systems modelling work (O3).

O1.2 To address gaps in current methodology, tools will be developed for inference from longitudinal data that account for demographic change and testing regime, resulting from management changes or wildlife population dynamics. These will enable inference of epidemiological quantities critical to management and control from data describing the demography of host populations and disease dynamics e.g. paraTB.

Key deliverables: Y1-2: D1a. Identification of risk factors and production of risk maps for BVD; D1b. Assessment of the Scottish sheep abattoir population and its suitability for use in targeted surveillance; D1c. Evaluation of utility of farm sampling for detection of VTEC; D1d. Paper on longitudinal data inference work/model; D1e. Assessment of potential future applications, e.g. BVDV (RD2.2.6) and pest-natural enemy interactions (RD2.1.6)

Objective 2: New strategies for disease control. This work focuses on developing new approaches to implement disease control:

O2.1 Optimisation of disease control programmes and 'end-game' scenarios: firstly, simulation models developed (CEPIC) for exotic pig diseases will be adapted to endemic and zoonotic diseases, using *Salmonella* as an initial example. Secondly, as differences in improvement between farms could be a result of management practices and/or regional characteristics, models will be used to segregate cattle farms based on their improvement status over time, thereby isolating farms for targeted interventions. The cost/benefit of different testing regimes once the disease is eradicated will be estimated, (links with RD2.2.2 Evaluation of Livestock Health)

O2.2 Socioeconomic incentives for implementation of disease control strategies: Farmer attitudes and behaviour are key drivers of effective disease control. Building on work to identify barriers to implementation of desirable behaviours (CWP6.1), e.g. monitoring disease and improving biosecurity, incentives for disease control will be identified. This will include the contribution that veterinary surgeons make, as the major source of health advice for farmers and a better understanding of their role facilitating behaviour change is required (RD2.3.12: Increasing uptake of best practice and NEPIC).

O 2.3 Application of improved diagnostics for fluke control: Liver fluke, *Fasciola hepatica*, is a growing threat to our livestock industry due to emergence of drug resistance and 'unseasonal' fluke disease after over-winter survival. Rumen fluke has also emerged as a concern. Fluke risk can be forecast at regional level or diagnosed once livestock are infected but the ultimate indicator of risk is pasture challenge. Fluke cyst challenge on pasture and in feed will be identified and quantified to support risk assessments and targeted disease control (RD1.3.3: Resilience of ecosystems and biodiversity).

O 2.4 Improved understanding of sheep scab transmission and the effect of vaccination: The sheep scab mite, *Psoroptes ovis*, represents a major animal welfare concern and economic threat. Its transmission is by contact with infested animals or contaminated fomites/environments and can be influenced by numerous factors. Results from earlier within-flock transmission trials are being analysed and modelled (CEPIC) to measure such factors. Using penned trials, those findings will be validated and the effect of

vaccination on within-flock transmission of sheep scab measured.
Key deliverables: Y1-2: D2.1a. Within-farm model for *Salmonella* transmission for the Scottish pig industry. D2.1b. Report on patterns of farm level BVD status change over time. D2.1c. Report cost/benefit of BVD testing regimes in end-game scenario. D2.2. Description of motivators for animal disease control among Scottish farmers. D2.3. Methodology for detecting fluke risk at pasture. D2.4. Report detailing parameters for sheep scab within-flock transmission.

Objective 3: Zoonotic diseases

Zoonotic pathogens can be transmitted between people, animals and environmental reservoirs. Transmission of two high profile zoonotic enteric pathogens, VTEC and *Cryptosporidium parvum,* will be investigated; with the ultimate aim of minimising human exposure

O3.1 VTEC: A key knowledge gap for VTEC concerns genetic traits that allow persistence and colonisation of secondary hosts, including plants. The combined historic archives (O1.1.2) will enable comparison of genomes of bovine and environmental isolates of *E. coli*, including VTEC, to identify genes that may contribute to niche adaptation. VTEC collections will be screened for these genes to inform the likelihood of persistence and spread via alternative niches (hosts/environment), (links to functional analysis in RD2.3.3, Disease threats in the environment).

O3.2 *Cryptosporidium: Cryptosporidium* causes enteric disease in people, calves and lambs. It is the most commonly diagnosed cause of enteritis and death in neonatal calves in the UK (VIDA data). There is no vaccine available and there is only one licensed treatment for calves, which needs to be given prophylactically on seven consecutive days, making management particularly difficult for the beef industry. It is therefore important to establish how to minimise disease risk in calves and exposure risk in humans.

Key deliverables include: Year1-2:D3.1a. Summary of bioinformatics requirements for genome processing and multi-locus alignment D3.1b. Report identifying VTEC genes associated with environmental survival and candidates for diagnostic screening D3.2a. Molecular speciation, typing and quantification tools for *Cryptosporidium*. D3.2b. Report identifying sources of *C. parvum* in calves. D3.2c. Y3-5: Farm management guidelines to minimise cryptosporidiosis in calves and help reduce human exposure.

Objective 4: Understanding antimicrobial resistance (AMR) An array of interlinked approaches to improve knowledge of AMR for a range of key bacterial species and inform the design of active surveillance strategies:

O4.1 Establishing estimates of AMR prevalence in Scottish ruminant livestock: prevalence of AMR resistance genes, as determined using PCR-based analysis of historic Scottish cattle samples, will be compared with traditional measures of AMR that were acquired at the time of sampling and in CWP6.1. Data will be compared to that from the subset of Scottish farms from the VMD-funded APHA/ERU (Animal and Plant Health Agency) study (ref: VM0526). Additional 2014-15 archived FSA cattle samples may also be tested. Outputs will contribute to O4.4 and RD2.2.2 O3).

O4.2 Improved knowledge of the epidemiology of AMR in sheep: work on cattle in O 4.1 will be complemented by work on sheep samples (milk, faeces) that will be tested with both traditional and molecular methods. This will enable comparison of methodologies and AMR prevalence across host species and sample complexities, and provides baseline data on AMR in a second key Scottish livestock species.

O4.3 Relationship between AMR measures and clinical outcome Building on O4.1 & 4.2, models of the variability of resistance will be developed at a range of scales (Farm, Animal, Sample, etc.) to identify the scale that is most relevant to different outcomes, e.g. the clinical value of AMR testing for prediction of treatment outcome. The latter will involve collection and analysis of antimicrobial treatment data, (RD2.2.2, O3).

O4.4 AMR genes may also be found in the environment. Work on AMR abundancies in Scottish soils will be coupled to the development of a systems model of a simplified farm to fork system that will use existing data, information, and expert opinion to identify where the critical control points of intervention might be for the control of AMR transfer. The RESAS-funded National Soils Inventory of Scotland (NSIS 2, 2007-2010) is a comprehensive resource of high density coverage (10 Km grid), which will provide a baseline of AMR gene abundance. Soils are a little considered source of AMR that can be cycled within an agricultural system.

Key deliverables include: Y1-2: D4.1a Report on AMR prevalence comparing RT-PCR and traditional approaches for historical cattle samples; D4.1b Report on AMR prevalence comparing RT-PCR and traditional approaches for recently archived cattle samples; D4.2 Preliminary report on AMR prevalence in sheep; D4.4a First inventory of AMR gene abundances in Scottish soils; Y3-5: D4.3 Model of the variability of AMR at a range of scales; D4.4b. Report identifying soil types and characteristics that are indicative for high AMR burden.

Objective 5: Utilisation of new tools

O5.1 Nematode population structure: new molecular tools, e.g. metabarcoding of DNA, provide new opportunities to characterise abundance, and drivers of abundance, of pathogen populations and subpopulations in livestock species and their environment. These tools (RD2.2.4 Novel diagnostic tools) will be used to measure changes in gastro-intestinal parasite populations of sheep over time, space and in relation to interventions.

O5.2 Definition of the mechanism underlying the difference between lambs that demand high or low levels of anthelmintic support: Targeted selective treatment (TST) experiments highlighted a spectrum of need for anthelmintic treatment in lambs, from low to high numbers of drenches. The lambs within a flock differ significantly in their requirements for anthelmintic treatment and this is not directly linked to worm burden. Host traits associated with treatment phenotype will be characterised to allow for prediction of treatment need and selection of lambs.

O5.3 & O5.4 Improved knowledge of TBD and OPA: Field application of diagnostic assays from CWP6.2 (TBD pathogens, respiratory diseases) is proposed in RD2.2.2, 2.3.3 & 2.2.4. Once validated, those assays will be used to study the epidemiology of TBD, specifically its role in livestock abortion, and respiratory disease. Using existing questionnaire data, risk factors for the latter will be identified.

Key deliverables include: Y3-5: D5.1 Report on impact of control strategies on worm population and structure; D5.2. Report on prognostic markers of anthelmintic-need phenotype in lambs D5.3 Estimate of role of TBD in livestock abortion; D5.4. Report on risk factors for respiratory disease in sheep.

Technical approach

Objective 1: Analyses of existing large datasets.

O1.1.1. Improved methods for detection: spatio-temporal analyses will be applied to

ScotEID-BVD data to identify clusters. Using movement and demographic data (BCMS/CTS for cattle tracing), risk factors for these clusters will be identified this will help to target control measures at end of eradication programme. This will inform work in O. 2. Descriptive, spatio-temporal and network analysis will be applied to ScotEID and denominator data to determine how to design abattoir sampling schemes for targeted surveillance of endemic diseases in Scottish sheep. The type of estimates that can be obtained and the biases that exist will be identified. Liver fluke in sheep will be the initial example. Once established, later work could include economic analyses of the cost-effectiveness of different surveillance design options, the application to other points of access for diagnosis of disease, and an investigation into correlations with clinical diagnostic data to provide a multiplication factor/reporting ratio that may be used as an indicator of prevalence between active, targeted surveys. O1.1.2. Historic VTEC data collections (Wellcome, MAFF, FSA) will be used to mathematically assess, for cattle herds and sheep flocks, the predictive value of a positive farm sample within one month of slaughter for positive carcasses at slaughter – this is one of the agreed EU Harmonised Epidemiological Indicators (HaEI), proposed for use to determine the risk-basis for slaughter inspection purposes.

O1.2. Bayesian inference for partially observed Markov and semi-Markov process, potentially including novel computational techniques based on Markov chain Monte Carlo (MCMC) and particle MCMC (RD2.2.3), will be applied to longitudinal testing data e.g. for paraTB in Scottish dairy herds (Defra, SFC, QMS). The benefits of incorporating information on demography and testing regimes will be assessed, as will the application to pest-natural enemy interactions (RD2.3.3).

Detailed work plan Year 1: Review and acquire data for all three planned analyses (M1.1a); Describe (from denominator data) the spatio-temporal 'send and receive' characteristics of the Scottish sheep abattoir population (M1.1b); BVD: produce risk maps and report on risk factors (M1.1c); KE event via sheep industry interface group, with RD2.2.2 (KE1.1a); Develop epidemiological model, inference methods and acquire longitudinal data (M1.2a). **Year 2:** Describe the risk profile of the Scottish sheep abattoir population and design options for abattoir sampling (M1.1d); Report on the value of the proposed HaEI (M1.1e). Apply methods and assess potential for application (M1.2b).

Objective 2: New strategies for control of disease

O2.1. Optimisation and 'end-game' scenarios: i) a stochastic within-farm transmission model for Salmonella will be adapted to the Scottish pig sector, then combined with a between-farm transmission model based on animal movement data (as per CEPIC pig exotic disease model). ii) BVD eradication data and latent class models will be used to segregate farms and identify characteristics associated with improvement. The cost/benefits of different test regimes will be assessed for diseases near to, or after, eradication, e.g. BVD, as eradication of a disease may not imply elimination of associated costs.

O2.2. Socioeconomic incentives: Semi-structured one-to-one interviews will be carried out with farmers and veterinary surgeons (approximately 12-15 per group) to explore motivation for disease control among farmers and communication of disease control strategies by vets. Interviews will be recorded, transcribed and analysed qualitatively using self-determination theory as a theoretical framework. Outputs will be used to improve vet-farmer communication. Existing networks of vets and farmers engaged in programmes for control of endemic diseases in Scotland will be used to assist with recruitment and dissemination of results.

O2.3. Application of improved diagnostics for fluke control: The focus here is on improved diagnosis of levels of infectious fluke stages in the environment. The work will include adaptation of methods to detect viable fluke cysts and assessment of factors influencing survival; preliminary farm-based studies to determine the diagnostic value of these methods using field material; and finally application of the methods at a larger scale with extension to other potential sources of infection, e.g. feed, water, environmental sources.

O2.4. Transmission dynamics of sheep scab and the effect of vaccination: The aim is undertake penned transmission studies for sheep scab to measure and validate the impact of various factors on transmission. Later, the effect of vaccination on the transmission dynamics will be assessed through pen based infestation/vaccination trials.

Detailed work plan Year 1: (2.1) Adaptation of simulation models to represent the Scottish situation for salmonellosis in pigs (M2.1a). Analyse BVD status change over time using latent class models (M2.1b). (2.2) Develop interview schedules and recruit vets and farmers. (M2.2a). (2.3) Optimise ITS-2 molecular assays to confirm species identity of liver fluke and rumen fluke cysts (M2.3a). (2.4) Initiate challenge studies to collect data on factors affecting sheep scab epidemiology (M2.4a). **Year 2:** (2.1) Use simulation models to test within and between farm intervention strategies that might be used as part of a control programme for pig disease (M2.1c). Use models (BVD) to assess how the testing regime should be optimised as the control programme gets close to full eradication (M2.1d). (2.2) Conduct interviews and data analysis (M2.2b). (2.3) Apply tools, optimised in laboratory (M2.3a), in the field to determine the presence and the viability of liver fluke and rumen fluke cysts (M2.3b). Investigate biology and life-cycle of rumen fluke (M2.3c). (2.4). For sheep scab, determine the effect of i/ stocking density (M2.4b), ii/ the number of infested “index cases” (M2.4c) on the rate of transmission and, iii/ the exposure time required for the appearance of clinical lesions in naïve animals (M2.4d).

Objective 3: Zoonotic diseases for public health

O3.1. VTEC: Genomic comparison of existing large datasets will identify the pan-genomes (i.e. shared) and accessory genomes (i.e. horizontally acquired islands specific to an individual or to a group of individuals), which in turn will allow idenfication of genes associated with preferential colonisation of a particular host or habitat. This ‘genetic signature’ together with pathogenic potential (e.g. Shiga toxin allele) will provide data on risk factors for pathogen transmission. Genotypic signatures will be determined in VTEC collections, obtained from ongoing collaborations and from SRUC (Inverness) that include environmental and animal isolates. SRUC will isolate genomic DNA from 100 isolates in a Containment Level 3 (CL3) facility, which can then be screened at Hutton by PCR. Collaborative phylogenetic analysis of selected genes will be carried out with BioSS, through development of bioinformatics software (TOPALi).

O3.2. *Cryptosporidium*: Molecular typing tools and qPCR for identification, characterisation and quantification of *Cryptosporidium* spp. will be further developed and validated. Using those tools, within-farm transmission routes of *Cryptosporidium* spp. will be evaluated. Associations between management practices such as biosecurity behaviour and diversity/stability of genotypes of *C. parvum* will inform farm management and aid in the reduction of *Cryptosporidium* exposure of livestock and humans (link to between-farm transmission work in EPIC).

Detailed work plan Year 1: (3.1) Assemble datasets to identify bovine & environmental VTEC isolates for screening (M3.1a). Develop bioinformatics software (e.g. TOPALi), and expertise (e.g. through BioSS-run training workshops) (M3.1b; KE3.1a). Genome Sequence, assemble, annotate, align and compare genomes (M3.1c). (3.2) Validate molecular speciation, typing and quantification tools for *Cryptosporidium* spp. (M3.2a). **Year 2:** (3.1) Identify gene lists from core and accessory genomes (M3.1d). Screen VTEC collections for the presence/absence of genes associated with either bovine or plant hosts (M3.1e). (3.2) Farm based study to identify sources for *C. parvum* infection in calves (M3.2b).

Objective 4: Understanding antimicrobial resistance (AMR)

O4.1. Estimates of AMR prevalence: Archived faecal samples from the 1998 Scottish cattle survey will be tested using RT-PCR to gain baseline estimates of the presence of resistance genes. The PCR results will be linked to alternative measures of AMR taken for that survey to determine any genetic association.

O4.2. AMR in sheep: Both existing sample collections and new material (faeces, swabs, milk; cross-sectional on-farm sampling of lactating flocks) will be used to establish a baseline for AMR in sheep and to generate material for comparison of indicators of AMR across sample types, host species and detection methods (genotypic, PCR vs. phenotypic, traditional).

O4.3. AMR measures and clinical outcome: Initially, the focus will be on understanding the relationship between indicators of AMR at different levels of aggregation from farm to clone. In Y3-5, the intention is to shift focus to establishing empirical evidence on the relationship between different measures of AMR and clinical outcome after treatment.

O4.4. AMR gene abundancy in soils and critical control points: Using quantitative PCR, archived soil samples (NSIS2 archive) will be screened for a range of known AMR genes. These will be tested for statistical associations with existing data on soil or land-use characteristics. This will be the first inventory of AMR gene abundances in Scottish soils and may inform models on AMR transfer.

Detailed work plan Year 1: (4.1) RT-PCR analysis of archived cattle samples (M4.1a). Statistical comparison of results for PCR-derived and historic AMR results (M4.1b). (4.2) Cross-sectional survey of lactating sheep flocks ($n < 10$; M4.2a) Phenotypic and genotypic analysis of AMR in archived and survey-derived sheep faeces, swabs and milk (M4.2b). Screen nationwide soil archive for a range of AMR gene abundances and thus provide baseline data for development of conceptual models (below) (M4.4a). **Year 2:** (4.1) PCR and selected traditional methods of measuring AMR applied to archived 2014-15 cattle samples (M4.1c). Statistical analysis of, and report results from 2014-15 archived samples (M4.1d). (4.2) Cross-sectional survey of lactating sheep flocks ($n < 10$; M4.2c). Phenotypic and genotypic analysis of AMR in survey-derived sheep faeces, swabs and milk (M4.2d). Report on baseline AMR levels in sheep (M4.2e). (4.3) Prototype model of heterogeneity in AMR at different biological scales (M4.3a) (4.4) Inventory of current AMR gene abundances in Scottish soils (M4.4b) Report identifying soil types and characteristics that are indicative for high AMR burden (M4.4c). Develop and run conceptual model for AMR transfer and validate outcomes using scenario analysis and sensitivity analysis (M4.4d). Analyse network to determine entropy of beliefs to determine the most important drivers in the system (M4.4e).

Objective 5: Utilisation of new tools

O5.1. Nematode population structure: Recently developed molecular techniques will be applied to three distinct nematode populations: (a) archived from TST field studies, to establish if changes in parasitic nematode population occurs over time (within grazing season and/or between years); (b) recovered from field experiments in paddocks carrying only *T. circumcincta,* to determine the effects of introduction of different proportions of anthelmintic resistant *T. circumcincta* on nematode population structure; (c) recovered from field experiments on paddocks carrying mixed nematode species, to determine the effects of various control strategies on numbers and population composition.

O5.2. After Year 2, The mechanisms underlying the difference between lambs that demand high or low levels of anthelmintic support will be defined. Challenge studies with a range of worm species will be used to determine if natural antibodies (Nab) predict the anthelmintic need of lambs.

O5.3. TBD: The suitability of multiplexed diagnostic tests for tickborne pathogens (e.g. *Anaplasma*, *Borrelia* and louping ill virus for the diagnosis of abortions will be investigated (RD2.2.2 O2). In Y4-5, the tests will be used to study the epidemiology of TBD and their role in livestock abortion.

O5.4. OPA: Archived sera from a previous SG-funded programme will be used to validate a new diagnostic assay for preclinical OPA. Once validated, this assay will be used (Y4-5), in conjunction with associated farm level questionnaire, to investigate risk factors associated with preclinical OPA.

Detailed work plan Year 1: (5.2) Analysis of the outcome of ongoing studies, and planning of Y2 studies (M5.2a). **Year 2**: Depending on results from Y1, the effect will be assessed of *T. circumcincta* challenge on housed lambs grouped by NAb level, incl. effects on faecal egg count, onset of egg laying, worm size/fecundity, etc. or a TST field study will be conducted to select lambs based on anthelmintic requirement phenotype, with post-mortem studies to characterise differences between phenotypes (M5.2b).

Expertise: Hutton, SRUC, MRI and BioSS are all recognised nationally and internationally for their expertise in their respective fields as are many members of this team. They play leading roles in EPIC and/or are recognised international consultants in livestock disease epidemiology and public health. MRI is a world renowned animal health research institution with laboratories and animal facilities attaining the highest standards. The SRUC lead cEPIC and the CL3 laboratory is already engaged in UK level research into VTEC and AMR. The Hutton has extensive plant and soil science, microbiology expertise and facilities. All these skills have been blended in a synergistic collaboration embracing many facets of animal and public health epidemiology.

Key linkages, interdisciplinarity & collaboration:

The work involves multiple disciplines, from molecules to models, and is an interdisciplinary effort between Hutton, SRUC, MRI and BioSS. It builds on and expands existing RESAS funded work and links with other major governmental initiatives, e.g. EPIC and CSPASE, which are all underpinned by epidemiology. Members of the team have played a central role in the generation of large datasets to be used in the work proposed. Examples include:

1. VTEC: Historical and recent datasets of VTEC isolates, funded by SG, DEFRA,

Wellcome Trust and FSA to be used in genomics screening (Obj. 3.1). Identification of 'genetic signatures' that are associated with secondary hosts/habitats are candidates for functional screening RD2.3.3 Obj.3.1 (Disease Threats in the Environment). 2. AMR: Work on antimicrobial usage in RD2.2.2 (Evaluation of livestock health) will complement work on AMR in cattle (SO4.1), whereas the presence of AMR in the environment (SO4.4) will be used in modelling in RD3.1.3 (Food Safety) to assess relative impacts of environmental sources on AMR contamination/ dissemination. 3. EPIC: Work undertaken currently in CEPIC is relevant to targeting surveillance for key endemic diseases in sheep (SO1.1). Previous analyses and models produced for sheep scab will be validated using penned trials (SO2.4), linking to CEPIC and NEPIC. 4. Fluke: Improved tools for monitoring of liver fluke (SO2.3) will be used for ecosystem management/biodiversity conservation (RD1.3.3; Resilience of Ecosystems and Biodiversity). 5. Stakeholder & HEI links: Statistical models (SO1.2) will be supported by development work in RD2.2.3 (Disease mechanisms); contribute to NEPIC and systems approaches for paraTB in RD2.3.3 (Disease Threats in the Environment), and pest-natural enemy interactions (RD1.3.1: Biodiversity and ecosystem functions and RD2.1.6: Integrated Pest Management.). Work on identifying and applying incentives to producers for disease control (SO2.2) links with RD2.3.12 (Increasing Uptake of Best Practice). Several topics link to large externally funded projects involving the RD team.
Added Scientific Value: All of the members of the team have extensive networks with academia and non-MRP research institutions, e.g. the Universities of Edinburgh (Royal (Dick) School of Veterinary Studies; Roslin Institute), Aberdeen, Dundee and Glasgow as well as many in England and abroad (e.g. the Netherlands, Belgium, Germany). RESAS funded work will be promoted internationally and will remain nationally and internationally competitive via the use of good working relationships to leverage related projects. CEPIC serves as a solid basis for expansion of different areas; work initiated in SPASE will be extended by using existing datasets for VTEC, ideally using specific expertise available at Glasgow University. Recognition of the work also adds value to non-academic spheres, e.g. to provide *ad hoc* advice on advisory panels like ACMSF (Advisory Committee for the Microbiology Safety of Food).
KE, Audiences and Impact: The main interest in this RD will come from stakeholders with vested interest in farm animal health but also from those in public and environmental health. Research is relevant to policy and at arms-length governmental agencies, but of particular interest to the livestock sector. **Audience:** Major findings will ultimately result in changes in practice induced at policy or industry level. Findings will be communicated through the Centre for Knowledge Exchange and Impact (CKEI) and established networks, e.g. CoZEE (Cooperative of Zoonoses Experience and Expertise). Policy-relevant information will be directed to the Scottish Government Animal Health and Welfare section, and UK-wide to the APHA. Those likely to take up any changes in practice to improve animal health are centred in the food animal industry. Close contact will be maintained with intermediaries to disseminate findings and recommendations, through levy boards (e.g. QMS, Dairy Co, AHDB, HDC), providing a direct link to the livestock industry. Contacts with the veterinary profession will be utilised, via BCVA (British Cattle Veterinary Association), SVS (Sheep Veterinary Society), SRUC Inverness' Veterinary Advisory Group and SAC

Consulting's Veterinary Services. Work of public health relevance will be directed to the FSS, FSA, and HPS. Reference laboratories will be informed of the findings.

Impact:

- The main impact will be improvement in animal health through better understanding of the epidemiology of the underlying diseases (O1). For AMR/zoonotic risks, greater impact may be on public health (SO3, 4).
- O2 actively involves farmer participation and will positively impact on vet-farmer communication. This activity is extremely beneficial in building a network between RESAS-funded work and primary producers and their advisors, with positive implications for future engagement.
- Development of statistical (O1) and bioinformatics (O3) tools will potentially have wide-ranging use in the animal and public health community.
- Tracking, surveillance and improved typing of zoonotic pathogens (O4) is relevant to reference laboratories, e.g. for VTEC (SERL), and the *Cryptosporidium* Reference Unit, and will contribute to better public health.
- As part of the proposal, new tools will be developed to select animals for anthelmintic treatment (O5). This will help to reduce chemical usage and the threat posed by resistant parasites to the future of our livestock industry.

RESEARCH DELIVERABLE NUMBER: 2.2.6 Animal Disease Epidemiology
Work planning and timetable for Year 1

Year 1: 2016/17	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Large datasets							M1.1a		M1.1b	KE1.1a	M1.1c	D1.a
O1.2 Large datasets:								M1.2a				M1.2b
O2.1 Control strategies: models									M2.1a		M2.1b	D2.1b
O2.2 Control strategies: behaviour												M2.2a
O2.3 Control strategies: fluke												M2.3a
O2.4 Control strategies: scab												M2.4a
O3.1 Zoonoses: VTEC							M3.1a	M3.1b	M3.1c		KE3.1a	D3.1a
O3.2 Zoonoses: *Cryptosporidium*												M3.2a
O4.1 AMR: Cattle						M4.1a			M4.1b			
D4.2 AMR: Sheep						M4.2a						M4.2b
O4.4 AMR:												M4.4a

Soils												
O5.2 New tools: treatment phenotype												M5.2a
Annual report (Yr1)												R1

RESEARCH DELIVERABLE NUMBER: 2.2.6 Animal Disease Epidemiology
Work planning and timetable for Year 2

Year 2: 2017/18		Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Large datasets						M1.1d	D1.b			M1.1e	D1.c		
O1.2 Large datasets										M1.2a	M1.2b	D1.2a	D1.2b
O2.1 Control strategies: models							M2.1c		M2.1d	D2.1a		M2.1d	D2.1c
O2.2 Control strategies: behaviour										M2.2b	D2.2		
O2.3 Control strategies: fluke												M2.3b	D2.3
O2.4 Control strategies: scab			M2.4b	M2.4c	M2.4d		D2.4						
O3.1 Zoonoses: VTEC										M3.1d		M3.1e	D3.1b
O3.2 Zoonoses: *Cryptosporidium*												M3.2b	D3.2b
O4.1 AMR: Cattle			M4.1b	D4.1a						M4.1c		M4.1d	D4.1b
O4.2 AMR: Sheep						M4.2c				M4.2d		M4.2e	D4.2a
O4.3 AMR: Models													M4.3a
O4.4 AMR: Soils			M4.4a	D4.4a					M4.4b ,	M4.4c		M4.4d	M4.4e
O5.2 New tools: treatment phenotype													M5.2 b
Annual report (Yr2)													R1

Name of RD: 2.2.7 Welfare assessment techniques
Research aim and key drivers A key recommendation by FAWC (2009), and since reiterated by Scottish Government Animal Health and Welfare Strategy Group, Welfare Working Group (SGWWG) is that 'All animals should have a life worth living and most animals should have a good life [in Scotland]'. The aspiration to improve positive welfare in Scottish livestock faces the challenges of understanding what is meant by positive welfare (including the balancing of negative and positive experiences across the animals' life), and hence how to assess positive welfare. Furthermore to promote the concept of positive welfare in farm animals requires that we have an understanding of the 'demand' for positive welfare in society and persuading the 'supply chain' that there is value in farm animals having positive experiences. To address the policy driver of promoting positive welfare in Scottish livestock we propose the following inter-related research areas (Objectives): (**O1) Understanding expert and lay perspectives of positive welfare** and the implications for assessing positive welfare; **(O2) Investigating the role of maternal care in positive welfare** for mothers and their offspring; **(O3) Understanding the welfare impact of harms** such as disease and 'passivity' to quantify the balance of negative and positive experiences across an animals' life history; **(O4) Implementing Qualitative Behavioural Assessment (QBA),** as a tool for farmers to recognise and enhance expressions of positive welfare; **(O5) Development of 'automatic' assessment approaches** to monitor a range of negative and positive welfare measures. These areas have been chosen following discussion with policy and stakeholder contacts (Andrew Voas (SG), Nigel Miller (NFUS), Stuart Earley (SSPCA)), matched to the expertise and skill-base within the MRPs in order to maximise the scientific value and impact of the research.
Summary of the proposal: **Objective 1 Understanding expert and lay perspectives of positive welfare** There is an increasing policy interest in ensuring that animals are provided with 'positive welfare' where we seek both to prevent harms to animals and allow them to have positive experiences. There are a number of scientific perspectives emerging on what might be 'positive animal welfare' which place different emphases on how to provide for positive welfare and how it can be assessed, and there is a need to synthesise these. Whilst there have been social science studies exploring wider perspectives of animal welfare, none have specifically analysed expert and societal understandings of positive animal welfare and their underlying bases. The extent to which expert and lay views of positive welfare align is therefore unclear and a potential significant constraint to improving positive welfare in Scottish livestock approaches will be used to analyse expert and lay understandings of 'positive animal welfare' (O1.1; O1.2), and the implications of these both for assessing positive welfare (O1.3) and characterising the capacity of Scottish livestock systems to deliver positivewelfare (O1.4). We have an established track record in studying the biology of positive welfare and also psychologically based study of peoples' perceptions of animals and their welfare. There is much novelty in bringing these 2 aspects of our science together to directly address positive animal welfare, linking to RD2.3.12 (O4). Key deliverables include: O1.1 Published review of natural science perspectives of positive welfare (Month 18); Refereed paper on expert and lay perspectives of

positive welfare and the underlying bases for these perspectives with summary for wider distribution (Month 30); Mapping of assessment approaches to natural science and lay perspectives of positive welfare (Month 30); Publish report on characterisation of Scottish livestock systems to deliver positive welfare from natural science and lay perspectives (Month 54).

Objective 2: Investigating the role of maternal care in positive welfare: Farm livestock numbers are largely comprised of mothers and their offspring with systems varying in the length and quality of direct maternal care provided. In humans and rodents, offspring development is influenced by maternal relationships and the opportunities for offspring to express positive welfare may be constrained by their early life experiences, although this has rarely been considered in livestock. Based on a long track record in maternal behaviour research, this work will consider the role of maternal behaviour in providing positive welfare for the mother and a good life for their offspring, using experimental studies that will make use of planned work on QBA in O4 and in other RDs (e.g. lamb castration (RD2.2.8, WP2.2) and food restriction in sows in RD2.2.8, WP2.2).

Key deliverables include: O2.1 Report on associations between maternal care, positive welfare and offspring production and positive welfare benefits (Month 10); 2. Assess the impact on positive welfare of current commercial systems that promote maternal care, and consider options for development of other systems (Month 24; M6-7; KE3); 3. Assess longer term impacts that increased maternal care may have in buffering offspring pain responses (Month 48, M8); 4. Publish paper on the role of maternal care in promoting good welfare for mother and offspring (Month 60).

Objective 3 Understanding the welfare impact of harms: The welfare costs of disease are rarely quantified in relation to the cost to the animal. Disease treatment often deals with the disease source, without considering the impact of the symptoms (e.g. discomfort) on the animal. Evidence suggests that there may be both productivity benefits and welfare improvements in considering disease symptoms. The two areas of work proposed under this Objective cover an endemic disease in sheep (‘sheep scab’) and the role of ‘passivity’ in welfare and production diseases in dairy cattle. *3.1 Sheep scab* is an unpleasant and highly contagious disease which has also been developed as a robust disease model. Our preliminary work suggests that considering the impact of the disease on animal behaviour and physiology can help to identify early indicators of disease and to evaluate the welfare impact of treatment. In collaboration with RD2.2.5 we will quantify the welfare costs of sheep scab, before investigating whether treating the symptoms of scab, as well as the infestation, can improve recovery and welfare.

3.2 Dairy cow passivity: Our previous work shows dairy cows are increasingly housed for longer periods. Cows spend a significant period of their time when housed in passive ‘low activity’ states (standing without rumination, social activity, oestrus and exploration). We aim to recognise, along with work in O4, the relationships between ‘low activity’ states and health and welfare concerns. Volunteer dairy farmer groups in Scotland will be assessed for attitudes to ‘passivity’ and any methodologies farmers use to reduce ‘low activity’ (e.g. exercise areas, grooming brushes); this will complement our previous work on loafing areas for housed cows.

The key deliverables will include: 3.1 Calculate the welfare costs of sheep scab to infested sheep (M9; O3.1.1 Month 20); 3.2: 1. Assess welfare of cows that exhibit passive behavioural states, using behaviour and physiological recording (Month 15; O3.2.1). 2. Investigate database to retrospectively pinpoint cows showing passivity to investigate co-occurring states of welfare. (Month 36); 3. Farmers focus groups to understand attitudes and mitigation strategies (Month 40).

Objective 4 Implementing Qualitative Behavioural Assessment (QBA): QBA focuses on whole-animal expressivity and is an indicator for positive welfare in the protocols from EU FP7 projects 'Welfare Quality' and 'Animal Welfare Indicators'. Its robustness in on-farm conditions was further validated from the 2011-2016 SRP. Scottish farmer focus groups indicated that farmers value QBA as an extension of traditional stockmanship, and prefer a participatory, self-management approach to explore its benefits. Focusing on positive welfare expression will shed light on how animals experience its absence, through little-studied states such as boredom, lethargy, or exhaustion (linked to Objective 3). 2011-2016 SRP research on pain in castrated lambs showed QBA to be adept at distinguishing between positive and negative 'low activity' states. This research will collaborate with industry (OMSCo for dairy cattle and BPEX for pigs), to develop practical strategies for implementing QBA as a tool for enhancing positive expressions of welfare on farms. This will involve work with small volunteer farmer groups (linking to RDs 2.2.8 and 2.3.12). SRUC provides international leadership in scientific and applied QBA research. This will be the first collaboration with livestock industry to investigate the uptake of QBA in commercial food production.

The key deliverables will include: 1. Develop farmer-driven mechanisms for implementing QBA on farms (Month 12; A15;KE5); 2. Apply QBA to the recognition of positive and negative 'low activity' states (Month 24; A17; KE8); 3. Further develop QBA app and website to support this research (Month 18; A20; KE9).

Objective 5 Development of 'automatic' assessment approaches New technologies have potential to monitor animal welfare remotely in real time. We will study sensor systems and video-based technologies to monitor both negative and positive welfare states. As potentially useful new technologies become available for 'Smart Farming' systems in livestock farming, underpinning science to validate their use against conventional animal-based welfare measures based on behaviour, health or function is needed. Integration of data from multiple sensor modalities has potential to improve measurement of animal states. Work is proposed in four areas: 1) Detection of pain in dairy cows (e.g. caused by lameness) using video to detect 'pain faces'. Research has shown that animal facial expressions can indicate pain; 2) Use of 3D video images for automatic detection of behaviours indicating both positive welfare (e.g. play) or early stages of negative (e.g. tail biting) welfare events enabling assessment or real-time monitoring systems; 3) Assessment of the ability of different kinds of sensors (e.g. thermal imaging, water use) to detect poultry production and welfare-relevant states: e.g. thermal stress, feather cover, disease; 4) Development of statistical methods to interpret high volume data.

Key deliverables will include: 1. Assessment of cattle 'pain faces' in response to different painful conditions (Month 24; A26); 2. Collection of video and animal data on pigs showing play and pre-tail biting behaviours and determine whether early-warning behavioural indicators for a tail-biting outbreak can be identified (Month 24; A23 and A27); 3. Evaluate different sensor modalities in poultry housing to determine which are most useful at detecting deviations from 'normal' indicating health or welfare issues (Month 60). Adaption of Generalizability Theory to behavioural assessment data classes (Month 24; A29).

Technical approach

Animal work will be approved by our Animal Ethics Committee; sample sizes will be based on our previous experimentation and in consultation with BioSS.

Objective 1 Understanding expert and lay perspectives of positive welfare

1.1 Positive animal welfare from natural and social science perspectives:

Natural science: We will synthesise existing literature on positive animal welfare and identify knowledge gaps to inform our experimental work (with Objectives 2 and 3). Social science: We will undertake an interview study of understandings of positive welfare involving experts and the lay public**.**

1.2 Factors underlying different understandings of positive animal welfare:

Social science: We will develop and apply a questionnaire using data from the interview study to establish psychological constructs influencing different perceptions of positive welfare and the relationships between factors. We will sample 'supply- side' experts and 'demand-side' citizens/consumers. We aim to establish this as a longitudinal study (for the first time in animal welfare studies) to test causality between factors using Structured Equation Modelling (SEM).

1.3 Map assessment approaches to different meanings of positive welfare: *Natural and social science:* We will map existing welfare assessment protocols against expert and lay understandings of positive welfare, and identify knowledge gaps that can be addressed through experimentation.

1.4 Characterise existing systems for capacity to deliver positive welfare:

Natural & social science: We will develop a framework to characterise the main systems of production for Scottish livestock species in terms of their capacity to deliver positive welfare; e.g. the repertory grid method could be used to elicit preferences for welfare systems. We will identify areas where innovation could be used to enhance achievement of positive welfare.

Detailed work plan

Year 1: *Natural science*: Report on preliminary synthesis of natural science perspectives of positive animal welfare (including reference to human studies) illustrating overlap and distinction between scientific perspectives (M1). Start experimentation on knowledge gaps (e.g. do early positive experiences such as play lead to longer-term positive mood) (M2). Social science work cannot start before Month 12 due to other commitments. Report to stakeholders (KE1). This will link to work with supply chain actors in RD2.3.12.

Year 2: *Natural science*: Publish review of natural science perspectives of positive welfare (O1.1); initiate mapping of existing welfare assessment protocols against expert and lay understandings of positive welfare including review of evidence on the reliability, validity and practicality of assessment approaches (M3). Publish experimental results on knowledge gaps from Year 1 (O1.2) and carry out further experimental work (M4); e.g. use of compositional data analysis approaches that explicitly account for the relative and constrained nature of behavioural data in order to improve data analysis and scientific conclusions. Social science: Interview study of expert and lay perceptions of positive welfare will be a matched sample design using a continuous association technique, to assess the free associations people form with respect to 'positive animal welfare'. Participants will self-evaluate these associations to create a nominal scale (negative to positive), which we will translate into quantitative terms. A repertory grid approach or similar will be used, to identify the main psychological constructs influencing perceptions of positive welfare (M5). Report to SGWWG (KE2). Continue links to RD2.3.12.

Objective 2 Investigating the role of maternal care in positive welfare*:* 2.1: Using existing and new video footage of maternal animals and their offspring we will analyse (using QBA and other indicators of emotionality e.g. ear postures) the potential affective state of maternal animals when interacting with their offspring. In combination with evidence in the literature (e.g. neurological state of maternal females) we will assess the capacity of maternal care to generate positive affective states in mothers and offspring. With O4 and industry stakeholders, we will use the video material to assess attitudes to rearing practices that maximize expression of maternal care (KE3). 2.2: To test hypotheses addressing the benefits of maternal care in *sheep* (with RD2.2.8) we will extend current research findings from 2011-16 SRP on maternal response to offspring pain caused by on farm procedures. Using castration or tail-docking models, we will assess whether maternal care can buffer offspring pain responses in the short and longer-term. 2.3 In *pigs*: we will link with research on play behaviour (Objective 1) and feeding the pregnant sow (RD2.2.8) to assess the contribution of maternal behaviour to expressions of positive welfare in her offspring.

Detailed work plan

Year 1: Complete video analyses of existing footage. Report on evidence that maternal care influences positive affective state in the mother and offspring (O2.1). Liaise with work in O4 on stakeholder engagement with positive welfare. Liaise with work under RD2.2.8 (lamb pain and feeding the pregnant sow), and play behaviour to develop protocols to identify the role of mothers in offspring positive welfare (M6).

Year 2: Investigate attitudes and interests of public and industry stakeholders towards the role of maternal care in offspring development to gauge motivation to bring about husbandry changes (M7; KE3). Initiate an experimental study to investigate whether this increased maternal care has a functional benefit to the lamb in mitigating some pain and/or buffering longer term responses to pain (M8).

Objective 3 Understanding the welfare impact of harms:

3.1 Sheep scab: Building on our previous research we will assess the welfare impact of sheep scab using cross validation of existing (e.g. faecal cortisol metabolites) with new (QBA, immune markers) welfare measures to identify changes associated with infestation with the sheep scab mite (*Psoroptes ovis*). We will investigate the use of a systemic non-steroidal anti-inflammatory drug (Metacam™) as a means of alleviating the symptoms of sheep scab that persist following traditional treatment with injectable macrocyclic lactones (i.e. Dectomax) and its impact on selected welfare and inflammatory markers of disease. We will use the sheep scab studies in RD2.2.5 to assess the effects of vaccination on welfare and inflammatory markers associated with sheep scab (including measurement of cytokines in serum and potentially blood cells). We will further consider how other endemic diseases may impact on animal welfare, to assess a) how these may be incorporated into economic models of disease impact, and b) whether options to treat the welfare symptoms of disease might be exploited.

3.2 Dairy cow passivity: We will carry out behavioural and physiological recordings from cows showing variation in passive 'low activity' states at early and late lactation, to assess relationships between 'passive' cows and key behaviours, physiological changes and production levels. The 'Langhill' herd database will be interrogated to retrospectively assess patterns of early health and welfare problems in cows that later show passivity. We will use farmer groups to understand attitudes to passive 'low activity' states and methods used to mitigate low activity (with RD2.3.12).

Detailed work plan

Year 1: *3.1 Sheep scab:* Complete two further replicates of pre- and post infestation data collection (behaviour and physiology data collected for 9 weeks per replicate) (M9). Analyse activity time budgets, and behaviours specifically associated with scab (e.g. newly identified 'head-roll' behaviour). Collect high quality video data for QBA, and assessment of other markers of animal emotional state (e.g. ear posture), blood and faecal samples for analysis of stress physiology and immune function (cytokines), and assess the clinical symptoms (lesion size). Analyse these data alongside existing data, and the application of QBA, to understand the impact of scab infestation on sheep emotional state. Publish results (O3.1.1); *3.2 Dairy cow passivity*: Initiate on-farm behavioural and physiological measurements (M10); Recruit farmers to the study (M11; KE4).

Year 2: *3.1 Sheep scab:* Publish results from Experiment 1 (O3.1.1). Conduct detailed planning for experiment, to investigate the impact of MetacamTM, on the most relevant markers for animal welfare (M12). *3.2 Dairy cow passivity:* Interrogate database and carry out focus groups (M13). Publish results from Year 1 (O3.2.1).

Objective 4 Implementing Qualitative Behavioural Assessment (QBA):

4.1: Uptake of QBA by farmers: Volunteer groups (each 5-10 farmers) will be recruited through Omsco (dairy cattle) and BPEX (pigs). Group locations will be logistically determined. These locations may fall outside Scotland, however the selected farmer groups will serve as case-studies applicable to Scotland. Farmer groups will receive basic QBA training, including video-based and on-farm reliability testing. They will create a plan for pilot-testing implementation of QBA as a welfare management tool involving: 1. collection and evaluation of on-farm video footage; 2. development of QBA terms for assessing qualities attributable to positive animal welfare; 3. baseline data-collection on these terms using QBA-apps, multivariate data-analysis and evaluation of emerging 'quality of life' dimensions; 4. management interventions aimed at enhancing welfare, data-collection/analysis and evaluation of the interventions' efficacy in improving the animals' quality of life. Outcomes of these activities will be evaluated and integrated into personal QBA uptake plans. Larger meetings will be organised to compare outcomes and formulate QBA uptake strategies.

4*.2 Apply QBA to the recognition of positive and negative 'low activity' states*: (with Objective 3). Video footage will be collected of individual dairy cattle and pigs in low activity states (e.g. standing, resting), under various housing and environmental conditions, at standardised times of day, including repeat filming of the same animals in indoor winter and outdoor summer conditions. Video footage will be assessed using QBA, presenting individual clips randomly to 'blinded' observers (not linked to farm groups).

4.3: Further develop QBA app and website: The QBA app is developed for online automated data collection and benchmarking of multiple farms through Principal Component Analysis (PCA). We will now develop it for longitudinal on-farm data collection, using PCA to generate time-lines and patterns of baseline variation against which the effects of interventions can be evaluated. The QBA website will be further developed for accommodating video libraries, and a QBA scoring training tool by which assessors can calibrate use of QBA scales against distributions of PCA scores generated by expert cattle and pig teams.

Detailed work plan

Year 1 *4.1:* Deliverables and timings will be subject to engagement with and feedback from, Omsco and BPEX. Organise two meetings for dairy cattle and pig farmer groups for QBA training and to create work plans (M14; KE5); *4.2:* Start collection of video footage of low-activity states in cattle and pigs (M15); *4.3:* Completion of QBA app for longitudinal off-line on-farm use (M16; KE6).

Year 2: *4.1:* Collection of on-farm video footage by farmers, and generation of QBA terminologies for positive welfare by each group (M17; KE7). Two meetings for each group to initiate video footage collection, and to assess this footage for generating QBA terms (M18; KE8); *4.2:* Continued video collection and editing coordinated with 4.1 (M19); *4.3:* Pilot QBA website with stakeholders (M20; KE9).

Objective 5 Development of 'automatic' assessment approaches: We will collect sensor and video data and corresponding conventional measures, to characterise states of interest. Producing automated algorithms to process data in real time requires external collaboration for which our data will be a starting point.

5.1 Pain faces in cattle: We will collect images of individual cattle during painful conditions and compare them with appropriate controls. We will start with an acute state (parturition) and then expand states associated with semi-acute (mastitis and acidosis) and chronic (lameness) painful conditions.

5.2 Detection of pig behaviour: For piglet play, existing video sequences have been watched and behaviours of interest characterised by observers. 3D video will be collected in the next phase of this work. For pig tail biting, 'precursor' behaviours will be identified by an observer from video collected in the week prior to an outbreak. We will work towards commercialisation, or may investigate other welfare-relevant behaviours such as farrowing difficulty later in the programme.

5.3 Sensors to detect welfare issues in poultry houses: Different sensor modalities will be trialled in poultry housing to find a system(s) that detects animal or flock-level changes indicative of behaviour, health and welfare (e.g. vocalisations correlated with video recordings of behaviours). Thermal images will also be analysed (e.g. to quantify bird feathering). Appropriate variables will be correlated with other data (e.g. performance, health status, or carcase traits).

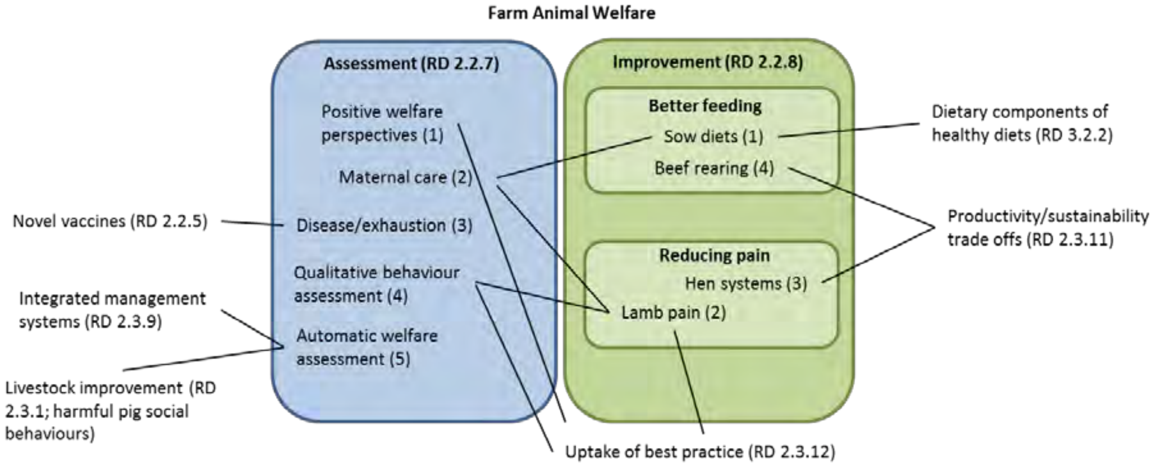
5..4 Application of Generalizability Theory to welfare diagnostics: Current work adapting and applying Generalizability Theory to diagnostic test data will continue with a focus on data from Objective 5, including development of Markov Chain Monte Carlo (MCMC) based models, extension to non-normally distributed data, and development of suitable frameworks for application to Objective 5 datasets.

Detailed work plan

Year 1 *5.1 Pain faces in cattle.* Images of faces of cattle in known, but spontaneous, acute pain states (e.g. mastitic or in labour) will be captured and compared to faces 2-3 weeks later (if the animal is deemed healthy) and key facial features analysed (e.g. tightening of nares and eyes) to define facial changes characteristic of pain (M21); *5.2 Detection of pig behaviour* Piglet play Seek collaborative opportunities to automate play detection using existing annotated video of playing pigs (M22). Collect new 3D video of young pigs expressing different behaviour (play and non-playful activity); produce detailed behavioural annotations, for automation of behavioural classifications through collaboration (M23); *5.3 Sensors to detect welfare issue in housed poultry*. Individuals and groups of birds will be studied. Stressors would include e.g. thermal stress, altered litter moisture and quality. A variety of sensors of different modalities and video will be mounted in the housing to record responses (M24); *5.4 Generalizability Theory*. MCMC formulation of standard model completed (M25).

Year 2: *5.1 Pain faces in cattle*: Images will taken from animals in chronic pain (e.g. lameness), and repeated once the animal has been treated and recovered. Images will be compared to determine whether changes in expression can be detected (M26); *5.2 Detection of pig behaviour Tail biting* A situation with a high risk for tail biting will be continually monitored with 2D and 3D video. In the event of an outbreak, video from the week prior to the outbreak from affected pens (and unaffected controls) will be watched to identify 'precursor' behavioural differences. Annotated videos will form the basis for collaborative work to develop algorithms to automate behavioural classification as an early warning for tail biting; (M27); *5.3 Sensors to detect welfare issue in housed poultry*: Analysis of sensor data relating to for example vocalisations, and water use to identify features which correlate with physiology and production and health parameters. (M28); *5.4 Generalizability Theory*. MCMC formulation of non-Normal model developed (M29).

Key linkages, interdisciplinarity & collaboration (industry links underlined)



(1) WP2.2: There are strong inter-linkages within RD2.2.7 with its overarching focus on positive welfare (from natural and social science perspectives), and between the work in RDs 2.2.7 and 2.2.8 where complementary work is being planned to ensure collaboration and efficiency of research use; e.g. **Objective 2 Maternal care** will share experimental design aspects and data collection with RD2.2.8; **Objective 4 QBA** will use video footage collected in RD2.2.8. With respect to other RDs in WP 2.2: Objective 3 Welfare studies of harms will work in conjunction with RD2.2.5 on development of vaccines and if novel markers of inflammation/welfare are identified these may feed into RD2.2.4.

(2) WP2.3: **Objective 1** will provide the basis for discussions <u>with supply chain actors</u> in RD2.3.12 to understand how positive welfare can be promoted in practice. **Objectives 2 and 3.1** will feed into RD2.3.11 contributing to welfare assessment of extensive sheep systems. **Objective 3.1 and 4 QBA** inputs directly into, and benefits from, <u>RD2.3.12 research on increasing uptake of best practice</u>. The volunteer farmer groups driving this work can be considered as a 'community of practice', and will ensure that procedures followed and data collected with these farmer groups are relevant to both RDs. **Objective 5 Automatic monitoring** will collaborate with RD2.3.9 to bring synergies to both programs in developing and utilising sensors for detecting welfare issues (e.g. dystocia in ruminants).

(4) Across MRPs: We will continue to develop promising work on mathematical modelling of behaviour, e.g. applications of compositional data analysis and latent class modelling. Our joint work on welfare aspects of disease has scientific novelty

and is relevant to development of policy in this area.
(5) The work planned here is relevant to the aim of the SG Animal Health and Welfare to improve positive welfare in Scottish livestock. We will keep the SGWWG informed of our progress on a regular basis and be open to discussion and interactions on our future plans.

Added Scientific Value: There is growing academic interest in understanding the importance of positive experiences for human and animal health and well-being. This RD will make a significant contribution to scientific understanding of positive animal welfare, in collaboration with other national and international research. **Objective 1 Understanding positive welfare** will be closely associated with the Roslin Institute where Lawrence holds a joint position. This will allow for neuroscience research on the biology of positive welfare with colleagues Meddle and Brown. **Objective 2 Maternal care and positive welfare** is in part a continuation of SPASE research linked to other HEI partners (e.g. Universities of Edinburgh and Glasgow) and will extend our understanding of the contribution of maternal behaviour to positive welfare in later life**. Objective 3 Welfare studies of harms** continues a research collaboration between SRUC/MRI on the welfare impact of disease and further exploits a well established sheep scab disease model, which is supported by Underpinning Capacity. **Objective 4 Implementing QBA** continues a long-standing line of research with University of Bristol (with Main and Mullan) on introducing QBA to the livestock industry. More widely we are aware of other groups working on positive welfare (e.g. Boissy, Mellor, Keeling, Mendl) and will seek appropriate collaborations where possible. **Objective 5 Automatic monitoring** encompasses a number of academic and industrial collaborations relating sensor and video use to monitor behaviour and welfare. We will continue to submit proposals on all aspects of RD2.2.7 to RCUK and other appropriate funders (e.g. Innovate UK, NC3Rs, ANIWHA).

KE, Audiences and Impact
Audience
Policy: This research is intended to directly inform the SG Animal Health and Welfare Board and other relevant policy groups (FAWC, AHWBE, industry groups, EU) in their aim to promote positive animal welfare in Scottish livestock. We will communicate with UK and international policy groups (e.g. Scottish Sheep Scab Industry Group; Defra, FAWC, EU). *Industry:* The research will have a direct relevance to the supply chain. For example Objective 4 Implementing QBA will work directly with cattle/pig farmers and directors of OMSCo and BPEX. *Public*: Dissemination of our research will be enhanced through linkages with Welfare Quality and AWIN networks and Edinburgh University online animal welfare education courses such as the MOOC on Animal Welfare https://www.coursera.org/course/animal. We also intend to establish a virtual Animal Welfare Centre with partners, which would be a publicly available site providing access to amongst other things news and results regarding animal welfare activities in the programme.
Impact
O1: Perspectives on positive welfare: We will report annually to the SG Animal Health & Welfare Board and seek advice as to further KTE activity to promote positive welfare across supply chains and to the public. At the programme mid-term we will run (in conjunction with RD2.3.12) an open meeting for stakeholders and public to discuss findings and future actions; we will adjust our future work accordingly. By the end of the programme we will be demonstrate changes to

welfare standards in at least 2 supply chains to accommodate positive welfare aspects.
O2: Maternal care and positive welfare: With O4 we will work with farmers using video footage made on farms, as a means to open a dialogue with the public and industry on the role of maternal care on farm. We will develop material for dissemination via the web and our biannual October Animal Welfare Days
O3: Welfare impacts of harms: Work on sheep scab will be disseminated via existing links to the Scottish Sheep Scab Industry Group and at Sheep Veterinary Society meetings and to members of the National Sheep Association.
O4: Implementing QBA: This work is aimed at enhancing uptake of QBA in commercial farming practices, and at achieving a greater awareness of best practice in farming communities. Outcomes will be disseminated through internal and public stakeholder reports, articles in the farming press, presentations at livestock industry meetings (and via the routes described under Audiences (above).
O5: Automatic monitoring: We will liaise with farmers and stakeholders in farm animal precision livestock management, such as agricultural engineering companies involved in designing health and welfare monitoring tools, and welfare assessment bodies who may ultimately use these remote assessment tools.

RESEARCH DELIVERABLE NUMBER: 2.2.7 Welfare assessment techniques procedures

Gantt chart for Year 1: Showing Key research activities (A), deliverables (D), KE/impact events (KE) and Reports to RESAS (R)

Year 1: 2016/17 Activity	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
1.1 Natural science perspectives of positive welfare – preliminary report											**M1**	
1.1 Commence experimentation as indicated from synthesis of science						**M2**						
2.1 Analyse data on links between maternal care and positive welfare										**O2.1**		
2.2 Develop protocols to investigate the role of maternal care in offspring positive welfare												**M6**
3.1 Complete replicates of sheep scab experiment												**M9**
3.2 Initiate farm study of cow passivity using video, sensor and parlor data		**M10**										
3.2 Recruit farmers to cow passivity study									**M11**			
4.1 Organise meetings with farmers for training and creation of work plans			**M14**						**M14**			
4.2 Collection of video for QBA study of low activity states in cows									**M15**			
4.3 Complete QBA app for on-farm use												**M16**
5.1 Capture images of cows to determine facial characteristics of pain												**M21**
5.2 Seek collaboration to automate detection of play behavior in pigs						**M22**						
5.2 Collect 3D video of young pigs to detect play and non-playful behaviour												**M23**

RESEARCH DELIVERABLE NUMBER: 2.2.7 Welfare assessment techniques procedures

Gantt chart for Year 1: (continued) Showing Key research activities (A), deliverables (D), KE/impact events (KE) and Reports to RESAS (R)

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
5.3 Use of sensors to study responses to various stressors in poultry												M24
5.4 Complete formulation of standard model to implement Generalizability Theory												M25
1.1 Report on synthesis of natural science perspectives to stakeholders (SGWWG)												KE1
3.2 Engage with farmer stakeholders on cow passivity study									KE4			
4.1 Engage with farmer groups in QBA study									KE5			
4.1 Engage with stakeholders on completion of QBA app												KE6
Annual report												

RESEARCH DELIVERABLE NUMBER:

Gantt chart for Year 2: Showing Key research activities (A), deliverables (D), KE/impact events (KE) and Reports to RESAS (R)

Year 2: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1.1 Publish: natural science perspectives on positive welfare; experimental results					O1.1 O1.2							
1.1 Map welfare protocols to positive welfare perspectives; experiment			M3/ M4									
1.2 Analysis of psychological constructs influencing positive welfare perceptions												M5
2.1 Stakeholder study of attitudes to the role of maternal care in positive welfare												M7
2.2 Initiate experiment to investigate a role for maternal behavior in pain mitigation										M8		
3.1 Publish – results from sheep scab work in Year 1									O3.1.1			
3.1 Initiate Metacam® experiment										M12		
3.2 Publish – results of farm study of cow passivity			O3.2.1									
3.2 Interrogate data-bases and carry out focus group work with farmers												M13
4.1 Collect on-farm video; generate QBA terminologies						M17						M18
4.2 Continue to collect and edit video footage												M19
4.3 Pilot QBA web-site with stakeholders						M20						

Gantt chart for Year 2 (continued): Showing Key research activities (A), deliverables (D), KE/impact events (KE) and Reports to RESAS (R)

Year 2: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
5.1 Detection of pain faces in cattle												M26

2.2.7 Welfare assessment techniques

5.2 Annotation of video in tail-biting work and development of collaborations												**M27**
5.3 Identify sensor parameters that correlate with health and welfare												**M28**
5.4 MCMC formulation and non-Normal model developed												**M29**
1.1 Report to stakeholders (SGWWG) with update on positive welfare research												**KE2**
2. KE with stakeholders in relation to the role of maternal care in positive welfare											**KE3**	
4.1 Work with stakeholders on development of QBA												**KE7/ KE8**
4.3 Work with stakeholders on QBA web-site						**KE9**						
Annual report												**R**

Name of Research Deliverable: 2.2.8 Improved husbandry & reduction of painful procedures

Research aim and key drivers

The welfare of farmed livestock is a high-profile ethical issue of concern to citizens and consumers, as recognised by Scottish Government, UK and EU policy and legislation. Food companies including wholesalers and retailers (e.g. Marks & Spencer, Waitrose, and Sainsbury's), welfare charities (e.g. SSPCA, RSPCA) and levy bodies (e.g. Quality Meat Scotland (QMS)) engage with producers in various ways to promote and sell food products with standards of welfare higher than the legal minimum. The work of this RD will inform these stakeholders and livestock producers of husbandry and management approaches to reduce negative welfare and promote positive animal welfare. This aim accords with the Scottish Government Animal Health and Welfare Strategy Group, Welfare Working Group (SGWWG) aim that 'All animals should have a life worth living and most animals [in Scotland] should have a good life'. As well as assessing welfare impacts, we will work with socio-economists to explore trade-offs (or potential win-wins) between welfare and production economics of the different management/housing/husbandry practices we investigate.

Our work will focus on case studies corresponding to the four areas for research listed by RESAS in the Invitation to Tender for Grant Funding (ITGF), resulting in four objectives (O#). These areas of work build on existing knowledge and expertise held in the MRPs. For each objective, welfare and production aspects of livestock husbandry methods or management systems will be investigated to provide a scientific evidence base to benefit farmers and other stakeholders.

Two of the objectives relate to painful management practices: tail docking and castration of lambs (O2) and beak trimming of laying hens (O3). In each case we will investigate and promote management changes which reduce the need for these painful procedures and in O2 will look at less painful alternatives. The other two objectives relate to pregnant animals (sows in O1 and beef cows in O4) in which feed is restricted. We will investigate the benefits of different management and feeding methods to promote satiety and optimise the welfare and production of the dam and offspring. In the development of this proposal, we have consulted with stakeholders including feed companies, QMS and SSPCA, and for O3 with the WPSA's working group on poultry behaviour and welfare, Defra's Beak Trim Action Group (BTAG) and the British Free Range Egg Producers Association (BFREPA).

Summary of the proposal:

O1 *Food restriction in pregnant sows*

O1 Pregnant sows are fed a restricted amount, whilst EU Council Directive 2008/120/EC and UK codes of practice (Defra 2003) require the use of feeding systems to ensure that sows get sufficient food and are "given a sufficient quantity of bulky or high-fibre food as well as high-energy food". Consultation with commercial feed companies suggests that typical sow diets are relatively low in fibre, assuming that straw bedding constitutes an additional source of fibre. Novel co-product feed ingredients may represent an opportunity for adding fibre to sow diets. In this objective, we will review the variety of pig industry responses to the requirement for fibre, the diverse systems for defining and describing dietary fibre types, and consider the wider practical issues affecting the use of high fibre diets (1.1). Welfare measures of hunger (such as abnormal oral behaviour) in dry sows will be identified by observational studies in different systems (1.2). Recent research at RINH (CWP Healthy, Safe Diets 7.1.2) using rats has shown that dietary fibre is 'filling'. It increases gut hormones which signal 'fullness' leading to reduced energy intake, body weight and obesity. Different types and quantity of dietary fibre will be fed to rats to investigate and quantify the physiological processes (in the brain and gut) underlying hunger/satiety which will inform experiments in sows (1.3). Specific systems and diets will be experimentally tested in terms of their welfare impact in sows (i.e. their effectiveness at reducing behavioural signs of hunger such as abnormal behaviour) and in terms of their impact on sow (and piglet) performance and production (1.4). The work will build on existing expertise in behaviour and welfare, nutrition and physiology relevant to hunger/satiety, and complementing previous RESAS and ongoing BBSRC and EU-funded related projects.

Key deliverables include: Web-based article on dry sow diets and systems for farmers (KE1). Refereed papers on sow oral behaviours (D2), rat fibre (month 30) and sow fibre experiments (month 36). KE presentations at industry events reporting on sow fibre findings (month 48). (Numbering system for deliverables relates to Gantt Charts listing Activities (A#), Deliverables (D#) and KE/impact events (KE#)).

O2 *Reducing pain associated with management procedures in lambs*

O2 Castration and tail docking of lambs without using anaesthesia or analgesia are permitted (at particular ages). Research over 20 years shows that these procedures cause pain, which depends on the method used. Castration is used to prevent unplanned mating and aggressive behaviours, but the most painful method (application of tight rubber rings to the scrotum or tail) is still the most commonly used in the UK. In CWP 6.3, we identified less painful methods of castration, and proved the efficacy of a virtually pain-free alternative (sterilisation of rams using vaccination against hormones involved in the production of testosterone). Further, we showed that leaving male lambs entire had significant growth and carcase benefits. We also found that farmers understand that these procedures cause pain, but are not aware of low pain alternatives that in some cases could improve production. In O2 we will provide more information for farmers on different methods of lamb castration, and investigate if alternative methods, or a reduction in castration, can be encouraged and used on farm to achieve welfare benefits for male lambs. We will also experimentally investigate any new developments in castration methods or alternatives to determine their effectiveness in reducing pain.

Tail docking is used to reduce the risk of flystrike, which occurs when blowflies lay their eggs in faecal matter attached to the wool under the tail, resulting in maggots which feed on sheep, causing significant suffering. However recently evidence to support its efficacy has been questioned. We will review the evidence on whether tail docking does provide protection against flystrike in Scottish flocks and disseminate the findings to farmers. Incidence of flystrike may occur in less than 5% of animals, whereas all tail docked lambs experience pain. Furthermore, evidence from 2014 suggests that tail docking can influence responses to painful events (such as giving birth) much later in life. We will apply novel methods, including Qualitative Behavioural Assessment (QBA), to investigate the impact of pain exposure in early life on the experience of animals and whether this can be mitigated by practical on-farm methods.

Key deliverables include: Web based and other KE materials (KE2) and attendance and Knowledge Exchange at farmer focus groups (KE3) on lamb castration. Review on the effectiveness of tail docking in preventing flystrike (D4). Testing efficacy of new castration methods (as needed up to month 60).

O3 *Improved housing for laying hens that reduces the need to beak trim*

O3 Laying hens are usually beak trimmed, as feather pecking continues to be a major welfare concern and moves to end beak trimming require housing and husbandry (along with genetic approaches) which reliably reduce the chance of feather pecking developing. Husbandry practices, however, have undergone rapid changes recently: following the ban on conventional cages, laying hens are housed in furnished cages, or loose housed in single or multi-tier systems, and are kept in much greater numbers than previously. There is concern that, despite fulfilling legislative requirements, hen welfare may be compromised where the 'spirit' of the law is not being upheld in some systems. For example, the required litter areas in furnished cages vary in size between manufacturers, and litter may not be provided by some producers. Also, we lack basic evidence on the welfare effects of the newest systems (e.g. multi-tier). Our past work on perches for laying hens for RESAS and on furnished cages for RESAS and Defra give us a broad base of experience of housing effects on bird health and welfare, and we have strong links with producers enabling work on commercial farms. We aim to: Identify features of hen housing systems beneficial to hen welfare (particularly those which reduce the need to beak trim) while maintaining productivity and sustainability (3.1); Investigate the uptake of alternative management practices and their effect at reducing feather pecking and the need to beak trim (in complement to work being undertaken elsewhere, e.g. Univ of Bristol) (3.2); Engage in discussion with industry economists to determine if some housing systems produce win-win situations such as good egg production, good use of space (house footprint), low mortality, and good freedom of behaviour (3.3).

Key deliverables include: KE report and journal article on how multi-tier housing compares to single-level housing for productivity and welfare of free-range hens (KE5, D5). KE report and journal article on how provision of scratch mats/litter affect behaviour and welfare; Report on effective management practices to reduce feather pecking and thus the need to beak trim; Produce a summary with BFREPA for industry KE of the best (and worst) impacts on hen welfare and productivity, and identify win-wins.

O4 Beef cattle early life: Relationship between body condition score during pregnancy, and health, welfare and production efficiency in progeny

O4 In beef production, spring-calving suckler cows are managed to lose body fat (indicated by body condition score; BCS) over the winter. This is because feeding cattle over the winter is expensive, and because fat cows can have difficult calvings.

The work builds on the findings, expertise and industry contacts we developed during the SPASE and Defra AW0509 project on early life experiences. During farm visits we found condition score for some cows falling below acceptable levels, with 12% percent of cows 'very lean' and 32% of farms had ≥10% of very lean cows (with >60% on one farm). For these farms it is likely that changes to calf development may impair subsequent welfare and performance. Farmers primarily judge the success of their winter feeding strategy on whether a live calf of healthy weight is produced without a difficult calving, and then on the subsequent fertility of the cow. Our previous research has highlighted the impact of maternal stress on offspring, and effects of maternal nutritional stress in later life are known from other species, but the relationship between maternal nutrition and progeny welfare has not been investigated before in cattle. If present, such prenatal effects could offset the financial benefits gained from restricted feeding of pregnant cows, and limit the capacity of Scottish suckler farms to achieve the goals outlined by the Beef2020 working group of increased productivity and improved calf health and welfare.

This work will investigate how BCS changes in spring-calving beef suckler cow over winter (during pregnancy) affect progeny from birth to slaughter, and will address two key questions concerning beef suckler cow management: 1. Are current targets for winter BCS change appropriate for optimal farm performance (when calf growth to slaughter is included) and for animal welfare? 2. What are the implications for profitability of having cows that are under target? This would inform decisions on the trade-off between spending on winter feed versus animal welfare outcomes, and expected return from animals at slaughter.

Key deliverables include: Article reporting on the effect of cow body condition on offspring lifetime productivity (D6), KE materials for SAC consultants advising on optimal feeding targets for suckler cows over winter (KE6).

Technical approach

O1 Food restriction in pregnant sows.

1.1. Sow diet information. We will begin with a review and fact finding to determine current industry practice and the variety of systems, diets and supplementary fibre sources being used in Scotland and the UK (bringing in international contrasts where relevant), to determine how EU rules requiring fibre for sows are being addressed. Also different terminologies and measurements used to describe types of dietary fibre used in biology, animal science and in the industry will be examined. This exercise will also consider manure management, transport costs and GHG implications of using different types and quantities of fibre.

1.2 Sow oral behaviour. We will carry out detailed behavioural observation of contrasting systems identified in 1.1 (e.g. SRUC research farm, at least one commercial farm) to determine the amount, type and timing of oral behaviours, especially abnormal behaviours (e.g. windsucking, sham chewing) which might raise welfare concerns.

1.3 Rat fibre experiments. Because of their size, long pregnancy and economic value, pregnant sow experiments are expensive (especially if euthanasia to obtain brain and other tissues for physiological studies is the end point). Rats and pigs are both litter-bearing monogastrics that show similar physiological control of food intake and ranking of fibre source digestibility. Thus to inform experimental sow work and to elucidate underlying physiology we will use pregnant rats as a model to assess impact of fibre dimensions on feeding behaviour. Behavioural and physiological measures of hunger/satiety will be used to determine the effectiveness of different kinds of fibre feeding (quantity and type) to reduce hunger. Behavioural observations (time taken to finish food, activity and oral behaviours) and food motivation tests will complement physiological measures of hunger/satiety which may include blood metabolites and hormones such as glucose, non-esterified fatty acids (NEFA), insulin, leptin, glucagon-like peptide (GLP), peptide YY, cholecystokinin (CCK) and brain energy balance related genes in the hypothalamus (e.g. neuropeptide Y (NPY), agouti-related protein (AGRP), Pro-opiomelanocortin (POMC), Cocaine and amphetamine regulated transcript (CART), leptin receptor), brain stem (GLP-1, CCK), and nucleus accumbens (dopamine receptors, opioids).

1.4 Sow fibre experiments. Experimental work on sow management and diet at SRUC's pig research centre will be informed by rat experiment outcomes and industry current practice, and could include the use of current (e.g. wheat feed) or innovative fibre ingredients (e.g. Distiller's dried grains with solubles, DDGS). We will combine behavioural measures of sow welfare (oral behaviours and activity) with production/performance measures from the sow (weight, back fat, condition scoring) and piglets (health, survival, growth) over at least one parity.

O2 Reducing pain associated with management procedures in lambs

We will work on two important and still widely used but painful procedures: lamb castration and tail docking:

2.1 Uptake of methods to reduce the pain of castration in lambs: The castration work will build on work conducted under CWP6.3 and will be closely linked to work under *RD* 2.3.12 Increasing Uptake of Best Practice. Dissemination materials on alternative methods and analysis of lamb pain following castration will be developed; e.g. by using existing and new video material. Researchers will participate in focus groups planned in RD 2.3.12. We will also actively investigate new developments in castration technologies and experimentally investigate their effectiveness in reducing pain. Methods to assess pain will include both quantitative behavioural analysis of active pain behaviours and Qualitative Behavioural Assessment (QBA). Pilot work carried out under CWP 6.3 suggested that QBA was particularly sensitive at identifying quality of different low activity behaviours for lambs following castration by different methods.

2.2: Reduction of pain associated with tail docking of lambs: We will conduct a comprehensive structured review of the literature on tail docking and flystrike, including both scientific and grey literature, to assess the welfare risks to Scottish hill and lowland lambs of tail docking or of being left with full tails. It was recently argued that evidence of whether tail docking protects against flystrike is lacking Therefore, we will investigate whether the data do support a role for tail docking in best practice to reduce flystrike, or whether other less painful methods can achieve the same benefits. The outputs of this exercise will be disseminated through farmer focus groups planned under RD 2.3.12, and at farmer-focussed events (e.g. ScotSheep). As tail docking is still practiced by most sheep farmers, we will also characterise the nature and duration of the pain following tail docking on lamb welfare, using QBA methods developed for castration and novel methods such as conditioned place aversion and changes in motivational state. In CWP 6.3 we found that ewes direct increased maternal care towards lambs in pain from castration. We will investigate whether a similar effect occurs following tail docking, and if so, will investigate whether the presence and care of the mother helps to mitigate pain, either at the time, or on later development (with RD2.2.7). This information will help in building a complete picture of the longer term impact of painful management procedures on lamb welfare.

O3 Improved housing for laying hens that reduces the need to beak trim

3.1: Identify features of hen housing systems beneficial for welfare (particularly those which reduce the need to beak trim) while maintaining productivity and sustainability. We will: a) Collect key production data (e.g. investment costs, energy costs, feed intake, floor eggs, second quality eggs) system descriptors (e.g. beak trimming, provision of additional enrichments such as sand baths or pecking blocks) and welfare indicators (e.g. feather scores, mortality, perch, nest box and range use, keel bone damage) from UK commercial single- and multi-tier egg production units to compare the pros and cons of these two forms of loose housing. b) Collect data on UK commercial and/or research furnished cage egg production farms with regard to scratch mat use, and how use varies with space provided per hen, and/or number of litter provisions per day. We will follow this up with controlled studies where litter area size and frequency of litter provision vary and compare welfare-relevant behaviours (foraging, dustbathing, feather pecking) and egg production (particularly eggs laid on the scratch mat and dirty eggs).

3.2: Investigate the uptake of simple alternative management practices and their effect at reducing feather pecking. On the basis of data collected in 3.1a and 3.1b, and building on CWP 6.3 and in complement with other UK research, we will recruit commercial farms to install simple enrichments (e.g. pecking blocks or mats) intended to reduce feather pecking, particularly in non-beak trimmed flocks. Where possible, half the flock will have access to the enrichments and half will not, enabling within-farm comparisons.

3.3: Consider economic aspects to determine whether housing systems produce win-win situations. With BFREPA economists we will explore data from 3.1 and 3.2 on the cost effectiveness of various housing methods. For example, if furnished cage studies in 3.1b find that larger litter areas with more frequent litter provision enhance welfare, we consider the likely effect on system profitability, trading off costs of enhancing welfare with any financial benefits (e.g. reductions in mortality due to reduced feather pecking/ cannibalism) or costs (e.g. more dirty eggs). Likewise for single- versus multi-tier, we will investigate trade-offs between positive outcomes such as: being able to stock more birds per shed footprint (multi-tier) and possibly reduce feather pecking in non-beak trimmed flocks and thus generate more egg revenue with any detrimental effects (such as greater keel bone damage). This analysis will identify any win-win housing situations (for production and welfare) and may feed into RD 2.3.11 Trade-offs between productivity and sustainability.

O4 Beef cattle early life

4.1: BCS effects on calf outcomes in existing data. Existing data will be used from previous experiments (e.g. CWP 6.3) and from routine records from the SRUC Beef Research Centre. Records include cow BCS and live weight at multiple points in pregnancy and calf outcomes (calving ease, birth weight, weaning weight, slaughter weight, health treatments, response to handling). Relationships between cow condition and calf outcomes will be assessed to identify key points in pregnancy that affect calf development.

4.2: On-farm assessment of BCS. Cow BCS will be assessed at two winter visits (at housing, and prior to calving) to ~25 spring-calving commercial farms representing a range of typical management systems. Farms sampled will have a minimum herd size of 30 cows and will be targeted to represent the national herd size profile. A minimum of 1200 cows will be sampled. Carcass traits of progeny at slaughter, and farm data to allow assessment of technical efficiency of farms will be recorded.

4.3: Investigate progeny health and welfare outcomes throughout life in relation to maternal BCS. Based on findings of 4.2 a smaller number (~6) of farms representing a range of cow BCS will be recruited for a more detailed study. Farms will be selected that were shown in 4.2 to have diverse BCS. Data on performance (birth weight, growth and carcass quality) and health (including calving difficulty) will be collected to inform economic modelling in RD 2.3.11 Trade-offs between productivity and sustainability (on possible trade-offs between winter feed management and return on finished progeny). We will also visit each farm on two occasions during the progeny lifetime (e.g. at weaning, and at another pre-slaughter time point) to assess behaviour and welfare outcomes (e.g. temperament testing, “Welfare Quality” assessment, indicators of positive welfare such as play).

Detailed work plan

Year 1 (2016 - 2017)

Numbering system for deliverables relates to Gantt Charts listing Activities (A#), Deliverables (D#) and KE/impact events (KE#).

O1 Food restriction in pregnant sows

1.1 Sow diet info. Undertake fact-finding, prepare report and distil key information for knowledge transfer to farmers and other stakeholders (Pigworld article, KE1). 1.2 Sow oral behaviour. Carry out detailed study of type, timing and amount of sow oral behaviours in different systems. (Submit article, D2). 1.3 Rat fibre experiment 1 At least 5 different fibre dimensions (quantities and/or types) will be investigated and compared to a control diet (n=10 per treatment; complete experiment and collect tissue, A1).

O2 Reducing pain in lambs

2.1 Castration: Develop web-based and other dissemination materials (e.g. videos, Learning Objects) on alternative methods of lamb castration (KE2); participate in focus groups planned in RD2.3.12 (KE3). 2.2 Tail docking: Conduct a comprehensive review of the literature on tail docking and conduct a risk assessment of docking by different methods, or leaving tails full, of hill and lowland lambs (Submit article D3).

O3 Housing for laying hens

3.1a Single vs multi-tier in conjunction with BFREPA members, identify free-range egg producers with single tier or multi tier housing systems, and select farms or flocks within farm based on 'matched pairs' of similar genotype, whether or not beak trimmed, and management system (n=20 flocks per housing type; begin data collection A2).

O4 Beef cattle early life

4.1 BCS vs calf outcomes data: gather data into new database; analysis of previous data (A3). 4.2 BCS on farm: preparation for farm visits (observer training in condition scoring etc); recruitment of farms; conduct autumn farm visits (n=25; A4); conduct spring pre-calving farm visits (n=25; A5). Data collection for 4.2 in year 1 is BCS at two time points of pregnant cows, which will calve at the end of Year 1 / start of Year 2. Data will be collected from these calves at slaughter (Year 3 or 4 depending on age at slaughter).

Year 2 (2017 - 2018)

O1 Food restriction in pregnant sows

1.3 Rat fibre experiment 1. Lab analysis of brain and blood at RINH (A5). 1.4 Sow diet experiment 1. Investigate the interacting effect of sow additional fibre access (e.g. straw bedding or silage) with in-ration fibre, comparing at least 2 different iso-energetic fibre diets in comparison to a standard control diet (2 x 3, n = 18 sows per treatment; total 108; begin animal work A6).

O2 Reducing pain in lambs

2.1 Castration. Discuss with relevant parties developments in technological innovation in lower pain castration methods; or pharmaceutical developments in immunocastration (KE4). Plan studies to test these developments if further evidence is required. 2.2 Tail docking Investigate the impact of tail docking pain on the expression of maternal behaviour in ewes by means of quantitative and qualitative behavioural responses of ewes and lambs (One lamb of a twin pair will be tail docked; A7). The impact of early pain exposure on later pain responsiveness, conditioned place aversion and/or motivation state will be assessed (Submit article D4).

O3 Housing for laying hens

3.1a Single vs. multi tier complete data collection (A8), data analysis and report to farmers (KE5), submit article (D5), 3.3 discuss economic data from 3.1a with BFREPA and produce industry article (A9). 3.1b Furnished cages identify furnished cage farms of various models and colony sizes, plan data collection schedule (A10).

O4 Beef cattle early life

4.1 BCS vs. calf outcomes preparation of outputs based on year 1 data analysis. 4.2 BCS on farm: data analysis from autumn and spring visits (submit article, D6; Prepare materials for SAC consultants advising on optimal feeding targets for suckler cows over winter; KE6); recruitment of second phase farms; discussion with economists on data collection. 4.3 BCS and welfare on farm conduct autumn farm visits (n = 6; A11); conduct spring pre-calving farm visits (n=6). 4.2 BCS on farm BCS at two time points of pregnant cows which will calve at the end of Year 2 / start of Year 3 (A12).

Key linkages, interdisciplinarity & collaboration

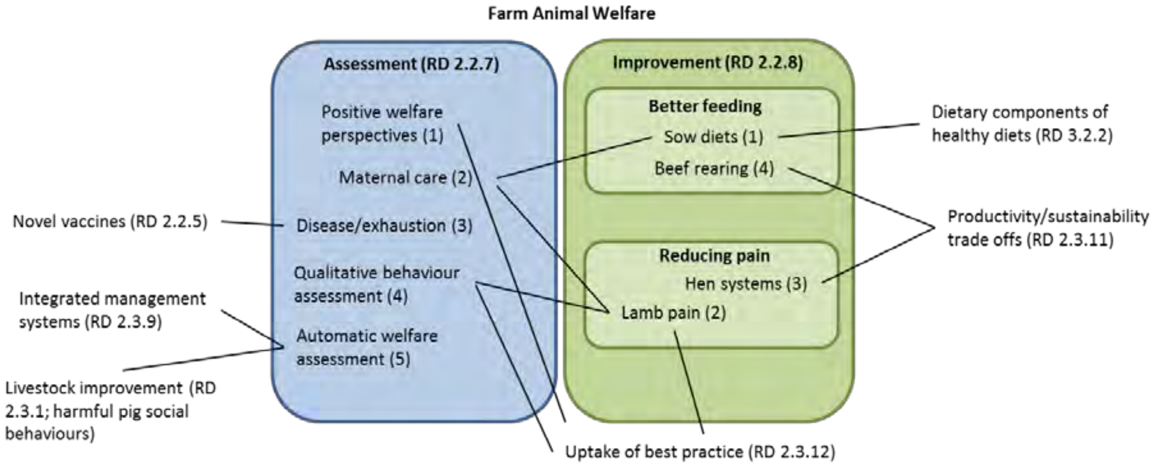
(1) This RD has been developed in complement with RD2.2.7 Welfare assessment techniques, enabling collaborative work to add value and maximise efficient use of resources: Work on castration and tail docking in *O2* will combine with RD2.2.7's work on maternal care and will provide video for assessment by QBA.

(2) The SRUC/ RINH collaboration in O1 will underpin work on human diet and health in RD3.2.2 Dietary components of healthy diets and their effects.

(3) Work in O1 will also complement the BBSRC-funded work on hunger/satiety in broiler breeders at SRUC (in collaboration with Edinburgh University: Roslin Institute), providing critical mass and a platform for further funding in this area.

(4) Work on castration and tail docking in *O2* links *to* RD2.3.12 Increasing uptake of best practice, with researchers attending farmer focus groups with the aim of reducing the use of lamb castration and tail docking, and encourage less painful methods.

(5) The housing systems explored in O3 and O4 provide data on trade-offs and win-win situations where productivity and welfare are enhanced, providing case studies for work in RD2.3.11 Trade-offs between productivity and sustainability. We expect these interactions with socio-economists will lead to joint KE and scientific publications as they did in CWP 6.3.



Added Scientific Value

O1 There is no current work on this area in the UK or elsewhere. It complements our past RESAS and BBSRC-funded work on hunger/satiety in broiler breeders, rats and humans and the use of fibre and innovative feeds. New physiological measures in the gut and brain will enable us to better understand which dietary components affect satiety and how. O2 builds on BBSRC-funded work at Bristol on impact of early life pain and later development. Developing novel methods to assess pain may attract commercial interest and funding e.g. pharmaceutical industry. O3 Bristol University work on management of non-beak trimmed flocks in free-range systems ends in 2015. We will complement that programme through the addition of furnished cages and work on single vs. multi-tier barns. This work also complements a Danish Funding Council Grant application on furnished cage design in 8 EU countries (outcome known July 2015), strengthening our international collaborations. O4 builds on prior RESAS and Defra funded work in this area and aims to generate information of direct applied relevance to farmers and the industry. To support this we intend to apply for additional funding from industry sources (AHDB Beef & Lamb, QMS).

KE, Audiences and Impact

Audiences

Farmers and other farming industry stakeholders are the primary KE audience (animal feed companies, breed societies, poultry production companies, equipment manufacturers, QMS, AHDB Pork, BFREPA). Information on industry variation in sow diets (*O*1) will be communicated via an article in Pigworld (KE1), and later experimental findings will be communicated to AHDB Pork and QMS and by attendance at and posters and leaflets at pig industry events (e.g. Pig and Poultry Fair in May 2018 (year 3), 2020 (year 5)) as well as more targeted KE for nutrition specialists (e.g. Society of Feed Technologists). Work on alternatives to lamb castration or reduced pain methods (*O*2) will be communicated to sheep farmers by via web-based (downloadable) training materials (KE2) which can also be accessed by vets, educators and SAC Consulting staff to encourage the use of alternative methods. SRUC has considerable expertise in developing innovative web-based materials (incorporating video and interactive elements) gained in the EU FP7-funded AWIN project and their effectiveness has been evaluated positively. Video training materials will also be developed and disseminated via SRUC's Behaviour and Welfare YouTube channel. Face to face interaction with farmers will occur during focus groups with RD2.3.12 Increasing uptake of best practice (KE3)*;* and web-based materials can also be presented at farmer focussed shows: NorthSheep (2017; KE4) and ScotSheep (June 2018). For laying hen systems (O3), KE will include the provision of economic modelling outputs (3.3) to all egg producers in Scotland plus UK BFREPA members. The economic modelling results of 3.1a will be made available in year 2 to BFREPA (who are providing the farms). All Scottish egg producers will be notified of results from 3.1a and b after complete analysis in Year 4 via distribution to the egg inspectorate; publication in poultry magazines (e.g. Poultry World; World Poultry, The Ranger) of the various study results, Years 3 and 4; poster display and leaflets at the Pig and Poultry Fair in May 2018 and 2020 (years 3 and 5). For O4, messages concerning the optimal use of BCS for suckler cows to improve animal welfare, performance and profitability will be disseminated to farmers by speaking at beef producer group events (average of 2 per annum from year 2), via bespoke advice to SAC consulting and written materials for press and direct distribution via SAC consulting (e.g. Beef & Sheep News, Scottish Farmer).

The wider scientific community will be informed of work in this RD through articles and reviews in high quality refereed journals, and conference presentations.

Policymakers will be kept informed via direct contact and meetings (at least annually) attended by RESAS (principally Andrew Voas and Nia Ball), and through the publication of knowledgescotland briefs to highlight important new findings. Where advised by RESAS, policy briefs will be produced in partnership with the SRUC Rural Policy Centre and face-to-face meetings offered to directly interact with policy staff.

The general public will be informed of our work through displays and exhibits prepared for presentation at events such as Science Festivals, the annual Midlothian Doors Open Day and the Royal Highland Show.

Impact

Pig farmers and feed companies (and industry bodies such as QMS and AHDB Pork) will benefit from ideas and information generated in O1 concerning the effect of fibre on sow welfare and productivity, and the use of innovative feed ingredients. For *O*2, sheep farmers (and industry bodies such as breed societies) will benefit from improved lamb growth rates if the goal of reducing lamb castration and/or reducing the use of the most painful methods are realised. For O3, we aim to increase awareness among Scottish and UK egg producers and assurance schemes; in the first instance amongst free range producers (BFREPA), of the relative cost-effectiveness of different laying hen systems for production and welfare, and encourage the use of beneficial systems, practices or enrichments. Outputs from the work on enriched cages (3.1b – poultry press articles) will be used to influence cage manufacturers to improve cage design. O4 has the potential to simultaneously reduce input costs (feed) whilst improving cow and calf welfare and environmental sustainability through better targeting of feed use and improved calf performance. Improvements in animal welfare resulting from this RD will benefit the animals themselves, citizens concerned for their welfare and policy makers responding to this concern.

To measure impact, evidence of changes in guidance for farmers from key opinion formers such as consultants, breed societies, AHDB Pork, QMS or assurance schemes (Red Tractor, Freedom Foods) or in products produced by commercial companies (e.g. high fibre sow feeds, low pain devices, new laying hen cage designs) would indicate impact. All major events and focus groups will be formally evaluated for impact.

RESEARCH DELIVERABLE NUMBER: 2.2.8 Improved husbandry & reduction of painful procedures

Gantt chart for Year 1: Showing Key research activities (A), deliverables (D), KE/impact events (KE) and Reports to RESAS (R)

Year 1: 2016/17 Activity	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
1.2 Sow oral behaviour observations, analyse and submit article									D2			
1.3 Carry out rat fibre experiment												A1
2.2 Tail docking review/risk assessment								D3				
3.1a Select farms and begin (A2) single vs. multi-tier laying hen flock study				A2								
4.1 Beef BCS vs. calf outcomes- analysis of databases					A3							
4.2 Beef BCS: Select farms and begin autumn and winter on farm data collection								A4				
1.1 Interact with industry to review sow diets and systems and produce Pigworld article						KE1						
2.1 Lamb castration- develop web and other materials on alternative methods					KE2							
2.1 Lamb castration- participate in farmer focus groups (with *RD 2.3.12*).								KE3		KE3		
Annual Report (Year 1)												R1

RESEARCH DELIVERABLE NUMBER: 2.2.8 Improved husbandry & reduction of painful procedures

Gantt chart for Year 2: Showing Key research activities (A), deliverables (D), KE/impact events (KE) and Reports to RESAS (R)

Year 2: 2017/18 Activity	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
1.3 Rat fibre expt- laboratory analysis of hunger/satiety physiological markers												A5
1.4 Sow fibre diets experiment			A6									
2.2 Tail docking experiment- maternal response to lamb pain (A7) and submit article (D4)			A7						D4			
3.1a Complete single vs. multi-tier laying hen flock study (A8) and submit article (D5)			A8			D5						
3.3 Economic aspects of 3.1a with BFREPA economists, produce KE report									A9			
3.1b Laying hen furnished cage study- identify farms, plan data collection (A10)												A10
4.2 Data analysis of Beef BCS studies (A5), submit article (D6)	A5											D6
4.2/4.3 Beef BCS: data collection from farm visits in autumn (A11) and spring (A12)							A11					A12
2.1 KE on lamb castration/tail docking- present information at NorthSheep 2017.			KE4									
3.1a KE on single vs multi-tier laying hens: report to farmer/industry groups						KE5						
4.1 Prepare written KE materials for SAC consultants and press advising on optimal feeding targets for suckler cows over winter												KE6
Annual Report (Year 2)												R2

Name of RD: 2.2.9 GHG reductions from livestock.

Research aim and key drivers:

There are challenging national and global targets to reduce greenhouse gas (GHG) emissions, including from livestock production. The coordinated programme of research conducted by the UK GHG Research Platform has resulted in a much clearer picture of emissions and mitigation opportunities from UK livestock farming. We have ongoing engagement with policy and industry stakeholders, particularly those involved with the GHG platform (Scottish Government, DEFRA, levy bodies and wider industry) and this has been used to simultaneously disseminate information and identify remaining knowledge gaps. We are actively involved with international fora for discussion of scientific opportunities in the GHG area (e.g. networks of the Global Research Alliance Livestock Research Group; COST action 'Methagene' Working Group on methane proxies; FACCE JPI 'Global Network' and 'Rumen Stability' projects).

A wide range of production systems, livestock classes and feed types were studied by the GHG Platform, though the technical difficulty of making estimates in fields means that data from studies with fresh herbage and grazing animals are more limited. There is considerable unexplained variation in GHG emissions from livestock grazing herbage and this is a serious knowledge gap given the importance of grazing to sheep and cattle systems in Scotland. A recent review of over 70 treatments from 22 studies conducted around the world with grass as the sole feed showed a large range from 6.4 to 37.4 g methane/kg DM intake. Work with sheep in New Zealand has identified considerable animal genetic/genomic variation in methane emissions, though progress in exploitation will be slow because of the difficulty of making measurements with sufficient animals. Work on grazing effects and genetics of GHG emissions would accelerate rapidly if we could identify suitable proxies for GHG emissions, or other low cost/rapid methods based on samples that are easy to collect from large numbers of animals.

There is a need to study the role of endemic disease on production efficiency and GHG emissions from livestock – this will be explored in a Scottish context. Complementary work to model genetic relationships with other traits (health, fertility and longevity) will be conducted in RD2.3.1. In addition to the requirement to fill information gaps on specific mitigation options, there is a growing need to explore synergies and antagonisms when applying combinations of mitigation options. We will assemble information for this analysis as part of this RD and develop further modelling, leading to new experimentation, as part of new RD2.3.6.

The overall aims of this RD are to:

1. Understand the effects of herbage species, environmental conditions and sward management on emissions of methane from grazing sheep and cattle;
2. Develop rapid, low-cost methods/proxies to measure emissions from sheep and cattle – with a particular focus on tools for (a) exploiting

Summary of the proposal:

The main foci of the work will be GHG emissions by grazing livestock, development of rapid methods to estimate GHG emissions (for use in animal breeding and grazing studies), as well as understanding between-animal variation in emissions.

O1: ***Development of rapid methods/proxies for GHG emissions***
The respiration chambers at the SRUC Green Cow unit provide the gold standard measurement of methane emission, but cannot be used for grazing livestock. In the first step of work to evaluate refined techniques and rapid proxies for methane emissions, we will conduct zero-grazing studies with grass fed to cattle in the respiration chambers. We will evaluate and refine marker/proxy methods for use with grazing animals alongside these measurements. Techniques under development for methane emissions include: (a) the sulphur hexafluoride (SF_6) method – which is already in use at SRUC (refinements proposed by Australian researchers), (b) methane sensors (to be developed in RD2.3.9) mounted on head collars, and (c) faecal NIR spectroscopy. The idea of using faecal NIR spectroscopy is based on our earlier work measuring ether lipids (from the membrane lipids of rumen methanogens) in faeces. Those compounds are difficult to measure, but have unique structures that may be distinctive in NIR scans. In the event that these approaches do not work, we would consider using the 'GreenFeed' system (from the USA) for grazing work in RD2.3.6, though this would be more costly, require some development work, and is unsuitable for some grazing situations. We will also work to refine the laser methane detector approach for use to identify genetic/genomic variation in methane emissions from housed dairy cows – including exploring potential for use it in fixed locations, such as in animal weighing equipment. Key Deliverables: Results on effects of grasses and grassland management on methane emissions. Tools for use to estimate methane emissions for use in future work on dietary mitigation, breeding programmes for reduced emissions, and for farm monitoring. [D1.1: paper produced month 24; D1.2: paper produced month 24; D1.3: paper produced month 42]. Joint O1/O4: Stakeholder meeting (animal breeding) to discuss progress and options for methane proxies to be implemented in animal breeding [KE1.1: month 20].

O2: ***Understanding and exploiting relationships between rumen fermentation, the rumen microbiome and GHG emissions***
Studies as part of the CWP have identified variation in the rumen microbiome related to methane emissions. This may provide the basis for a new proxy for methane emissions (improving on the simple archaea/bacteria ratio proxy identified in the CWP) and the basis for new strategies to reduce GHG emissions. Rumen samples will be taken from the animals undergoing methane measurements as part of the zero-grazing studies for O1 and the grazing studies described in RD2.3.6.
We will work with the Universities of Aberdeen and Edinburgh to cover sequencing and bioinformatics analysis for 16S community analysis, as well as gene-centric metagenomic/metatranscriptomic analyses, in a one of the RESAS-funded HEI Collaboration projects. These rumen samples will also be analysed for volatile fatty acid fermentation products and data used to further develop a mechanistic model of rumen methane production created during SPASE. Key Deliverables: Samples for future work (including RESAS-funded HEI Collaboration project) that will increase understanding of diet effects and between-animal variation in methane emissions – ultimately for use to design

new diet-based mitigation options and breeding programmes. [D2.1 and D2.2: months 8 and 20]. Further evaluation of the mechanistic model of methane production. [D2.3: paper submitted: month 60].

O3: ***Effects of livestock disease and disease control measures on GHG emissions and animal productivity***

Efficient and sustainable livestock production is constrained by a number of key endemic diseases. There is increasing evidence from a number of sources that overall emissions from grazing livestock can be reduced by dealing effectively with endemic, production-limiting disease. For example, climate chamber work during the CWP (Houdijk et al.), has shown little effect of gastrointestinal nematode parasitism in sheep on GHG emissions expressed on a DM intake basis. However, the resultant inappetance and anorexia did have a significant impact on GHG emissions overall. This represents a key area where gains in sustainable intensification are possible; in this case, disease control means increased production efficiency and reduced emissions. This was supported by retrospective modelling of the GHGs associated with fattening lambs in field trials under different anthelmintic (drug) treatment regimes (including the targeted selective treatment (TST) approach being investigated in other RESAS-funded work; e.g. new RD2.3.11). Similarly, a recent Defra study (A0120) ranked ten important health conditions in UK dairy cattle in terms of their GHG footprint and the relative benefits of successful disease control. Modelling of the consequences of disease/disease control depends on the consequences for feed intake and productivity. We will gather information about these effects, particularly seeking to separate 'causes' and 'effects' for important endemic disease (focusing on those in the 'top 10' that are most important for Scottish agriculture, along with important issues for beef and sheep production), in preparation for modelling work as part of RD2.3.6. We will use a combination of internal discussions and stakeholder engagement to prioritise issues for Scotland. Data will be a combination of (a) performance results from studies of diseases and disease control/treatment measures and (b) feed intake, performance and health records allied to estimates of methane emissions from nutrition/genetic studies at Crichton Royal Farm and work on targeted selective treatment/sustainable parasite control at Kirkton Farm. <u>Key Deliverables:</u> Data on animal disease/disease control assembled in preparation for modelling work as part of RD2.3.6 [D3.1: month 24]. Stakeholder meeting (animal health) to produce priority list of cattle/sheep diseases [KE3.1: month 4]. Meeting for farmers and vets about animal disease/ treatment implications for GHG emissions [KE3.2: month 20].

O4: ***CT-based predictors of methane emissions***

Research in New Zealand found that sheep divergently selected for methane emissions (high or low emitters), as measured in chambers as ewe lambs, had significantly different rumen morphology, when measured by CT as ewes. As part of the Defra-funded GHG inventory project, SRUC found some evidence of differences in methane emissions between different genetic lines of sheep, divergent for maternal weaning weight EBV. These lines will be used as a starting point to further investigate potential rumen differences linked to methane emissions. The objectives of this work are to: (i) establish the relationship between CT gut measurements and methane emissions in sheep; (ii) analyse previously-collected CT images (from research and/or commercial sheep) to determine the variation in these traits in different breeds / age groups / sexes etc. and potentially genetic relationships between these measurements. Key Deliverables: Information about the relationship between rumen volume, rumen anatomy and methane emissions that will contribute to the discussion about trade-offs between productivity and environmental effects of mitigation options. [D4.1: paper submitted month 36]. Joint O1/O4: Stakeholder meeting (animal breeding) to discuss progress and options for methane proxies to be implemented in animal breeding [KE1.1: month 20].

Additional KE activity

In addition to the Objective-specific KE activity, we will also make presentations of GHG research at public-facing events such as the Royal Highland Show and Midlothian Science Fair each year [KE0.1, KE0.2, KE0.3 and KE0.4].

Technical approach

Animal work will be approved by the relevant Animal Ethics Committees; where relevant, sample sizes will be based on our previous experience and consultation with BioSS. The secondary use of data and samples from previous studies will involve the appropriate permissions.

Experimental work planned for RD2.2.9 will all take place within years 1 to 3 of the Programme, with final data analysis and reporting in year 4 and some animal-level modelling activity continuing into year 5. Results from these component studies (grass species, grazing managements, rumen physical attributes (CT scanning) and animal health incidences/ consequences) will feed into system level experimental and modelling studies planned for years 3 to 5 within WP2.3 (RD2.3.6).

Detailed work plan

O1: *Development of rapid methods/proxies for GHG emissions*

'Zero grazing' studies at the SRUC Green Cow unit will be used to investigate effects of different grasses and/or grassland management strategies on methane emissions. Methane emission will be measured in studies in which growing cattle are offered cut grass in the six respiration chambers. In each of two years (Years 1 and 3 of the programme; A1.1 and A1.3), we will evaluate three grasses/grazing managements in studies with three experimental periods resulting in 54 experimental units for each study (6 per treatment). A1.2: these measurements along with historical data (from CWP 3.2) will also be used for ground-truthing of potential proxy methods, namely the methane collar (from RD2.3.9), laser methane detector and faecal NIR; we will explore potential for automation of LMD measurements when animals are stationary for periods of time, for example in a weigher or at a water trough. We will not use the SF6 technique for this work, but may need to work on it for grazing studies proposed in RD2.3.6, depending on progress with the alternatives listed above. Samples will be collected for microbiome analysis (O2).The use of zero-grazing is necessary to provide the level of control over herbage intake and 'gold standard' measurements of methane emissions needed to develop and ground truth improved methods for implementation in the real grazing situation. Zero-grazing also removes the possibility of grazing selectivity from confounding results, but we will work on methods (e.g. faecal NIR scanning) to help identify grazing selection effects in the 'real' grazing studies that are planned to follow this work in RD2.3.6.

Interim Milestones: Chamber study complete [M1.1: month 7]; Initial evaluation of proxies complete [M1.2; month 12]; Lab and statistical analysis completed [M1.3: month 16]; Chamber study complete [M1.4: month 32]; Lab and statistical analysis completed [M1.5: month 40].

O2: *Understanding and exploiting relationships between rumen fermentation, the rumen microbiome and GHG emissions*

A2.1: Rumen samples will be taken from animals undergoing methane measurements as part of the zero-grazing studies for O1, the stocking density study described in RD2.3.1, and the grazing studies described in RD2.3.6. They will also be collected at slaughter of animals with methane emission and rumen volume measurements (O4). Samples will be selected for further 16S community and gene-centric metagenomics/metatranscriptomic analysis – focussed on pathways of methane production, as well as pathways of N metabolism such as denitrification or anaerobic ammonia oxidation that are either rare or not previously described in the rumen or intestinal microbiome. Sequencing and bioinformatics will be funded through a RESAS-funded HE Collaboration project. A2.2: Samples will also be analysed from VFA fermentation products and results (feed intake and composition; fermentation products and methane production) used for further testing of a mechanistic model of methane production. The simple mechanistic model for methane production from ruminants developed within SPASE will be extended to include nitrate-reducers and sulphate reducers. Parameters for the model will be obtained from data on different diets (e.g. nitrate and rapeseed oil cake) and the predictive power of the model assessed. Hypotheses concerning the influence of different microbial groups for methane production based on the genomic data collected in years 1-2 will then be incorporated and tested within the mechanistic model.

Interim Milestones: Model extended to include nitrate-reducers and sulphate reducers [M2.1; month 12]; Predictive power of the revised model assessed [M2.2: month 24]; Incorporation of new rumen microbiome data into model [M2.3: month 36].

O3: *Effects of livestock disease and disease control measures on GHG emissions and animal productivity*

The first step in this work will be to confirm disease targets that are most important to Scottish agriculture from within the top ten most important endemic diseases identified in the Defra study, also taking into account the main disease/disease control issues with sheep. A3.1: we will gather information about productivity effects of the key endemic diseases, as well as treatment options, using sources that include:

- Literature reviews of the effects of disease/disorders on livestock productivity, aiming to separate out 'causes' and 'effects' in the relationship between the two;

- Data from experimental quantification of GHG emissions associated with infectious disease (conducted in the previous RESAS Strategic Research Programme (SRP) in the SRUC GHG chambers);
- Data from studies of the efficacy of treatments conducted by the Moredun Institute (e.g. anthelmintic and flukicides);
- Data from studies of targeted selective treatment (TST)/ sustainable parasite control (Moredun/SRUC work at HMRC Kirkton Farm in the previous RESAS SRP and proposed for RD2.3.11);
- Production and health data drawn from the SRUC Crichton Royal dairy farm database. Further methane data will be collected using the LMD, with methane measurements taken three times a week per cow (milk sampling day plus the day before and the day after).

Interim Milestones: Priority list of top 10 sheep/cattle diseases [M3.1: month 6]; Gap analysis of data required/available for GHG modelling in RD2.3.6 completed [M3.2: month 12]; Draft GHG calculations available for discussion with stakeholders [M3.3: month 18].

O4: *CT-based predictors of methane emissions from sheep*

A4.1: During year 2 of the Programme, Scottish Blackface ewes from existing selection lines, divergent for maternal weaning weight EBV, will be CT scanned and then methane emissions measured in the Green Cow respiration chambers. Ewes will be measured in matched pairs (24 pairs per line), to allow sufficient volume of methane to be measured. Rumen measurements will be made from CT images and related to methane measurements using regression techniques. Samples of rumen digesta will be collected on slaughter of these animals (or obtained by another method if animals are to be retained) – and used for rumen metagenomics analysis as part of a RESAS-funded HEI Collaboration project.

In year 3, any promising CT predictor traits will then be measured in appropriate previously-collected CT images from different breeds, sexes, age groups etc. to enable variation in these traits within different groups to be quantified and potentially genetic analyses to be performed.

Interim Milestones: CT scanning complete [M4.1: month 20]; Methane chamber measurements completed [M4.2: month 24]; Lab and statistical analysis completed [M4.3: month 32].

Expertise

SRUC now has world-class livestock greenhouse gas (GHG) emission research facilities as part of the new SRUC Beef and Sheep Research Centre at the Bush Estate near Edinburgh. These include state-of-the-art equipment for measuring methane emissions and feed conversion efficiency, as well as leading-edge capability for developing rapid, low-cost methods for estimating emissions. MRI has considerable expertise in endemic disease research aimed at improving the biological- and production-efficiency of livestock through sustainable endemic disease control. An associated HEI project with the Universities of Edinburgh and Aberdeen will deliver expertise in nucleic acid sequencing and bioinformatics necessary to identify effects mediated by changes in the rumen microbiome (O2).

Key linkages, interdisciplinarity & collaboration

1. In the animal health area, there will be necessary strong interactions and flows of information between RD2.2.2, RD2.2.9, RD2.3.5 and RD2.3.6. Improved estimates of the prevalence of specific diseases within RD2.2.2 will act as baseline for work on disease incidences and consequences for productivity planned in RD2.2.9. Information from both of these RDs must flow to RD2.3.6 to inform an analysis of the impact of disease on greenhouse gas emissions for modelling of abatement potential and costs using GLEAM in RD2.3.5.
2. In the grass/grazing management area, there will be a transition over the course of the Programme from component studies, in the lab or using 'zero grazing' (within RD2.2.9) to real grazing studies within RD2.3.6. The best technologies identified in RD2.2.9 will be modelled and evaluated in field-scale studies in RD2.3.6. We will link with work in RD2.3.12 about barriers to uptake of changes in grazing management (including reseeding) in order to ensure that this part of the work keeps on track with options that farmers will adopt.
3. The respiration chamber studies in RD2.2.9 will also provide the opportunity to simultaneously develop and evaluate novel sensor or proxy approaches for feed intake and methane emission as part of RD2.3.9. The best options from these sensor approaches will be used in the grazing studies in RD2.3.6.
4. Work on proxies for methane should also provide information about the basis for between-animal variation in GHG emissions and its inter-relationship with production traits – that could be used in developing new areas of livestock breeding (RD2.2.1) and new traits (RD2.3.1).
5. Linkage to the Universities of Edinburgh (Roslin Institute) and Aberdeen on rumen microbiome sequencing and bioinformatics, through RESAS HEI collaboration funding.
6. National and international research linkages – for example with AFBI, University of Reading and Aberystwyth University: combining resources and pooling archived samples and data to provide more robust evaluations of rapid/proxy methods. We will also seek to continue to play an important role in International GHG Research (e.g. Global Research Alliance Livestock Research Group; FACCE JPI initiatives; developing collaborations with EMBRAPA (Brazil) through a Newton Fund award; involvement in COST Methagene project Working Group on rapid/proxy methods for methane emissions).

Added Scientific Value

This work continues to build on substantial research effort in this area across the world, including the UK-wide collaborative GHG inventory project, with additional activity building on that project in RD2.3.7. In this RD, we advance some of the experimental questions and opportunities arising from previous national and international effort, for example (i) microbiome work advancing rapidly in many countries (including at the Roslin Institute and University of Aberdeen), (ii) substantial interest in developing rapid/proxy methods (e.g.

involvement in Working Group of COST Action 'Methagene' on proxies), and (iii) evaluating the relationships with CT data from New Zealand with a different (UK) sheep population.

KE, Audiences and Impact

Audience

Greenhouse gases research has a wide audience and we will continue to align provision of information to stakeholders with consultation with the industry and public about new research opportunities. We engage with a wide cross-section of industry who visit our research facilities, particularly the SRUC GreenCow unit. For example, we have met with senior staff from RESAS, EBLEX, QMS, NFU, NFUS – as well as many feed companies, abattoir companies and supermarkets. Many of these latter organisations bring both their own technical experts as well as farmer groups to discuss the research programme. We have ongoing contact with a wide cross-section of the animal breeding industry – breed societies, breeding companies etc. We also have many visits from students and engage with the public in this critically important area through Open Days (e.g. Midlothian Science Fair and Royal Highland Show).

A special event to bring together many of these industry and policy stakeholders to discuss recent research and new research opportunities was held at the Moredun Institute at the outset of the process (11 March 2015) that has led to the work proposed for this RD. We will hold similar annual events during the course of this RD – the first will look at prioritisation of livestock disease/disease control issues in Scotland (defining the further work in this RD and RD2.3.6) and the second will look at grassland management effects on GHG (also helping to define further work in this RD and RD2.3.6).

This RD, together with system level experimentation and modelling within RD2.3.5, 2.3.6 and 2.3.7 will inform Scottish Government policy in relation to "Farming for a Better Climate", providing an evidence base to help identify the most practical and effective mitigation options for livestock farming.

Greenhouse gas issues are by their very nature international in scope and our wide international engagement in projects and networks (described above) gives us excellent access to the international scientific community in this area. The RD lead was an organiser for the 'Greenhouse Gases in Animal Agriculture' major international meeting in Dublin (2013) – and we will aim to bring that meeting to Scotland in the future. We are heavily involved in international research groups working in the areas of environmental impacts of livestock (e.g. Global Research Alliance), genetic selection (many international animal breeding programmes), and CT scanning (e.g. established the EU FAIM network).

Impact

Developing grassland management, reducing the burden of endemic disease and breeding for both productivity and methane emissions offer most potential to mitigate GHG emissions from livestock, benefiting society and helping to meet government targets. A rapid/proxy tool for methane emissions will be of great value in advancing both work with grazing ruminants and in developing breeding programmes for low methane emitters.

Grass makes up a high proportion of the diet of many ruminants in Scotland – particularly breeding stock such as suckler cows and breeding ewes. There is a desire to increase the proportion of grass and grass silage in diets as part of the clean green profile of Scottish production. Consequently, understanding the effects of different grasses and grassland managements will have a large potential effect on greenhouse gas emissions provided that this work can be allied to strategies that increase production and/or efficiency and which will be adopted by Scottish farmers (associated work on farmer behaviour in RD2.3.12).

Greater understanding of relationships between genetic selection for productivity, rumen physiology, feed intake, and methane emissions will help inform recommendations on how to select for efficient sheep that can be managed in a sustainable way, with minimal environmental impacts. This opens up a series of new options for animal breeders to contribute to reducing emissions intensity, which will provide new opportunities for development and marketing of breeding stock, semen and embryos.

A ‘New action to reduce wastage by improving livestock health’ was recently identified by the Scottish Government as a measure to help tackle climate change with sufficient rationale to be implemented quickly. The impact of disease on productivity and emission will be presented to farms and other stakeholders a regular farm open days, held yearly or biannually at partner’s research farms.

RESEARCH DELIVERABLE NUMBER: 2.2.9

Work planning and timetable for Year 1: Please include major milestones, (key research activities, deliverables, KE/impact events) and their timing.

Year 1: 2016/17	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Objective 1.1 Methane chamber studies							M1.1					
Objective 1.2 Proxy development												M1.2
Objective 2.1 Rumen sampling								D2.1				
Objective 2.2 Rumen modelling												M2.1
Objective 3.1 Assemble data on health effects				KE3.1		M3.1						M4.2
KE event (public)			KE0.1				KE0.2					
Annual Report (Year 1)												R1

RESEARCH DELIVERABLE NUMBER: 2.2.9

Work planning and timetable for Year 2: Please include major milestones, (key research activities, deliverables, KE/impact events) and their timing.

Year 2: 2017/18	Lead	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Objective 1.1 Methane chamber studies	RD				M1.3								D1.1
Objective 1.2 Proxy development	RD								KE1.1				D1.2
Objective 2.1 Rumen sampling	RD								D2.2				
Objective 2.2 Rumen modelling	HK												M2.2
Objective 3.1 Assemble data on health effects	PS						M3.3		KE3.2				D3.1
Objective 45.1 CT scanning	NL								KE1.1, M4.1				M4.2
KE event (public)	RD			KE0.3				KE0.4					
Annual Report (Year 2)	RD												R2

Name of WP: 2.3 - Agricultural Systems

Introduction

Agriculture faces ever-increasing demands to achieve enhanced and sustainable productivity/economic resilience, including minimising adverse impacts while fostering positive changes on the environment (greenhouse gases - GHG, air, soils and water), product quality (including human health attributes), animal health & welfare and crop/plant/soil health. Combinations of solutions will be required within an integrated management framework to provide robust solutions for future application. This work package (WP) focuses on agricultural systems, developing the science from the current strategic research programme, in addition to establishing new areas of cross- and inter-disciplinary biological and socio economic sciences.

This WP contributes to many rural policy areas and legislative drivers, in particularly the Land Use Strategy, Scottish Soil Framework (2009), Scotland Rural Development Programme, Climate Change (Scotland) Act, Climate Change Adaptation Plan, The Third Report on Proposals and Policies (RPP3), Water Framework Directive (Priority Catchments), Scottish ‘Animal Health & Welfare in the Livestock Industry: Strategy 2015 to 2020’, European Union Zootechnics Proposal and Animal Health Regulation, UK National Action Plan on Farm Animal Genetic Resources (2011), Common Agricultural Policy (CAP) 2015 Pillar 1: Direct payments, CAP 2015 Pillar 2: Scottish Rural Development Programme (SRDP) 2014–2020 and proposed schemes including the Beef Efficiency Scheme (BES). The WP will support and provide information to help roll out/inform these policy areas. These drivers address key policy areas, specifically through the Pillar 2 priority areas identified in the SRDP 2014-2020 (*innovation in agriculture, animal welfare and risk management in agriculture, resilient economy in agriculture, food and forestry sectors*). For example, this WP will provide information on the development and delivery of the Scottish Government BES and strong policy links delivering RPP3 targets for GHG mitigation (e.g., developments of the Scottish inventory of GHG emissions and delivery of reduced emissions through Farming for a Better Climate).

Stakeholder Consultation: In the preparation of this WP stakeholders were consulted during the MRP Stakeholder Consultation at Moredun on 27 February and during a 2.3 specific workshop at Saughton House on 10 April 2015. In preparation for the second event a document comprising one-page summaries of each RD was prepared and circulated to a group of stakeholders including Scottish Government policy contacts, Levy Boards and NGOs. Feedback received either verbally or later in email was circulated to RD leads and acted upon where possible in the timeframe.

Coordination and management

a) Collaboration, co-ordination and networking between MRPs and with external communities. This WP comprises 12 research deliverables (RDs) based on well-developed and strong cross-MRP links between livestock, crops (including grass), soil, environmental and socio-economic scientists at SRUC, Hutton, MRI, RINH and BioSS. Examples include, SRUC and Hutton on soil management, crop protection and farm platforms, SRUC, RINH and MRI on healthy products from healthy animals and MRI and SRUC on identifying hurdles to uptake of best practice in disease control. This WP is also a key WP integrating biological and socio economic sciences with active links with WPs and RDs in within Theme 2, across to Theme 1 & 3 and to HEI bid 6. There are some main topic areas within this WP that link activities across the RDs and with other WPs (Figure 1).

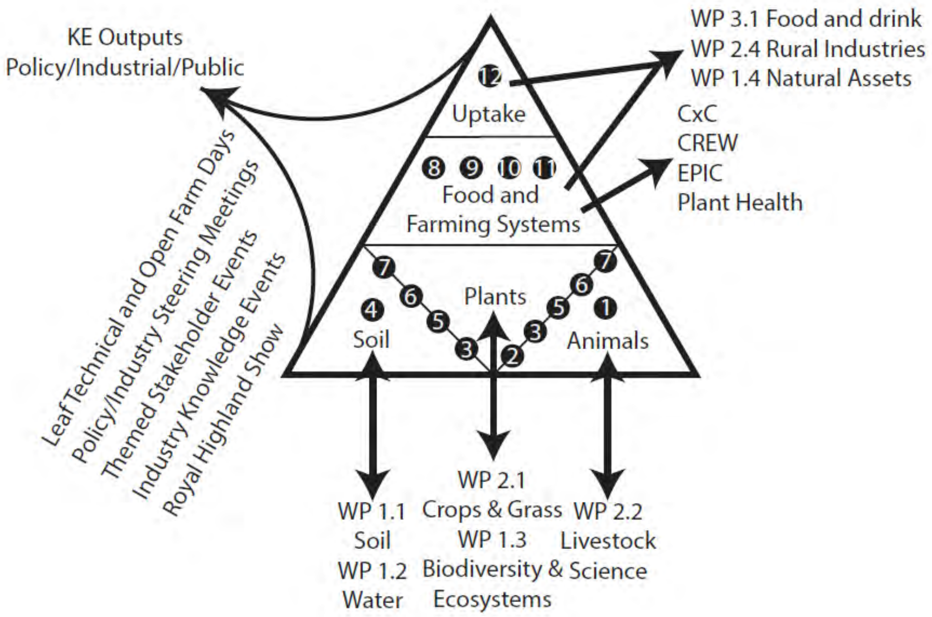


Figure 1: Interactions between the RDs and significant linkages to other WPs and major KTE vehicles.

Animals: Within this topic, this WP will examine how we can deliver sustainability at animal, system and food chain level. RD2.3.1 will examine how we can improve livestock for production, product quality (meat and milk), efficiency and fitness (i.e., health, resilience). Some of the novel methods for recording difficult to records traits in livestock (e.g., feed efficiency, immune function, parasite resistance, product quality) will link to the development of genetic improvement tools (RD2.2.1) and how such tools can be used in Integrated Management Systems (RD2.3.9). In the second half of the programme we plan to extend genetics R&D supporting the BES (RD2.2.1) to explore system wide economic (RD2.3.10) and environmental (RD2.3.5) impacts of the scheme as well as using the scheme to understand behavioural change and barriers to uptake (RD2.3.12).

A common disease systems approach will be taken to tackle plant and animal diseases in RD2.3.3 investigating the importance of the environment in disease transmission and host susceptibility to improve risk prediction and disease control. Key livestock examples, including Johnes and *E. coli*, will be tackled in this framework in collaboration with industry and policy stakeholders (e.g., Livestock Health Scotland, Health Protection Scotland). Common research and industry platforms will be used across RDs and/or MRPs, with a key livestock example being helminth control. Many aspects of this work will be informed by work being undertaken in WP2.2 and will scale up to the farming system through activities within this WP (RD2.3.10&11) and informing GHG mitigation options (RD2.3.6). Outputs from the animals topic area will be translated to industry and policy relevant outputs via Centres of Expertise of Disease Outbreaks (EPIC) and Climate Change (CxC).

Plants: This WP will examine how we can use plant selection and management to deliver agricultural sustainability at plant, system and food chain level. The primary role of work on plants in WP2.3 is to test how plants, with unique genetic and phenotypic traits, interact with their environment (both biophysical and socio economic) and how this interaction is integrated into the delivery of an improved system at a field scale. In general, information generated in WP2.1 on genetic and phenotypic variation in plant traits will be tested in field experimental platforms in WP2.3. Crop plants which are identified from traditional landraces, current elite cultivars, novel populations and novel species (to Scottish arable systems) will be tested for their utility in systems relevant to Scotland’s current and future agricultural environment. Traits involved in interactions between plants and soils (root traits) and plants and pathogens will be tested in “real world” environments where the ability of novel genotypes (RD2.1.1; 2.1.2), novel phenotypes (RD2.1.7) and novel crops (RD 2.1.8) to cope with environmental variation will be quantified. Insight generated on the ability to manipulate agricultural systems using plant genotype and phenotype will be integrated into novel cropping systems (RD 2.3.8 & 2.3.9) and industry and stakeholder acceptability will be assessed. Understanding of the impact of changes in plant genotype and phenotype in the field will be integrated with understanding of the impact of these plants on soil functions in WP1.1, water quality in WP1.2 and further onto impacts on wider ecosystem services in WP1.3. Information generated on plants will assist land managers in overcoming the challenges of increasing restrictions on agro-chemical use and government targets on pollution, climate change and biodiversity whilst maintaining crop yield and quality.

Soil: Optimal functioning and management of soil/land is crucial to the long-term sustainability of agriculture. RD2.3.4 will focus on the application of existing and novel models, management tools, plant genotypes and soil quality indicators to enhance sustainable use and management of soils and water in agricultural systems whilst reducing environmental impact. This will feed into, and link to, RD2.3.8 exploring how alternative crop (including grass), soil, livestock and uncropped area management and alternative farm system design influence productivity and the delivery of non-agronomic benefits of different systems. Links to Theme 1 are also important since many of the soil functions and indices of soil quality tested here in agricultural soils and with agricultural management, will also be applied in WP 1.1 in natural and semi-natural ecosystems. In addition, work performed here will directly inform the WP1.2 (Water Resources), providing information on the loss from arable soils of nutrients, toxic elements and eroded soil. Some common field experimental platforms will be used between the two WPs with important links to RDs 1.1.1, 1.1.2, 1.1.3, 1.1.4 and WPs 1.2, 1.3, 1.4. a number of these platforms include lowland grass either as the main land use or within a rotational context. The insight and outputs will be disseminated to stakeholders by an innovative package of KE activities.

Farming and Food Systems: The Scottish and UK Governments have ambitious targets to deliver reductions in GHG emissions of 80% by 2050, and it is anticipated that the agricultural sector will make a significant contribution to this. A number of mitigation measures seem to be “win-win” options, providing GHG mitigation and cost savings, but a combination of financial, technical, policy and behavioural barriers hinder their uptake. RD2.3.5 will provide information on barriers to farmer uptake and tools that may overcome them. Within RD2.3.6 we will examine newer and innovative approaches to the management of agricultural systems and reduction of GHG emissions in both livestock and cropping systems (including systems with rotational grass). This will be linked to, and help fill gaps in, wider UK funded research on GHGs (http://www.ghgplatform.org.uk/, RD2.3.7) namely, i) the high background emissions from Scottish soils in both grass and arable situations, ii) intake of grazing animals and iii) knowledge of what livestock are actually fed, have been identified. Work within RD2.3.5 & 6 will link to RD1.1.3 and utilise experiments on vegetation and soil management used in RD2.3.4 and RD2.3.8.

Farm animal and plant genetic resources are part of Scotland's natural capital, underpinning the current productive capacity and our resilience for future farming and food security. Using a mix of social, economic and biological skills, RD2.3.2 aims to identify the key mechanisms, drivers and threats related to the conservation, governance and sustainable use of selected native farm animal and crop genetic resources and develop supporting tools.

RD2.3.9 focuses on establishing and evaluating the benefits of new technologies and sensor systems as part of integrated management systems. Livestock will focus on ruminant production and the management benefits made possible by new systems, including grazing systems, and associated data processing. Arable will focus on assessing the impact of cropping systems to increase efficiency of production, reduce loss of resources and integrate alternative management strategies to maintain stable crop yields (linking with RD2.3.8).

Uptake: Ensuring uptake of best practice is essential to meeting the Scottish Government's objectives on sustainable economic growth, land use and food security and reducing in impact of livestock on the environment. With information feeding in from other RDs and WPs, this topic area will advance the uptake of best practices which improve the efficiency, productivity and sustainability of land, crop and livestock management throughout Scotland. This highly integrative topic area will be based on social, biological and economic approaches to examine barriers and uptake issues within case studies. Within this, we will explore the balance (co-benefits and trade-offs) between potentially competing outcomes associated with agriculture in Scotland (RD2.3.11). Through detailed research on major crop and livestock systems identified by our stakeholders, we will examine the relationships involved and draw conclusions that help farmers to adapt and improve their systems. Within RD2.3.12 we will examine the barriers to uptake of best practice, demonstrated by technologies, techniques and strategies, within specific livestock, cropping and related sectors. Work within RD2.3.11 and RD2.3.12 will link to WP1.4 to aid development of metrics and understanding of the farm level drivers for the sustainable intensification of these systems. The priorities are based on ongoing discussions with a number of policy and industry stakeholder groups. Work in this WP will inform KE elsewhere in the RESAS programme, via the Centre for Knowledge Exchange and Innovation (CKEI).

b) Interactions with underpinning capacity. Funding for BioSS inputs of a collaborative or advisory nature will be provided as described above through Underpinning Capacity Function 7, "Provision of Biomathematical & Statistical Consultancy Services". Management level inputs will be provided through identification of a BioSS WP Contact, who will be invited to WP level meetings and be involved in the preparation of Annual Reports and Knowledge Exchange activities. Although many interactions between staff in BioSS and the MRPs have a long and successful history, the nomination of a BioSS WP Contact will ensure that no scientist contributing to the WP is left without a point of contact in BioSS. In addition, the BioSS WP Contact will be well placed to maintain a watching brief over BioSS-MRP interactions here and to identify gaps in coverage or other mismatches between resource and demand which will be discussed with the BioSS Theme Contact along with other appropriate managerial staff in BioSS and the MRPs.

This WP is intrinsically linked to unique resources/facilities available at the MRPs, including collections of pathogens and pests of animals and plants, biological samples from non-diseased and diseased animals, post-mortem specimens, specific molecular probes and immunological reagents. The work will be conducted in state-of-the-art facilities for genomics, proteomics, cell culture, biological containment, animal accommodation (including farms specifically designed to host the required studies and experiments) and imaging. The resources are managed by appropriately skilled staff and are essential for delivery of the outputs from the SRP. Work in RD1, RD6 and RD9 will use data from our long running experiment on production, feed intake, health and reproduction in the Langhill dairy herd. Collection and maintenance of these data are part-funded via the SRUC Underpinning Capacity tender. Likewise, at MRI, a number of the best practice case study models in RD12 will be based at the institute's Firth Mains Farm. A number of crop based outputs across RDs will be driven (directly or indirectly) on developments at the CSC at Balruddery Farm and data and field resources from this platform will be provided through underpinning capacity funding.

c) Work package management structures and additionality. We will assign coordination roles at WP and RD Team levels. All coordinators will understand that a part of their role will be to help achieve coherence both within their teams and across WPs and Themes. We will sequence meetings to allow feedback from WP to Theme level to occur in a consistent way. We will actively engage with stakeholders to ensure that we address stakeholder priorities. Effective management and coordination depends on the existence of suitable structures and processes, and we will build on our experiences and successes in the previous programme to achieve this. We will make maximal use of internet resources for sharing documents and web-conferencing. Given the diversity and number of RDs within this WP, we propose to take a team approach to the management and delivery of this WP. Given the spread of areas in WP2.3, our first priority is to achieve sound collaboration within the WP 'Deliverable Team' (Figure 2) especially where this involves cross-institute working and sharing of resources/data (see also, Data Management Plan). Our experience of the current programme shows that WP interactions can be successfully fostered through regular meetings at project (RD) and WP levels, where the science is discussed and collaborations are developed.

Each **Research Deliverable Team** (RDT) will have a single lead coordinator (RDC), with all MRPs represented on an RD delivery team. The RDC will feed into the **Work Package Team** (WPT). The RDs will meet on regular basis (suggesting 6 months intervals) to discuss the science and progress on research and KE deliverables. The RD meetings will be timetabled before WP and Theme meetings to allow feedback from WP to Theme level. The RD convenors are distributed across the MRPs and will meet annually with the WPT to discuss progress and management in order to coordinate and finalise reporting as defined by RESAS.

The WPT has a representative from each MRP with significant contributions in the WP and will be chaired by a WP Coordinator (WPC). It will meet on a four-monthly basis, using online methods where feasible. One of the annual meetings will be convened with the RD leads, in order to prepare annual reporting requirements and discuss major issues. WPT meetings will partly focus on management issues including annual monitoring of progress against objectives for all RDs, facilitating resolution of problems, reporting of progress and exceptions to the Theme (in accordance with arrangements to be confirmed at Theme Level). WPT meetings will also discuss the on-going RD science against the backdrop of thematic and policy issues and the development of Theme-level KE outputs and interactions with the CKEI and sector champions. Minutes of WPT meetings will be communicated to all staff in the WP to ensure transparency.

Knowledge Exchange and interaction with stakeholders will be an important standing agenda item as well as having an annual meeting specific to KE. All relevant KE sectoral leads of CKEI (livestock, crops, environmental, communities) will join these KE focused meetings. As this WP is so diverse and large, it is felt that WP KE is essential to optimise and maximise the relevance of the KE outputs of the programme of work and ensure that we are exploring new opportunities to expand our KE base and stakeholders, in co-operation with CKEI. We will establish dialogue to exploit advantages that exist for cross-WP working within and across the Themes, building on the inter- and trans- disciplinary connections already establish and identify and develop new opportunities as the SRP progresses. Potential foci for cross-theme integration activites include: (i) resource efficiency which is a central theme across the WPs and offers opportunity for dialogue and integration across the crop, livestock and social science disciplines; (ii) inter-linkages between Themes on soils and (iii) data science within research that to inform our farming (RD2.3.9) and food (RD2.3.10, WP3.4) systems, our natural environment (WP1.4) and our economy (WP2.4). (see Figure 1 for other examples). Our management structures and processes will be established with a view to drawing out thematic issues and to facilitate networking and collaboration both within Theme but also across to other themes – including via CKEI led KE initiatives.

d) Key risks to delivery. In many areas, this WP builds on activity from the current RESAS work package (CWP), particularly building on work on agricultural GHG reductions (CWP3.2), soils (CWP3.3) and improving productivity and sustainability of livestock (CWP5.3) and crop (CWP5.2) systems. We will initially build on some of the resources, datasets and knowledge generated in those programmes of work so the level of risk is low in these areas. However, the WP also contains new innovative science, some of which will integrate across disciplines and, therefore, involve a range of researchers, sometimes across institutes. This WP will be delivered by experienced scientists that span the range of expertise required to undertake innovative integrated systems research. Innovative science is dependent on highly-skilled individuals working within specialised infrastructures which inevitably carry risk. Risks will vary depending on the activity, hence a **Red**, **Amber** or **Green** indicator status will be used to assess and manage risks (Table 1a&b).

Table 1. Initial Risk Register for WP2.3 - reviewed regularly by the WPT who decide to either: 'tolerate', 'continue to monitor', 'take action' or 'escalate' the risk.

Risk Assessmt	Description	Escalation
High	Showstoppers: risks extremely likely to occur and would have a very serious impact on delivery.	Escalated by Risk Owner (RO) to WPT and Programme Advisor (PA). PA will immediately consult with RO and Theme Coordinator and report to DEC.
Medium	Risks that could become showstoppers if not effectively managed and monitored.	RO to manage and monitor these risks, providing updates to the WPT through the highlight and exception reports. Immediate escalation drawn to attention of PA if an amber risk is re-assessed as red.
Low	Low risk that requires minimal management, although monitoring is still required.	Responsibility of RO to manage and monitor these risks. If reassessed as amber they must be reported to the WPT through the highlight and exception reports.

Risk Descriptor	Risk Assessmt	Impact	Controls	Risk owner	Update including recommendations for risk mitigation

Specific areas of expertise with limited staffing numbers	Medium	Some specific areas of expertise are located within a single MRP and sometimes within a single PI. Should those skills and expertise be lost, then it may be that some areas of work cannot be delivered, at least in the form in which they are originally envisaged.	Mapping of staff expertise within and between RDs and WPs	WP team, DEC	If there is loss of key staff then discussions would be held with RESAS (via DEC/ PAs) to redirect the work to areas that better suit the available expertise.
Provision and access to of private and public industry data	Medium	This WP reaches beyond the research/partner farm and looks to extend to farming and food industry data, and some of these linkages will need to be established.	We will establish industry stakeholder groups to guide/co-create work, help promote benefits of sharing data, support the supply and sharing of data and help identify implementation routes	RD team	We will initially focus on beef industry and policy stakeholder group linking work on genetic improvement (RD2.2.1), beef supply chain modelling (RD2.3.10) and beef production economics (RD2.4.1).
Failure/delayed delivery of outputs due to interdisciplinary dependences.	High	Interdisciplinary science involving many researchers can be more risky to deliver as inevitably there are dependencies in the work.	Planned and regular meetings at the RD & WP level to allow areas to be discussed and issues addressed promptly.	RD & WP team	Delivery plans and Gantt charts will be reviewed regularly and dependencies noted and monitored
Building expertise in "Data Science"	Low	The emergence of large data and diverse environments & infrastructures is a new source for innovation in agriculture. Extracting value from such data can often be difficult due to the intrinsic nature of data, and requires expertise in databases, data management, analytics, informatics, and statistical/ mathematical modelling.	This WP has widespread expertise in many of these areas, not least in livestock industry informatics and through expertise from BioSS and wider researcher partnerships.	WP and Theme teams	We will support the development of informatics skills in the MRPs by ensuring that linkages are made between the data intensive work in this and other WPs.
Data management (security, IP….)	Low	This WP is likely to generate and utilise a lot of different data sources including (i) from experiments and research platforms, (ii) modelling and simulation and (iii) public and private industry. This complexity of data and security of IP of externally sourced data is paramount to the delivery of this WP	RD teams will ensure that researchers are complying with Data Management Plans. We will ensure that all researchers using industry-wide data (public, private, pre-competitive) will establish the data transfer agreements and put in place appropriate data security measures, reviewed annually	RD lead and WP team	Review data management proactive in line with programme guidelines

Impact and KE. The KE plan for this WP will largely follow the topic area groupings identified in Figure 1. With 12 RDs and close links to the other WPs in Theme 2, we plan to hold our larger KE and consultative activities around these topic areas, and work collaboratively with the linking activities in the other WPs. We aim to run an annual event and the topic area(s) covered will be selected and prioritised in discussion with CKEI**.** Taking a systems approach, we expect that these consultative meetings will allow for smaller focal group discussions around particular (sub-)topic areas but also larger cross-linking topic areas incorporating multiple research disciplines and a more diverse stakeholder grouping. For example, one such cross linking theme could be agricultural GHG emissions and their mitigation.

This WP has a strong interdisciplinary theme underpinned by basic through to applied science. The proposed interdisciplinary approach will facilitate the design, testing and transfer of animal, crop and land management options. The lack of fundamental knowledge associated with some areas provides the opportunity to provide much novel scientific understanding and drive the science agenda in a critical area. Given the multiple disciplines across agricultural sciences involved, this WP has the potential to be a very successful interdisciplinary WP, within and across

MRPs and with wider HEI and industry/consultancy colleagues. We will monitor and scope new interdisciplinary and integration opportunities within WPT and through linkages to other WPs. If successful, the interdisciplinary aspects will deliver high ranking publications and impact in practice.

The provision of knowledge for sustainable agricultural systems will provide ample opportunity for innovation. Industry links provide opportunity to develop joint externally funded projects to further commercialise outputs from the programme. The development of novel tools to characterise crops and livestock has previously (and will continue to) lead a number of strong industry collaborations. The new traits work will help develop the next generation of targets for breeding programmes and feed into genetic improvement tools, such as those delivered by EGENES. Innovation expected to contribute to delivery of new mitigation tools include opportunities to develop precision farming techniques, soil management and use of improved livestock management. Further, work in this and linked WPs will have strong interactions with the planned AgriTech Centres for Innovation, particularly agricultural informatics (AgriMetrics, SRUC is one of the four core delivery partners) and the likely AgriTech Centres on crops, livestock and precision agriculture themes.

All the areas identified will deliver to, and are highly relevant for, a global and EU food security agenda, and be leveraged internationally for additional broader research. Via the identified scientists, this RESAS funded research will therefore be delivered on an international platform across the range of disciplines represented herein. We envisage strong overseas collaborations within Europe, and wider afield, particularly in China, Africa and Brazil, building on existing relationships and collaborations. Much of the work on novel traits in livestock requires international collaboration to build next generation genomic improvement tools as few research organisations could genotype and phenotype data on sufficient numbers of animals.

The highly collaborative nature of this WP will require close cooperation on KE events. These will include participation in key annual stakeholder focused events (LEAF technical and open days, Potatoes in Practice, Cereals in Practice, Fruit for the Future, SRUC field events, AHDB/SRUC/MRI Roadshow Workshops). Additional workshops will be developed separate to, and in association with, other WPs. Target audiences include CAMERAS; agronomic and agricultural companies targeted either directly or via intermediaries such as levy boards and commercial subsidiaries. KE partners include farm machinery manufacturers, precision farming companies, farm advisers, environmental regulators, and policymakers.

Given the strong policy focus to delvier and monitor the BES, we plan to establish a cross-WP (particularly linking to WPs 2.2 & 2.4) stakeholder group to consult on planned work (and prioritise work during the lifetime of the SRP), analysis and innovations for improving the efficiency of beef production in Scotland. This industry/policy stakeholder group will help to link work within Scotland to relevant and useful work elsewhere (e.g., Defra funded Beef Feed Improvement Programme).

The breadth of this WP will lead to many public and industry engagement opportunities and outputs. For example, we will continue to work with groups such as SAC Consulting, AHDB, Soil Association, RHET on public engagement.

Quality Assurance (QA). WP2.3 staff are dedicated to achieving and maintaining the highest possible standards of quality to meet the requirements of their work and the needs of their internal and external customers. To achieve this, they will:

- Comply with the requirements of the BBSRC/Defra/FSA/NERC 'Joint Code of Practice for quality assurance' and the BBSRC 'Statement on Safeguarding Good Scientific Practice'.
- Operate a quality management system that meets the requirements of the ISO 9001:2008 and which is systematically maintained, reviewed and revised to ensure continuous improvement.
- The relevant Quality Management Systems (ISO9001:2008 or equivalents) in each Institute will ensure:
  - Quality performance monitoring through internal and external auditing relating to the pertaining ISO standard;
  - Understanding of specific quality objectives and targets to staff;
  - Planning and developing of standard work processes by means of Standard Operating Procedures, where required;
  - Appointment of competent personnel to co-ordinate, implement and review quality management directives [existing MRP QA managers].
- Ensure adequate allocation of resources to achieve quality objectives and targets.
- Obtain and act upon feedback from key stakeholders and Scottish Government.
- Develop and maintain competency of all staff through the provision of tailored training and the clear communication of quality assurance requirements.

Ethical and regulatory issues. The proposed work within WP2.3 will involve the use of animals, genetically modified organisms, imported biological materials and hazardous materials. These activities will be reviewed, approved and regulated in accordance with the relevant legislative and QA procedures. The use of animals for research is regulated by the Animals (Scientific Procedures) Act 1986. All animal research will be conducted under Project Licences that are issued by the Home Office after Ethical Review with due regard to the 3Rs. GM organisms will be used in accordance with the Biological Agents and Modified Organisms (Contained Use) Regulations, the Genetically Modified Organisms (Risk Assessment) (Records and Exemptions) Regulations 1996 and the Genetically Modified Organisms (Deliberate Release and Risk Assessment – Amendment) Regulations 1997 and the Genetically Modified Organisms (Contained Use) Regulations 2014 ('the GMO (CU) Regulations'). Use of licensed plant pathogens and of imported soils and plant materials is governed by the Plant Health (Scotland) Order 2005, regulated by SASA for the Scottish Government. Importation of animal products will be conducted under an Import Licence/Authorisation for Animal Products or a Licence to Import an Animal Pathogen/Carrier into Great Britain (APHA). Environmental protection is enacted through the Environmental Protection Act 1990 (and amended Scotland 2001). Methodologies for collecting data from stakeholders will only be done with prior approval by the Scottish Government Survey Control Unit.

Contribution to the 3Rs (reduction, refinement and replacement). All animal work at MRI, RINH and SRUC is pre-assessed and then reviewed on completion by the relevant Committee to ensure that the 3Rs are/have been appropriately addressed. The MRPs actively pursue the 3Rs agenda and have regular contact with the regulatory bodies regarding issues raised by specific proposals.
Reduction: Production, resilience, health and welfare work (RD1, RD9, RD10) will be conducted on industry data (within and post farm gate) without the need to replicate these experimentally. Work in RD3 will make use animal disease models also used elsewhere in WP2.3 to reduce the need to specifically infect animals for this work.

Sharing of animal experimental resources (e.g., RD2.3.1 and RD2.2.9; RD2.2.9 and RD2.3.6; RD2.3.1, RD2.3.9 and RD 2.3.12) to achieve related but distinct outcomes in different RDs will also reduce the use of animals in this WP.

Refinement: RD1 and RD9 will develop a range of biomarkers from milk on immune function and, as such, minimises the need for blood sampling for either research or animal health management. Work on a hair-based biomarker for feed efficiency (RD1) will potentially reduce the need for testing animals in experimental conditions for said traits. Sensor technologies research (RD9) will reduce the need to sample from research animals as monitoring of conditions/disease will be provided automatically with minimal direct animal intervention.

Replacement: Use of national, commercial and existing datasets and materials (e.g., DNA and genotypes collected in the industry) to address questions of interest without collecting *de novo* experimental materials. Work in RD1 makes extensive use of banked tissues/samples and data sets collected via industry or in research contexts to minimise requirements for additional animal usage.

Sustainable Development. The Scottish MRPs associated with WP2.3 have Environmental Policy Statements which affirm that they are committed to preventing pollution, adopting and promoting environmental best practice in connection with operations and in support of sustainable and safe practices. In order to address wider sustainability issues, collaboration software will be used to facilitate messaging, group calendars, document sharing with versioning, and discussion boards organised around teams of people. Web-based video-conferencing will be used, integrated with concurrent sharing of the desktop display across multiple sites and organisations. The use of public or cost effective transport will be encouraged throughout the lifetime of the WP. We will monitor the impact of travel and, where possible, reduce the need to travel through use of tele/video-conferencing.

Name of RD: 2.3.1 Improvement of livestock
Research aim and key drivers This RD will examine how we can improve livestock for traits or management practices important for sustainability at an animal and system level, particularly focussing on animal health and welfare, product (meat and milk) quality and health attributes of these products, animal/system resilience, as well as a linking theme in the development of biomarkers for difficult-to-record traits (e.g., resilience to parasites, feed conversion efficiency) which may be used in livestock improvement programmes. This RD is largely focused on ruminant systems, although the identification of traits associated with optimal pig behaviours is also included. The key drivers for this RD are: • Improved efficiency and resilience of livestock farming • Improving the quality and health attributes of livestock products • Improvements in livestock health and welfare These drivers address key policy areas, specifically through the Pillar 2 key priority areas identified in the Scottish Rural Development Programme (SRDP) 2014-2020 (innovation in agriculture, animal welfare and risk management in agriculture, resilient economy in agriculture, food and forestry sectors), and were identified through consultation with a wide range of stakeholders including government, levy boards (e.g. QMS, AHDB), farmers, business development organisations and industry. Furthermore, a one page summary of this RD was circulated to a wide range of policy and industry stakeholders and general feedback incorporated. To address these areas, we propose eight related objectives (O) aimed at identifying a range of beneficial traits, or proxies of these traits, and management practices in livestock species which can be used to improve them through informing breeding programmes or altering current management advice. These include identification of traits based on rumen microbial information or changes in nitrogen isotopes associated with feed efficiency and meat quality in cattle and sheep; immune and nutritional traits associated with dairy cow health, productivity and milk quality; optimal use of anthelmintics in grazing sheep; immunological and genetic traits associated with resilience or vaccine responsiveness against gastro-intestinal parasites in grazing sheep; traits relating to climate resilience in cattle; and behavioural traits associated with optimal productivity and welfare in pigs.
Summary of the proposal: **O1: Strategies to use rumen microbial information in beef genetic improvement.** Feed efficiency (FE) is an important management (breeding and nutrition) target given that feed is a high system input cost for livestock systems. Traits of FE are or being in the process to be implemented in beef breeding programmes (e.g. UK Stabiliser™ Cattle Company & Canadian and American Hereford Association). O1 will build on preliminary results (CKEI5.3 & 3.2) which show that the microbiome and microbial enzyme genes are associated with FE in beef cattle. Furthermore, between animal variation in rumen microbial characteristics exists which is partly genetically determined. Analyses will be carried out to find the optimal combination of information on the microbiome and microbial enzyme genes, as well as proteins, to predict FE. The metabolic pathways of rumen microbes and microbial enzymes involved in FE will be identified. The impact of stress and competition on FE and the microbiome will be investigated and differences between breeds or sire progeny groups in susceptibility to stress will be assessed. Growth and its pattern as well as feed intake and its behaviour will be related to rumen microbial characteristics to understand their impact and to exploit this information for breeding of beef cattle. Rumen biohydrogenation of fatty acids may impact the fatty acid

profile of meat, which will be analysed based on the newly developed rumen microbial traits. New breeding strategies will be developed to incorporate rumen microbial information into practical breeding programmes. Key Deliverables (D): 1. Identification of associations between microbial information and feed efficiency, feed intake and feeding behaviour in beef cattle (D1); 2. Identification of interactions between stress, ruminal microbial information and feed efficiency (D2); 3. Determining the impact of rumen microbial information on meat quality (D3); 4. Development of methods to incorporate microbial traits into breeding programmes (D4).

O2: Novel biomarkers for feed efficiency in cattle and sheep. This work will explore the potential use of plasma and hair/wool-based proxies for feed conversion efficiency (FCE), based on Nitrogen (N) isotopic fractionation involving measurement of stable ^{14}N and ^{15}N isotopes in plasma and the diet, and builds on a recent successful Innovate UK Early-stage proposal for work in beef cattle. The objective will provide an increased understanding of the relationship between N isotopic fractionation and FCE in ruminants, and will extend work to consider use of the technique in sheep breeding for improved FCE. We also will test approaches to estimate N isotopic fractionation without the need for diet samples, which is critical when feed samples are not available (e.g. in grazing animals), using samples from other studies recording feed intake and FCE in beef animals. Key deliverables: 1. Identify stronger relationships between N isotopic fractionation and FCE (D5). 2. Determine whether faecal ^{15}N content of faeces can estimate FCE in ruminants (D6).

O3: Healthy milk from healthy cows. How dairy cow health relates to the human health-giving properties of the milk is poorly understood. This objective will extend work commenced in previous RESAS programme to examine the relationship between key health attributes of the cow and key human health attributes of the milk. From previous projects (CWP5.3 & externally funded) involving the SRUC Langhill resource population, we have data available on adult dairy cows, including steady-state blood and milk immune measurements, routine health and productivity and reproductive performance data, and milk mid-infrared (MIR) spectral data. These data will be combined with newly generated data exploring immune response measurements (as determined by whole blood stimulation assays with innate and adaptive immune stimulants), immune measurements in younger animals (neonatal calves and pre-service heifers) and micronutrient levels and status within milk and blood. Statistical and systems biology modelling of the combined dataset will be used to identify traits associated with dairy cow health, vaccine responsiveness, productivity and the nutritional quality of the milk. Using prediction equations we will also explore whether routinely recorded milk MIR spectral data can predict immune response and/or blood micronutrient levels. Key deliverables: 1. Identification of immune and micronutrient measurements associated with improved health, vaccine responsiveness and productivity (D7); 2. Identification of traits in cattle associated with healthier milk (D8); 3. Development of MIR-based methods to routinely predict key immune and micronutrient levels in blood and milk (D9).

O4: The impact of nematode refugia on anthelmintic efficacy and lamb growth. Gastro-intestinal nematode (GIN) infections are a cause of poor growth rates in grazing lambs. Current control relies on regular anthelmintic drug treatments, but this has resulted in the emergence of drug resistant parasites. This objective will specifically examine the role that parasite refugia (i.e. the parasite population unexposed to anthelmintic treatment) plays in prolonging anthelmintic efficacy, and the degree of refugia associated with optimal productivity in grazing lambs. Key deliverable: 1. Determine the effects of moderate and low parasite refugia on anthelmintic efficacy and production parameters in grazing lambs (D10). 2. Determine how different anthelmintic treatment regimes are affected by moderate and low parasite refugia (D11).

O5: Genetic and immunological basis of anthelmintic treatment requirement in grazing lambs. The rationale behind Targeted Selective Treatment (TST) for control of ruminant GIN is that anthelmintic treatments are only administered to individuals that most benefit from treatment. Considerable variation exists in treatment requirement to maintain lamb growth in the face of natural parasite challenge. Previous TST studies in Texel-cross lambs (CWP5.3), in which treatment decisions were based on live-weight gain, identified two serum immune traits (natural antibody levels and anti-parasite IgE) associated with reduced anthelmintic requirement. It is currently unknown if these associations are present in different sheep breeds reared under different management systems. Furthermore, the genetic basis of the extremes of the TST phenotype (i.e. individuals requiring multiple vs. no anthelmintic support) is unknown. This objective will determine if associations between immune traits and TST phenotype are shared across different sheep breeds and grazing management systems, and explore the genetic basis of the extremes of the TST phenotype. Identical TST experiments have been performed at the HMRC Kirkton research farm (CWP5.3), and we will use blood samples collected during these studies as well as from TST studies performed in RD 2.3.11. Importantly, the latter studies incorporate a system × breed comparison, with TST being performed on three genetic lines (High index Scottish Blackface, Control Scottish Blackface, Lleyn) reared under high vs. low input systems, allowing genetic and management effects on the TST phenotype to be explored. Key deliverables: 1. Validation of immune traits associated with reduced anthelmintic treatment requirement in different breed and management systems and estimate their heritability (D12); 2. Identification of MHC haplotypes associated with reduced anthelmintic treatment requirement (D13).

O6: Genetic basis of failure to respond to nematode vaccines in sheep. Genetic variability within the MHC region is known to influence the response to many vaccines. This objective will study an exemplar parasite vaccine (Barbervax®, a commercial *Haemonchus contortus* vaccine) in which a small group of animals (<5%) consistently fail to generate protective levels of antibody following vaccination. The relationship between MHC haplotype and low antibody responsiveness to the vaccine will be explored using previously collected samples. These results may be of wider relevance to vaccine responsiveness where antibody is the principal correlate of protection. The key deliverable for this objective is to identify MHC haplotypes associated with poor responsiveness to Barbervax® (D14).

O7: Incorporating resilience into Scottish breeding goals. Dairy cows produce less milk and poorer milk quality under higher temperature and humidity. Heat stress can also interfere with cows' ability to conceive and can increase early mortality and susceptibility to disease. Our preliminary analyses show that cows are not only affected by heat stress under current Scottish weather conditions but are also affected by a range of other weather conditions, such as precipitation, wind speed and solar radiation, sometimes even while they are housed (CWP3.2 & 4.2). We will identify mechanisms for climate resilience by using UK Meteorological Office data to investigate the effects of weather events on a range of existing phenotypic traits (e.g. milk yield and quality, health, survival and fertility) encompassing different management systems on a local (research farm) and national (UK-wide, commercial farm) scale. This will result in a framework for defining resilience and 'climate adaptive capacity' traits that could be extended to other livestock populations. We will use these data to undertake genetic studies on resilience traits and their relationships with other traits particularly some of the novel health, fitness and product quality (O3). Key deliverables: 1. Data mining of weather and phenotype rich research (and industry) animal performance to identify weather resilience and climate adaptive capacity traits (D15); 2. Estimate the genetic parameters for D15 traits (D16); 3. Test if signatures of climate resilience can be predicted from milk MIR (D17).

O8: Reducing harmful social behaviour in pigs Harmful social behaviour in pigs compromises health, welfare, disease resistance, product quality and production efficiency; each of which is a focus of this RD. Reducing harmful social behaviour may involve environmental, genetic and technological changes for farming systems. Work on aggression will primarily make use of genetic and phenotypic information already generated by previous or ongoing projects to clarify the traits to target in the breeding objective. Work on tail biting will develop novel practical solutions for improved stockmanship (to detect early signs of tailbiting) and management (to react once these signs are observed). Key deliverables: 1. Identification of phenotypic traits associated with optimal aggressive behaviour and their underlying genetic basis (D18); 2. Quantification of the production benefits of long-term social stability (D19); 3. Assessment of the impact of aggressive behaviour on pig welfare (D20); 4. Identification of early warning signs for tail biting outbreaks (D21).

Technical approach

Animal work will be approved by the relevant Animal Ethics Committees; where relevant, sample sizes will be based on our previous experimentation and in consultation with BioSS. In most objectives, the research will use pre-existing data, tools and/or samples collected from ongoing collaborations or previous work. The secondary use of data and samples from other studies will involve the appropriate permissions.

O1 Strategies to use rumen microbial information in beef genetic improvement

O1.1 Interactions between microbiome and microbial enzyme genes or novel proteins. Studies within the CWP 5.3&3.2 have shown considerable variation in the abundance of the rumen microbiome, microbial enzyme genes and proteins among animals. Interactions between microbiome abundance and microbial enzyme genes will be identified to determine the metabolic efficiency of different rumen microbes. These interactions will be the basis for strategies to use rumen microbial information in breeding programmes. Data and samples are available from microbiome and metagenomic studies from the CWP and EBLEX funded trials, and will be obtained from studies performed under RESAS **HEI bid 10** on the rumen microbiome.

O1.2 Examine the relationship between rumen microbial information and feed efficiency. Preliminary results have shown that microbial enzyme gene abundance explained substantial variation in feed efficiency (FE). Information on interactions between microbiome and microbial enzyme genes will be used to optimise the prediction of FE for implementation into breeding programmes. The analysis will focus on pathways of metabolism associated with the efficiency of rumen microbial fermentation, and will benefit from tools and software developed within a collaborative EU project: “Development of an easy to use metagenomic platform for agricultural science”.

O1.3 Analysis of the relationship between competition or stress responsiveness and feed efficiency. To assess the effect of management strategies on FE and growth, we will undertake a trial in which groups of low and high chronic stress will be compared. The choice of chronic stressor will be made after examining existing SRUC data on husbandry systems from commercial beef farms. Rumen fluid samples will be collected to determine changes in rumen microbial population due to chronic stress. These changes could be used as indicators of chronic stress among animal groups. Interaction between breeds (or sire progeny groups) and stress treatment groups will be estimated to identify the breed (or sires) with higher susceptibility to competition or stress.

O1.4 Determine the association between rumen microbial information and growth or individual animal variation in growth. Rumen microbial information developed in O1.1 will

be used to predict growth rate and growth pattern. Microbial enzyme gene information will be exploited to understand the microbial metabolism of growth and growth pattern.
O1.5 Understanding the relationship of rumen microbial information and feed intake and feed intake behaviour. Rumen microbial information traits as developed in O1.1 will be related to feed intake and feed intake behaviour to understand regulatory associations.
O1.6 The influence of rumen microbial information on product quality. Studies within the current SRP have provided information about carcass, meat eating and nutritional quality in beef cattle. In the trial described in O1.3, Near Infrared spectroscopy will be used to predict meat eating and nutritional quality. Rumen microbial characteristics are potentially correlated with fatty acids related to healthy meat (i.e. omega-3 fatty acids). This objective will investigate the impact of the rumen microbial composition on fatty acid profiles and other product quality characteristics.
O1.7 Development of the best strategies to implement novel microbial traits into practical breeding programmes. The results from O1.1-1.6 will be used to develop the best strategies to implement novel microbial traits into breeding programmes, the impact of which will be predicted based on potential selection responses in FE, growth, feed intake, stress susceptibility, animal behaviour and product quality.
Detailed work plan. Y1: O1.1. Estimate interaction between rumen microbiome and microbial enzyme genes at phylum (O1.1i, M1) and genus level (O1.1i, M2); Using metabolic pathways to understand the metabolic activity of different microbes (O1.1ii, M3); Disseminate results at beef open day (KE1); **Y2**: O1.2. Optimisation of the prediction of FE based on the rumen microbiome (O1.2i, M4) and all microbial information (O1.2i, M5); Understanding the relationship between FE and rumen microbial information based on metabolic pathway analysis (O1.2ii, M6); O1.3: Perform chronic stress trial (O1.3, M7) and record/prepare data for analysis (O1.3, M8). Disseminate results at beef open day (KE2).
O2: Novel biomarkers for feed efficiency in cattle and sheep
O2.1. Towards an improved understanding of the relationship between FCE and Nitrogen usage in ruminants. Existing individual animal data from N isotopic fractionation studies conducted with collaborators with a range of ruminant species and physiological states will be collated. The data will be used for empirical modelling of the relationships with FCE and Nitrogen (N)-use efficiency. In addition, ^{15}N analysis of feed, faeces and plasma samples taken from a sub-sample of cattle (n>30) from a previous DEFRA-funded FCE study will be used to determine whether improved relationships between N isotopic fractionation and FCE exist if the N content of live-weight gain is accounted for.
O2.2. Evaluate the potential of ^{15}N content in faeces to determine FCE in ruminants. ^{15}N analysis will be performed on feed, faeces and plasma samples from >30 animals offered a wide range of diets and the relationship between ^{15}N content of faeces (or faecal fibre) and FCE determined using appropriate statistical models developed through a current Innovate UK funded project.
O2.3. Evaluate potential of N isotopic fractionation measurements at the amino acid level to determine FCE in ruminants. Methods will be developed for ^{15}N analysis of major individual amino acids (AA) within plasma proteins to evaluate the potential to measure N isotopic fractionation based on AA that fractionate vs. others that do not. Such measurements may be used in future studies exploring N isotopic fractionation and FCE.
Detailed work plan: Y1: O2.1 Assemble existing individual animal data from N isotopic fractionation studies (O2.1i, M9). Undertake empirical modelling of relationships with FCE and N-use efficiency (O2.1i, M10); **Y1/2**: O2.1&2.2. Conduct ^{15}N analysis in feed, faeces and plasma samples from cattle fed a range of diets (O2.1ii, M11) and evaluate the relationship between N isotopic fractionation and FCE (taking into account the N

content of live-weight gain) (O2.2, M12); **Y2**: O2.3. Develop methodology for ^{15}N analysis of major individual AA within plasma protein (O2.3, M13).

O3: Healthy milk from healthy cows

O3.1 Association of immune response traits with dairy cow health and productivity. Using the SRUC Langhill resource population, individual cow immune responses to innate and adaptive immune stimulants will be measured before and after routine Bovine viral diarrhoea virus (BVDV) vaccination. Statistical models (O3.4 below) will explore the impact of variation in these measurements on dairy cow health, vaccine responsiveness (as determined by pre- and post-vaccination antibody titres to BVDV), and productivity.

O3.2 Examine the relationship between immune traits in pre-lactation dairy cattle and subsequent health and productivity. Serum immune traits associated with disease and/or production in adult dairy cows will be measured in blood samples obtained from neonatal calves (<1 week old) and pre-service heifers. Total colostrum antibody levels, as well as the volume of colostrum administered, will be measured to provide an estimate of passive antibody transfer to each calf. Data will be used to explore relationships between these variables and future health and productivity measurements (in O3.4)

O3.3 Examine the relationship between key health attributes of the cow and key health attributes of milk. Using samples collected through a current BBSRC project on dairy cow immune traits, work at RINH will measure key markers of nutritional health within animals of the SRUC Langhill herd (in bloods) and collate these with measuring markers of nutritional healthiness in the milk produced within the same cow across both summer and winter periods to determine how they correlate. In addition, bloods and milk (O3.1 & O3.2 above) will also be analysed in parallel for assessment of nutrient levels, trace element (iodine, selenium, zinc, copper) and macro-mineral (calcium, phosphorous, magnesium) status in order to identify the interactions between cow nutrient status, immune responsiveness and milk healthiness. Milk samples and work from this objective will also be used directly in RD3.1.2 (O3) examining the effects of advanced glycated end-products (AGEs) on food quality; milk nutrient composition data obtained here will be correlated directly with the ability of the milk to form AGEs to identify potential factors that may limit their production.

O3.4 Development of statistical models to explore relationships between immune measurements, nutritional status, and dairy cow health and productivity. Data generated in O3.1, 3.2 and 3.3 above will be combined with routinely recorded health and productivity data. The combined dataset will be analysed using statistical and systems biology modelling approaches to identify traits associated with dairy cow health, vaccine responsiveness, productivity and milk quality, and whether seasonal variation exists.

O3.5 Explore whether milk MIR spectral data can predict nutritional and immune traits associated with dairy cow health and productivity. Milk MIR spectra data will be recorded from individuals undergoing measurements in O3.1, O3.2 and O3.3 above. Prediction equations will be generated using approaches developed within the EU OptiMIR project to relate MIR spectral data with immunological and nutritional measurements.

Detailed work plan: Y1: O3.1. Optimisation of immune response assays using immune stimulators targeting lymphocytes and innate immune cell populations (O3.1i, M14); Perform immune response measurements on blood samples from adult cows before and after routine BVDV vaccination (O3.1ii, M15); measurement of pre- and post-vaccination neutralising antibody titres against BVDV (O3.1iii, M16); O3.3. Measurement of blood nutrient status of dairy cows to correlate with immune traits/vaccine responsiveness (O3.3i); Measurement of nutrient levels in milk to correlate to measurements of animal health (O3.3ii, M17); **Y2**: O3.2. Measurement of serum immune traits in pre-lactation dairy cattle (O3.2, M18); O3.3. Measurement of nutrient levels in bloods from dairy cows

(O3.3iii, M19); O3.4. Development of statistical (O3.4, M20) and systems biology models (O3.4, M21) to analyse previous and newly collected data on the Langhill resource population. Disseminate results at Royal Highland Show (KE3).

O4: The impact of nematode refugia on anthelmintic efficacy and lamb growth.

O4.1 Determine the effects of moderate and low parasite refugia on anthelmintic efficacy and production parameters in grazing lambs. Through grazing of plots seeded with characterised GIN isolates, this work will determine whether moderate or low parasite refugia affects the rate at which resistance to endectocides such as moxidectin develops and how this affects lamb growth rates.

O4.2 Determine how different control strategies affect anthelmintic demand. Using plots developed in O4.1, lambs grazing pastures will be subjected to different drug treatment strategies(e.g. moxidectin followed by an exit drench; use of a dual active compounds (e.g. STARTECT™); targeted treatment strategies developed under a previous EU project (PARASOL) and current SRP) to determine which combination of refugia and drug treatment results in optimal anthelmintic efficacy and lamb growth.

Detailed work plan: Y1: O4.1 Seed pastures with characterised drug-susceptible GIN isolates to generate plots with known levels of parasite refugia and assess nematode contamination levels (O4.1, M22); **Y2**: O4.2 Perform field trial to determine effects of parasite refugia levels on the development of resistance to moxidectin/lamb growth rates & collate trial data (O4.2, M23). Disseminate results at Moredun Road Show (KE4).

O5: Genetic and immunological basis of anthelmintic treatment requirement in grazing lambs

O5.1 Identification of serum immune traits associated with anthelmintic treatment requirement in lambs. Serum samples collected from 800 Blackface and Lleyn lambs over two lambing seasons undergoing TST (CP WP5.3) will be supplemented with samples (n=300) collected from a third lambing season (RD 2.3.11). Parasite-specific IgE and natural antibody levels will be measured by ELISA. Associations between serum measurements and anthelmintic treatment requirement will be explored statistically, taking into account breed and management system.

O5.2. Identification of associations between MHC genotype and anthelmintic treatment requirement in lambs DNA from whole blood samples collected at the same time as serum samples collected in O5.1 will be prepared from extremes of the TST phenotype to allow genotyping at the polymorphic class II MHC DRB1 locus by sequence based methods. Statistical analysis of associations between alleles, individual Single Nucleotide Polymorphisms (SNP), SNP clusters, and TST phenotype will be performed to identify genetic markers associated with anthelmintic treatment requirement.

Detailed work plan: Y1: O5.1 Collect blood samples from 300, ~3 month old lambs prior to commencement of TST. Archive serum and whole blood samples for subsequent use (O5.1i, M24); Measure antibody levels in archived serum samples by ELISA (O5.1ii, M25). O5.2 Prepare DNA from archived whole blood samples from individuals exhibiting extremes of the TST phenotypes (O5.2i, M26); Disseminate results at Moredun Road Show (KE5). **Y2**: O5.2 Genotype DNA samples at the class II MHC *DRB1* locus (O5.2ii, M27) O5.1&O5.2. Identify immunological (O5.1iii) and genetic (O5.2iii) associations with TST phenotype (M28); Stakeholder dissemination event - Kirkton farm open day (KE6).

O6: Genetic basis of failure to respond to nematode vaccines in sheep

O6.1 Identification of associations between MHC genotype and high and low antibody responders to Barvervax® vaccine. DNA will be extracted from archived serum samples from sheep previously vaccinated with Barvervax® and for which antibody titres to the vaccine are known. Individuals will be genotyped at the class II MHC DRB1 locus to identify associations between MHC diversity and antibody responses to the vaccine.

Detailed work plan: Activities in this objective with start in Y3.

O7: Incorporating resilience into Scottish breeding goals

O7.1 Phenotypic characterisation resilience traits. Historic records will be used to investigate effects of weather on a range of existing phenotypic production, fitness and novel traits. We will utilise SRUC Langhill research herd data to examine complete life history traits for their potential as indicators of resilience. Using historic data we have detailed lifetime phenotypes for >2,000 cows from the research farm. Phenotypic data includes daily records of individual productivity, fertility, survival, feed and water intake, behaviour and health, and weekly milk MIR spectral analysis. Building on CWP4.2 we will statistically model variation within and between animals, and across systems, in their responses to different weather variables.

O7.2 Genetic and management influences on resilience traits. Within the research herd data we will test the difference between the divergent selection lines and diet groups on the resilience of dairy cattle. These data will be then used in a genetic study of the resilience traits.

O7.3 Explore whether signatures of weather stress and/or resilience can be identified using milk MIR spectral data. Building on O3.5 we will test if signatures of weather stress (and resilience to it) can be predicted from concurrent milk MIR spectra. As milk MIR is available repeatedly over time we will explore if milk MIR can be used as an early warning indicator of weather related stress.

Detailed work plan: Y1: O7.1 Model weather impacts on milk yield (including fat, protein and particular milk fatty acids), fertility (cyclicity and conception ability) and health (e.g. mastitis and indicators thereof). This will produce a response curve for each animal to show how their individual production and fitness profiles are affected by different weather events. An individual's resilience will be quantified based on the magnitude of the phenotypic impact of weather, enabling each animal to be assigned a climate 'resilience' or 'susceptibility' value for each of the key production and fitness traits (O7.1i, M29). We will model animals' temporally to examine the ability of an individual to build up a tolerance to different weather events, termed herein the individual climate adaptive capacity (O7.1ii, M30); **Y2**: O7.2 Estimate the genetic (O7.2, M31) and phenotypic (O7.2, M32) correlations between resilience and climate adaptive capacity phenotypes. O7.3 Meeting with dairy industry on the broader utility of milk MIR based predictions of novel animal phenotypes (KE7).

O8: Reducing harmful social behaviour in pigs

O8.1. Quantify phenotypic and genetic relationships between regrouping aggression and long-term social stability to identify an optimal balance. To date, pig aggressiveness has only been studied at single time points, but must be controlled across life. Using existing data from two populations (both >1000 animals; collaboration with Michigan State University) we will identify key behavioural and lesion traits that are predictors of a pig's ability to optimise its use of aggression across social contexts. 'Optimum' in this case would be a pig which minimises the costs of aggression (e.g. total fight duration; total lesion count) in both regrouping and stable social group contexts. Using existing pedigree and genotypic data (collaboration with Pig Improvement Company), the genetic and genomic basis of these key traits will be estimated.

O8.2. Quantify the benefits of optimising long-term social stability for productivity. We will use existing growth performance and product quality data from the populations in O8.1 to estimate the phenotypic and genetic associations between economic performance traits and optimum aggressive strategies. Data on reproductive performance will be contributed by an existing collaboration with Teagasc.

O8.3. Assess the welfare outcomes of different fighting strategies and fight outcomes.

Data on welfare indicators (behavioural measures such as avoidance and inactivity, and the quality of behaviour (through Qualitative Behavioural Assessment) will be extracted from existing videos taken before, during and after standardised contests to assess the welfare impact of experiencing aggression. *O8.4. Identify early-warning signs for tail biting outbreaks.* In collaboration with the Danish Pig Research Centre, we will analyse the consequences of a cessation in tail docking in a well managed herd and record behaviour of pigs from contemporary pens with or without outbreaks of tail-biting to identify changes that may serve as warnings of an impending outbreak. **Detailed work plan: Y1**: O8.1.Identify traits associated with minimal costs of aggression at the social group level (O8.1i, M33) and at the individual level (O8.1i, M34); **Y2**: O8.1. Estimate genetic and genomic basis to traits associated with minimal costs of aggression (O8.1ii, M35). O8.2. Estimate associations between behavioural traits and performance (O8.2, M36); O8.4. Analyse consequences of a cessation in tail docking in a well managed herd (O8.4, M37); Industry technical report on O8.1/O8.2 results (KE8).
Key linkages, interdisciplinarity & collaboration: This interdisciplinary RD benefits from substantive linkages with other RESAS funded work and other UK & EU groups (primarily through collaborative research). This will facilitate exchange of ideas, expertise and dissemination of research outputs. Linkages/collaborations will be maintained by regular project-specific meetings and progress reports. **Linkages within RESAS Strategic Research Programme:** **WP2.2:** (1) RD2.2.1: *Livestock genetic improvement tools*. Heritable traits identified under RD2.3.1 will complement studies in this RD, including outputs from RD2.3.1 O1&O2, which will support beef improvement, including the Beef Efficiency Scheme (RD 2.2.1 O1). RD2.3.1 O5 will complement genetic association studies in sheep in RD2.2.1 O5 as both studies will measure identical immune trait phenotypes; (2) RD2.2.4: *Novel Diagnostic tools*. Nematode isolates recovered from RD2.3.1 O4 field studies will be used to evaluate novel molecular tests developed in RD2.2.4 to detect drug resistant parasites; (3) RD2.2.9 (*GHG reductions from livestock*) will use methane measures generated as part of experimental activity in RD2.3.1 O1. **WP2.3:** (1) RD 2.3.6: (*Novel GHG reduction measures)*. Traits associated with improved livestock efficiency have direct relevance to these RDs. Linkages will be explored at the WP level; (2) RD 2.3.11 *Trade-offs between productivity and sustainability*. Studies in RD2.3.11 O1 will be used to generate samples for analysis in RD 2.3.1 O5 and results from both RDs analysed collectively. **Theme 3:** (1) CWP5.3 showed significant differences between cows of differing genetic merit and on different diets and their fatty acid and micronutrient content. A more detailed extension of this work will occur in O3. Any protein and sugar

rich food such as milk will form glycated proteins when heated. O3 milk samples and data analysis will link to work exploring effects of glycated proteins on metabolic health and cognition (RD3.1.2). **HEI bid 10 (Rumen microbiome):** RD2.3.1 O1 scientists are co-investigators in this project and will exploit expertise from University of Aberdeen (microbiology) and Roslin (microbiome). **Underpinning Capacity:** O3&7 will use data from the Langhill dairy herd which is in part funded via the SRUC Underpinning Capacity.

Linkages with other UK and EU research:

O1 & O2 will exploit collaborative involvement in an EU project on the development of metagenomic platforms for agricultural science and will benefit from microbiological expertise from collaborators from Teagasc and INRA. O3 and O7 will exploit links with EU funded 'OptiMIR' project which provide MIR data analysis expertise relevant to O3 and O7; O1, O2, O3 and O7 will exploit linkages with EU funded 'Gene2Farm' project on the development of novel breeding tools for livestock improvement, which facilitates transfer of outputs from O1, O2, O3 and O7; O4 will exploit links with BBSRC sLoLa 'BUG' project on nematode drug resistance; O5 will exploit analytical and immunological expertise via links with the UK St Kilda Soay sheep project; O6 will exploit links with EU 'PARAGONE' project on animal parasite vaccines; O8 will exploit collaborations with Teagasc (provision of reproduction data), Michigan State University (behavioural data and genotypes) and Pig Improvement company (genotypes).

Added Scientific Value: Members of this RD currently hold competitive research grants complementary to many of the research areas proposed here including: BBSRC-funded projects exploring (i) the utility of immune traits to improve dairy cow health and welfare, and (ii) methods to control pig aggression; DEFRA-funded work on (i) FCE and (ii) feed efficiency in beef cattle, and European Union funding to optimise the use of milk MIR data (OptiMIR) and utilisation of genetic information in cattle (Gene2Farm). These projects provide significant added value to the RD through secondary use of samples, data provision, and development of tools and technologies applicable to the RD.

KE, Audiences and Impact

Audience: **Policy:** This work will inform Scottish Government policy within the context of the priority and focus areas of the SRDP as well as the existing "Modernising Scottish Agriculture" and "Farming for a Better Climate" agendas. Policy relevant outputs will be generated within the context of the Scottish Animal Health and Welfare in the Livestock Industry Strategy 2015-2020, and the Scottish Food Commission which aims to make Scotland a "Good Food Nation". Appropriate outputs will be directed through Policy Briefs. **Industry:** Direct KE to stakeholders will be through stakeholder events, in particular at the Royal Highland Show (KE3), Farm open days (e.g. KE1,2,6), industry meetings (e.g. KE7) and through Moredun Foundation road shows in October/November annually (KE4,5). We will disseminate articles in the farming press, through Moredun factsheets/news-sheets, and with industry technical publications (e.g. KE8). **Public and Professional**: Through publication in high impact open access scientific journals and presentation at national and international conferences annually (e.g. British Society of Animal Science meetings). KE and policy outputs will be unified through publication of key results on the knowledgescotland website under their "Success Stories" banner.

Impact: The outcomes of this work will have a significant impact on the rural and national economy by improving the efficiency and resilience of livestock production systems, as well as improving product quality. This work will lead to improvements in livestock welfare, which is of wider societal interest. These factors combined will have the effect of improving competitiveness of the Scottish food industry in the global marketplace, contributing to greater food security. To ensure this impact we will engage with Policy, Public and Industry stakeholders throughout the programme.

RESEARCH DELIVERABLE NUMBER: 2.3.1
Work planning and timetable for Year 1: (M= Milestone; D = Key deliverable; KE = KE output; R = report)

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i Microbial interaction analysis Estimate rumen microbiome & microbial enzyme gene interactions						**M1**						**D1** **M2**
O1.1ii Microbial metabolism analysis Pathway analysis of microbial enzymes												**M3**
O2.1i Modelling of N-use and FCE Assemble data and model relationship between FCE & N-use efficiency						**M9**				**D5** **M10**		
O2.1ii ^{15}N analysis of biological samples. Perform ^{15}N analysis on samples from different diet groups												**M11**
O3.1i Immune assay development Develop cell stimulation assays				**M14**								
O3.1ii Immune response. measurement: Measure cell stimulation responses before and after vaccination								**M15**				
O3.1iii Vaccine-response measurement Measure vaccine-induced antibody levels												**M16**
O3.3i Blood nutrient measurement Measure nutrients in adult dairy cow blood												
O3.3ii Milk nutrient measurement Measure nutrients in adult dairy cow milk												**M17**
O4.1 Generate pasture with known parasite refugia. Seed pastures with different levels of drug resistant GIN						**M22**						
O5.1i Blood sampling TST lambs Sample ~300 lambs undergoing TST and create sample archive					**M24**							

O5.1ii Antibody measurements Measure serum antibody levels in lambs undergoing TST										M25		
O5.2i DNA preparation from TST lambs Prepare DNA from lambs with extreme TST phenotypes								M26				
O7.1i Define weather resilience traits Assign resilience values for key production and fitness traits in cattle.								M29				
O7.1ii Define climate adaptive capacity Define capacity of individual cattle to develop tolerance to climates.												D15 M30
O8.1i Aggression associated traits Identify traits associated with minimal cost of aggression.						M33						M34
O1 KE1 SRUC Beef open day								KE1				
O4 KE5 Moredun Road Show								KE5				
R1 Year 1 Report to RESAS												R1

RESEARCH DELIVERABLE NUMBER: 2.3.1

Work planning and timetable for Year 2: (M= Milestone; D = Key deliverable; KE = KE output)

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.2i Microbiome based FCE prediction Optimise prediction of FE based on rumen microbiome information						**M4**						**D2** **M5**
O1.2ii FCE & microbial metabolism Determine relationship between FE and rumen microbe metabolism												**M6**
O1.3 Perform trial on stress & microbiome Perform trial to determine effects of high & low stress on the rumen microbiome						**M7**						**M8**
O2.2 Evaluate ^{15}N relationship with FCE Complete ^{15}N analysis and evaluate relationship with FCE				**D6** **M12**								
O2.3 ^{15}N amino acid assay development. Develop method for ^{15}N analysis of plasma amino acids								**M13**				
O3.2 Pre-lactation immune responses Measure immune traits in neonatal calves and pre-service heifers								**M18**				
O3.3iii Blood nutrient measurement Measure nutrients in adult dairy cow blood								**M19**				
O3.4 Data analysis Use statistical and systems biology models to identify traits associated with dairy cow health, productivity and milk nutritional quality						**M20**						**D7/8** **M21**
O4.2 Perform parasite refugia field trial Perform field trial to determine effects of parasite refugia on drug resistance and lamb performance						**M23**						

O5.2ii Genotyping TST lambs Genotype lambs with extreme TST phenotypes at MHC class II locus								M27				
O5.1iii/O5.2iii Data analysis Determine associations between immune traits/MHC class II and TST phenotype												D12/ D13 M28
O7.2 Genetic and phenotypic analysis of resilience Estimate genetic and phenotypic correlations between resilience and climate adaptive capacity						M31						D16 M32
O8.1ii Genetics of aggressive behaviours Estimate genetic basis to traits associated with minimal cost of aggression						D18 M35						
O8.2 Production consequence of behaviour Estimate associations between behavioural traits and performance												M36
O8.4 Consequences of tail docking Analyses consequences of cessation in tail docking in a well managed herd						D21 M37						
O1 KE2 SRUC Beef open day								KE2				
O3 KE3 Royal Highland Show			KE3									
O4 KE4 Moredun Road Show								KE4				
O5 KE6 Kirkton farm open day								KE6				
O7 KE7 Industry meeting – utility of MIR based predictions of novel phenotypes												KE7
O8 KE8 Industry technical report												KE8
R2 Year 2 Report to RESAS												R1

RD number: 2.3.2 Protecting Genetic Diversity

Research aim and key drivers

Farm animal and plant genetic resources are part of Scotland's natural capital (RDs 1.3.1, 1.4.1), underpinning our current productive capacity, encoding our cultural heritage and embodying the resilience for future farming and food security. Resources can be conserved both in farming systems (*in situ*), in genetic collections (*ex situ*) and through laboratory (*in vitro*) development. Although these genetic resources give rise to some public good attributes, stewardship is undertaken largely through private actions as part of breeding plans. To enable the preservation and development of this asset, it is important to identify its public and private good values and benefits, the costs of its maintenance or supply (including development using genetic/genomic tools), barriers to and drivers of conservation efforts (e.g. public policy, supply chain configuration) and the role of potential market and policy incentives to increase diversity and resilience.

Proposed research will explore elements of *in situ* and *ex situ* diversity in Scotland focussing on selected livestock and crop resources (beef, barley, wheat and potatoes) that demonstrate some of the key conservation values, actions, tools and barriers. Specific breeds and varieties will be identified through stakeholder engagement and data availability. A key objective is to represent genetic diversity in an economic framework, highlighting market/institutional structures and the costs and benefits (and their distribution) of conserving diversity. We aim to address a research gap by suggesting how policy can be designed to target maximum diversity conservation (including co-benefits) at minimum cost; where cost and benefits are both financial and social. A sub-objective is to demonstrate the extent to which this diversity objective corresponds to (or accommodates) a demand for other socially and culturally relevant objectives that also contribute to resilience such as maintaining population structures, health/welfare, cultural value of rare breeds and landraces in marginal areas. A further objective is to consider how modern DNA technologies can contribute to enhancing genetic diversity by controlling inbreeding whilst continuing improvement in livestock populations.

The research is primarily socioeconomic but will build on quantitative genetic activity in MRP science and in other RDs to provide diversity and value metrics for the target species. It will also link to Theme 1 work, locating genetic resources explicitly in the ecosystem services approach, addressing a conspicuous gap in that framework. The RD distinguishes between crop and animal breeding structures that have evolved differently. The work will also consider the complementarity between UK and Scottish breeding actions and tools and international initiatives. This includes supporting the aims of the UK Farm Animal Genetic Resources (FAnGR) Committee.

Summary of work:

O1 Industry and stakeholder workshops

Workshops will be conducted in the first, third and final year of the programme, bringing together socioeconomic and natural scientists (e.g. including scientists from RDs 1.3.1, 1.4.2, 2.1.1, 2.1.2) with industry members to co-construct the research agenda. The initial workshops will select the specific species for targeted research, and identify the government and industry-scientific issues surrounding conservation. The midterm workshops will present progress to date, and determine the direction of ongoing research (i.e. it is expected that barley, and beef will be the initial focus, with a shift from barley landraces to potatoes at midterm, to inform understanding of socioeconomic issues associated with preservation of the Commonwealth Potato Collection. The final workshops will address lessons learned and be opened to a wider stakeholder audience.

O2 Characterisation of diversity metrics for planned breeding & conservation

This objective will develop metrics for the objective characterisation of target species of animal and crops. It will review the applicability of tools from breeding and conservation and landscape genetics to the available data in Scotland; specifically with a view to designing the most parsimonious characterisation of diversity in target species. Note that activities within this Objective will interact closely with Objective 7 because of significant complementarities in objectives and expected outcomes.

O3 Social networks and animal/crop breeding

This research will utilise social network analysis to identify the industry (supply chain) structures underpinning the target species, assessing in particular the knowledge networks of members of the supply chain in each of the three selected species from Objective 1. Analysis will focus on up-take and use of genetic improvement tools, as well as breeder segmentation relating to preservation of native species.

O4 Market and non-market routes for the procurement /use of diversity

This work will consider how existing supply chains help and hinder the supply and demand for genetic diversity for selected commodities. It will also pilot a hypothetical conservation tender exercise on the willingness to supply diversity attributes form target producers.

O5 Industrial and supply chain barriers and genetic diversity

This objective will undertake a more formal analysis of market structures and behaviours in relation to the ownership and control of animal and plant genetic resources. Theories of industrial organisation will be used to explain the role of imperfect competition in the loss/maintenance of diversity in two commodities (one livestock, one cereal).

O6 Optimising *in* and *ex situ* diversity conservation

This objective will explore the interface between conservation options and attempt to evaluate the cost and benefits of mixed conservation strategies. Note that this objective depends on a successful outcome to a pending H2020 bid.

O7 Utilising genomic information to optimise management of genetic diversity in livestock populations

The proposed work will combine the principles of optimum contribution and genomic selection to optimise improvement, usage and matings in genomic breeding programmes of farm animals that will safeguard genetic diversity by controlling inbreeding. End-users (e.g. farmers, advisors, breeder associations) will be able to apply directly the outcome to select optimally and breed animals in both genetic improvement programmes and conservation schemes.

Technical approach:

This RD will be a transdisciplinary collaboration between research, industry and consumers involving geneticists economists, social scientists and plant and animal breeders, along with key actors in farming and food retailing. Limited existing socioeconomic work on farm animal and plant genetic resources suggests that the current status of breeding in animals and crops is segmented between accelerated breeding plans and breeding for conservation. Accelerated genetic characterisation of animals and crops has traditionally supported the development of traits that enhance the productivity of organisms with a focus on market value. This has led to the development of specific tools that target regional, chromosomal and genome-wide level markers and facilitated breeding indices that weight market and some non-market traits in the development of breeds and strains. Use of these tools can incorporate economic weights (i.e. market value) and consider the explicit costs of some trade-offs inherent in sustainable intensification. While this development has allowed productivity to be traded off with other public goods such as health and welfare traits or greenhouse gas emissions, intensification of production more broadly has led to a loss of resilience inherent in over-reliance on specific breeds and concomitant inbreeding. Although the role and status of cultural/traditional breeds is recognised, conservation of these breeds is considered separately from market productivity and long-term production system resilience. The overall governance of resources, including supply chain structures, arguably does not offer stewardship of overall diversity and there are clear elements of market, behavioural and institutional failures that can be targeted by this research.

There is increasing interest in the definition of conservation optimality/efficiency and the management of diversity *per se* (i.e. for more than productivity alone), but also for option value, for resilience and for cultural values. There is much less (if any) work considering the coincidence of optimal genetic diversity and other socially valuable attributes ascribed to both animals and crops. Nor is there an explicit consideration of the spatial distribution of *in situ* resources and the interface with *ex situ* collections and what this implies about policy targeting to support conservation. In this regard there is also a need to recognise the increased role of human agency in breeding (and tools) and how this adjunct to natural processes changes the calculus of optimality. More generally there is a need to understand both supply and market and non-market demand attributes of diversity and how markets (and market failure) have evolved to help or hinder the links between supply and demand.

O1 Industry and stakeholder workshops

In the first year, two separate Delphi/consensus exercises (beef and cereals) to determine the focus of the most endangered/priority genetic resources to prioritise in this RD. The workshop formats will be used to identify key measures of genetic diversity and how they are currently used to characterise breeds (non-native and traditional) used in Scottish production systems. The workshops will clarify breeds and structures, their genetic components and the key attributes targeted by recent genetic and genomic improvements. The aim is to clarify and match current genetic techniques with the objective of genetic diversity and to establish the validity of genetic diversity per se or in relation to socially valuable animal and plant attributes such as productivity, resilience to climatic stress, health/welfare, nitrogen use efficiency/greenhouse gas emissions cultural heritage. Follow-up workshops in year 1 will be conducted to further characterise the issues associated with the three identified focus species. For example for barley landraces, a workshop will bring together scientists working on assessing the genetic diversity and ecosystem service potential in related RDs (1.3.1, 2.1.1, 2.2.1) with industry stakeholders to identify issues surrounding production and marketing. Further workshops are planned in year 3 to discuss research findings with stakeholder groups, and undertake a similar process for assessing priorities in relation to potatoes. A final workshop is planned for year 5 to bring together the overall research findings. Outcomes from the beef workshops will inform O7 of this RD.

Key deliverables:

D1.1 Delphi workshop report (year 1)

D1.2 Selection of target breeds/varietals for focused research (year 1).

D1.3 – 1.5 Follow-up workshop reports

D 1.6 Further Delphi and follow-up workshops (years 3-5)

O2 Diversity metrics for planned breeding & conservation

O2 will focus on the identification of appropriate metrics for characterising diversity or genetic variation in target species. The aim is to consider the Noah's Ark problem first defined by Weitzman (1998); specifically how to identify maximum diversity in target populations considering specific (preferably at risk) landraces, the analysis will consider effective population size and whether meaningful measurement of genetic distance is feasible with current data. Ideally the analysis will lead to a phylogenetic or similar mapping of traits.

The work will draw on prior RDs 2.1.2, 2.2.1. Also on Theme 1 RDs where genetic diversity mapping should be considered in the natural asset accounting. This analysis is an important precursor to work in O's 3, 4 and 7.

Key deliverables:

D2.1 Information note on practical metrics for livestock and crop diversity

D2.2 Identification of data applications

D2.3 Peer reviewed journal article

O3 Social network analysis and diversity modelling

Genetic conservation is co-constructed within socioeconomic and geographical limits. To understand the relevant socio economic infrastructure (networks and linkages) underpinning the breeds and varieties selected in objective 1, we will apply qualitative Social Network Analysis (SNA) to understand how social relationships, which can include friendships, advisors, leaders, or peers – influence behaviour in a given group of individuals and organisations. SNA applies a range of tools largely based on graph theory, but grew out of anthropological research, in order to make sense of complex relational data. Analysis seeks to assess the individual nature of a person's social position, as well as the topography of the network as a whole: which individuals share information, who has a large number of connections, who is at the periphery and does not interact with the rest of the group? The analysis will have two foci – knowledge networks relating to the up-take and use of genetic improvement tools, as well as breeder segmentation relating to preservation of native species.

Empirical evidence about interactions within a social networks and the behaviour of individuals within the networks is growing. We know that many behavioural change interventions are delivered in a group setting, in the agricultural field of KTE these can be farm demonstrations, agricultural shows and workshops and group messages. Evidence also tells us that interactions within these group and collective settings have an influence on the sustained positive behaviour change. Specifically in this context we also wish to explore the relationship between financial (pecuniary) incentives for conservation and various forms of behavioural nudging messages that can enhance or reduce the need for financial compensation for conservation actions. In addition to SNA we will be exploring the use of econometric modelling to explain diversity. Findings on supply chain structure will feed into further supply chain assessment in O5.

Key deliverables
D3.1 Information note on network structure for landrace barley varietals, including identification of key nodal points for influencing behaviour change
D3.2 Joint information with RD 1.3.1 on use of barley landraces in achieving ecosystem services and associated issues with up-take
D3.3 Peer reviewed journal articles

- Note that this analysis for beef breeds and potato varietals will begin in year 3.

O4 Market and non-market incentives for genetic diversity
O4 will explore market incentives for diversity conservation. Specifically it will consider the topic of a) shorter supply chains for specialist or rare breeds; b) the use of incentive-compatible market mechanisms (auctions and tenders) in support of public procurement of diversity.
As a proof of concept for conservation (policy) targeting, this O develops a competitive tendering experiment to motivate the supply of genetic resources. More specifically to demonstrate the efficient procurement of diversity from a target cohort of producers identified as offering maximum diversity (as identified in O2) and specific health attributes associated with a specific breed relative to a common alternative. The exercise will be based on information from objective 1 that has identified the target participants in the exercise. Competitive tendering has been piloted elsewhere in the context of agri-biodiversity procurement and this O proposes a variant of a payment for ecosystem services (see RD 1.4.2). The aim will be to target a sample of producers using a hypothetical experimental approach to elicit their willingness to offer a specified level of conservation effort in a contract defined by a fixed value and conservation duration. The exercise will vary the contract terms (including the pecuniary/nudge content) depending on the sample size. It will also collect other relevant socio economic variables from the farm/household to enable the targeted diversity objective to be considered alongside other non genetic (but policy-relevant) objectives for support such as farm size, income, location on LFA etc. Alternative econometric approaches can be employed to estimate auction data and to develop the resulting diversity supply schedule. The policy relevance of the results will be demonstrated by graphing the level of diversity supply against alternative budgetary/support payment scenarios. Research on short supply chains will link to RD 3.3.3.
Key deliverables:
D4.1 Study note on conservation tender exercise
D4.2 Information note on SRDP development for diversity procurement
D4.3 Peer reviewed journal articles
O5 Industrial and supply chain structures and genetic diversity
Supply chains structures present both barriers and opportunities for the enhancement and use of genetic material. Only a small market niche can avoid supermarkets and hence formal supply chains are characterised by degrees of market power. While localisation of supply is an option for conserving valuable product attributes, this is unlikely to be on a scale that can deliver significant gains or overall system resilience. It is therefore important to consider how supply chains influence genetic diversity, both in general and in relation to specific species. In some cases (e.g. wheat, barley) genetics and breeding interests can exercise market power and are largely setting the agenda on breed diversity. To the extent genetics firms govern the supply chain they can protect the economic rents from their information asset as well as earn entrepreneurial rents. In crops

such as malting barley and wheat, processing demands can have a significant effect on variety use and hence crop homogenisation. Meanwhile the development of animal breeding tools and databases raises issues about proprietorial use, intellectual property and access and benefit sharing.

All these issues can be explored and characterised more comprehensively with reference to theories from industrial organisation. The economic characterisation of imperfect competition (the space between perfect competition and monopoly) is useful for providing insights into why heterogeneity can be lost in the production of final goods and services. An examination of market structures for UK agricultural production reveals a worrying extent of unregulated market power that has direct and indirect consequences for genetic diversity and potential system resilience.

This Objective will consider four main questions in separate studies of animal and crop genetics: 1) What market power do key breeding and processing actors exercise in the industry? 2) What are the major factors that determine market power and how does that influence the level of genetic diversity employed in products and at source? 3) How do companies strategies determine market power-including the use of direct contracting and the protection of intellectual property 4) What regulatory frameworks are in place which restrict genetic diversity (e.g. by inducing monocultures or restricting intercropping)? 5) What are the implications of supply chain regulation for farm system resilience?

Research will focus on the use of concentration measures, financial performance (mark up measures and rates of return) and other indicators of input and supply chain governance that influences (e.g. barriers to entry). Interaction with key industry stakeholders will be determined in the initial SD. The research will pervade separate studies to explain industry segmentation for animals and crops

Key deliverables:

O5.1 Information note on supply chain structures and impact on genetic diversity in the beef and wheat sectors.

O5.2 Peer reviewed journal articles.

O6 Optimising *in* and *ex situ* diversity conservation

Developing complementarity between formal breeding plans and breed conservation activities and between in and ex situ diversity. The advantages and disadvantages of *ex situ* conservation are well-documented although technological advances in cryobanking and use of DNA technology and reproductive physiology in collecting, storing and using biological resources are changing the cost-benefit calculus.This raises specific questions about the efficient interface between in and *ex situ* conservation and the respective roles of public and private partnerships. This RD is based on a pending H2020 bid and if successful will consider how *ex situ* options can best complement current in situ management. What is the actual or potential level of genetic diversity, either between or within breeds, available in genetic collections? Which part of it is not present in the mainstream livestock breeds dominating local and global food production? It will also consider how institutional structures for Scottish *in situ* and *ex situ* conservation effort interface and the relationship to international conservation effort, e.g. the EUGENA initiative to set up a European Gene Bank Network.

Key deliverables:

D6.1 Information notes on optimal conservation planning

D6.2 Peer reviewed journal articles.

O7 Utilising genomic information to optimise management of genetic diversity in livestock populations

Concurrent management of inbreeding and genetic diversity has been investigated in livestock breeding programmes by considering optimum management of candidate parents. The advent of modern DNA technologies, such as high-density array genotyping and sequencing, provides an excellent opportunity to extend this method to incorporate molecular data, thereby greatly increasing the effectiveness of the optimisation exercise. The objective of the proposed work is to use such molecular data to identify genomic regions of high impact on genetic diversity and develop optimum contribution tools at both chromosome and genome-wide level. These tools will encompass genomic selection and mating strategies and will be readily adaptable to both genetic improvement and conservation breeding programmes.

The scientific approach will include field data analysis and simulation studies. Field data will pertain to national records currently used in the genetic evaluations of livestock, which are routinely run at SRUC. Results from field data analysis will be used to inform simulation studies, and *vice versa*, and alternative forms of the optimisation tools will be evaluated and assessed. Outcomes from O1 and relevant metrics developed under O2 will also be considered as input to this work.

Key deliverables:

D7.1 The deliverable will be a method to optimise the usage and management of genomically-selected animals in a population. The outcome will include recommendations to end-users (farmers, breeder organisations, breeding decision makers) and the necessary software for implementation. The tool will be flexible in placing due emphasis on both genetic diversity and genetic progress, and will be equally applicable at population as well as farm level. At the same time, the tool would be applicable to conservation schemes aiming at maintaining and enhancing genetic diversity, and essentially ensuring the viability of a population.

Expertise This RD assembles an interdisciplinary team of experienced environmental economists, sociologists, geneticists (animal and crops). This team has an exemplary track record in both component research and in developing interdisciplinary research in genetic valuation improvement and environmental economics. This research deliverables enable cross-MRP research that allows interaction at a level not previously achieved with access to expertise and field sites across the MRP family. The PIs are established research leaders with national and international collaborations, who publish regularly in leading scientific journals, and are invited to present their work at international conferences.

Key linkages, interdisciplinarity & collaboration

The work locates genetic resources within the ecosystem approach and natural capital accounting in Scotland (RDs 1.3.1, 1.4.1). The incentives element links to work on conservation economics (payments for ecosystem services elements in RD1.4.2). Crop and animal genetic tools 2.2.1, 2.1.2 will be explored. O4 links to short food supply chains RD3.3.4. Breeding tools developed in O7 link directly to livestock genetic improvement tools (RD2.2.1) with regards to genomic data integration and outcomes implementation.

Other links are made to research on landrace barley varietals, specifically by identifying the opportunities and constraints to up-take by commercial farmers (e.g. of options developed in 1.3.1 for enhancing biodiversity through mixed varietal cropping). O6 is convergent with a H2020 proposal (SRUC as partner) on *ex situ* genetic conservation. O7 will link with and build upon collaborative research conducted through the EC-funded project on next generation cattle management tools (Gene2Farm) where SRUC participates as a partner. Furthermore, there will be interaction, data sharing and knowledge exchange between O7 and RD2.2.1. Additional links are envisaged with the Edinburgh Genetic Evaluation Services based at SRUC. One of the SRP geneticists involved in this currently sits on the UK Farm Animal Genetic Resources Committee (FAnGR) and as such will link this activity in this RD. We are also in contact with lead researchers in FAO and Bioversity International (CGIAR). Finally work in O4 and O6 is convergent with a NERC-funded PhD on rare livestock breeds being undertaken in SRUC

Added Scientific Value

The economic value and institutional management of genetic resources is generally understudied in the UK and globally, and this work builds on previous SRUC work on the rationale for public research on genetics (Defra) and our involvement in FAnGR. It complements genetic research in MRP organisations in relation to livestock and crops, including the conservation and analysis of land race materials. We also identify significant research gaps in terms of embedding genetic resources in the rhetoric of natural capital accounting and the contribution of these resources (and their stewardship) to ecosystem service flows. Other noteworthy gaps include the reconciliation of the supply of genetic resources with public good payment schemes, the role of supply chain power and appropriation/control of genetic resources, and the issue of optimising in situ and ex situ conservation efforts (including benefits and costs)

KE, Audiences and Impact:

As noted, while there is a public good interest in the maintenance of genetic diversity, resource stewardship is largely in private hands. Accordingly the KE effort spans this divide. We identify relevant KE challenges internationally via FAO and Bioversity International, the relevant CGIAR centre tasked with institutional analysis of agri-diversity. We also anticipate some interest in the EU as the research demonstrates how genetic resource conservation might be incentivised under Rural Development Regulations. We will also target the EUGENA initiative to set up a European Gene Bank Network, with the support of ERFP, the European Regional Focal Point for animal genetic resources. We also anticipate significant KE flows to and from current FP7 projects and H2020 bids in which we are currently engaged.

Beyond RESAS domestic public or third sector KE audiences include Defra, Natural England, JNCC, SNH, Rare Breeds Survival Trust, Scottish Crofting Federation. The research also contributes to work of the FAnGR Committee. To date the committee has apparently not undertaken any economic analysis. Key private sector bodies we will target include all the main supermarket chains, and levy bodies. Finally, participation in public KE events will allow the project information and storylines to reach a wider non specialist audience.

Currently anticipated KE activities are as follows

O1 KE 1 Workshops in years 1, 3, 5

Audience: Industry stakeholders (e.g. Rare Breed Survival Trust, Angus Cereals, Caledonian Organics, Grain Co, Quality Meat Scotland, NFUS, DairyCo, EBLEX), scientists, SNH, RESAS.
O1 KE 2 Engagement at industry events (e.g. Cereals in Practice, featured at Royal Highland Show)
Audience: farmers, plant and livestock breeders and geneticists
O2 KE1: RESAS workshop and technical note on Scottish animal/crop diversity metrics (e.g., NFUS, RBST SNH)
O3 KE1 Scientific conference paper
O3 KE2 Potatoes in Practice poster
O4 KE1 Edinburgh Discussion circle seminar
O5 KE1 Relevant food industry seminar to be identified
O6 KE1 Relevant stakeholder seminar to be identified
O7 KE1 Presentations to FAnGR and British Cattle Breeders' Club.
Impact
This research aims to raise awareness of the governance (or market failure) and economic value of genetic diversity and thereby seek to have this value feature in public and private decision making in conservation and breeding. Targeted KTE and publication will ensure that findings will reach key national and international audiences. We suggest that impact will be measureable in terms of calculated economic value of improved breeding decisions and eventually the ways in which government's choose to address the current lack of governance around maintaining genetic resources.
Outcomes of O7 are directly relevant with the European Union's zootechnical legislation to preserve and improve genetic resources, as stated in the "Proposal for a Regulation of the European Parliament and of the Council on the zootechnical and genealogical conditions for trade in and imports into the Union of breeding animals and their germinal products (Procedure 2014/0032/COD)". In particular, Article 4 in Chapter II entitled "Recognition of breed societies and breeding operations in Member States and approval of breeding programmes" clarifies that the nature of a breeding programme may be aimed either at the preservation or the improvement of a breed. This Chapter combines provisions of Council Directives 2009/157/EC on cattle and 89/361/EEC on sheep. The envisaged research results can directly contribute to regulations in Chapter II.
Moreover, the proposed work will facilitate preservation and improvement of genetic resources in a sustainable way, as directed by European Regulation 511/2014 implementing the mandatory elements of the Nagoya protocol dictated by the Convention on Biological Diversity (Council Decision 93/626/EEC).

RESEARCH DELIVERABLE NUMBER: 2.3.2
Work planning and timetable for Year 1: Major milestones, (key research activities, A#; deliverables, D#; KE/impact events KE#), and their timing.

Year 1: 2016/17	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
O1.1 Delphi workshops						D1.1						
O1.2 Targeted workshops (e.g. barley landraces, selected cattle and wheat varietals)								D1.2				
O2 Metrics						D2.1					D2.2	
O3.1 Social network analysis research design and approvals									M1			
O3.2 Data collection												
O3.3 Data analysis												
O4 Competitive tender												
O6 *in* and *ex situ* interface												
O7 Utilising genomic information												
Stakeholder workshops/ presentations (KE1-5)												
R1 Year 1 Report to RESAS												R1

RESEARCH DELIVERABLE NUMBER: 2.3.2
Work planning and timetable for Year 2: Major milestones, (key research activities, A#; deliverables, D#; KE/impact events KE#), and their timing.

Year 2: 2017/18	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
O2								D2.3				
O3.2 Social network analysis data collection – barley landraces						M2						
O3.3 Data analysis – social network analysis – barley landraces								D3.1	M3	D3.2	D3.3	
O4 Competitive tender										D4.1/4.2	D4.3	
O5 Supply chains												D5.1
O7 Utilising genomic information												D7.1
Stakeholder workshops/ presentations												KE6
KE O3 Conference paper				KE3.1								
KE O3 Poster at Cereals in Practice				KE3.2								
R1 Year 2 Report to RESAS												R2

Name of RD: 2.3.3 Disease Threats in the Environment

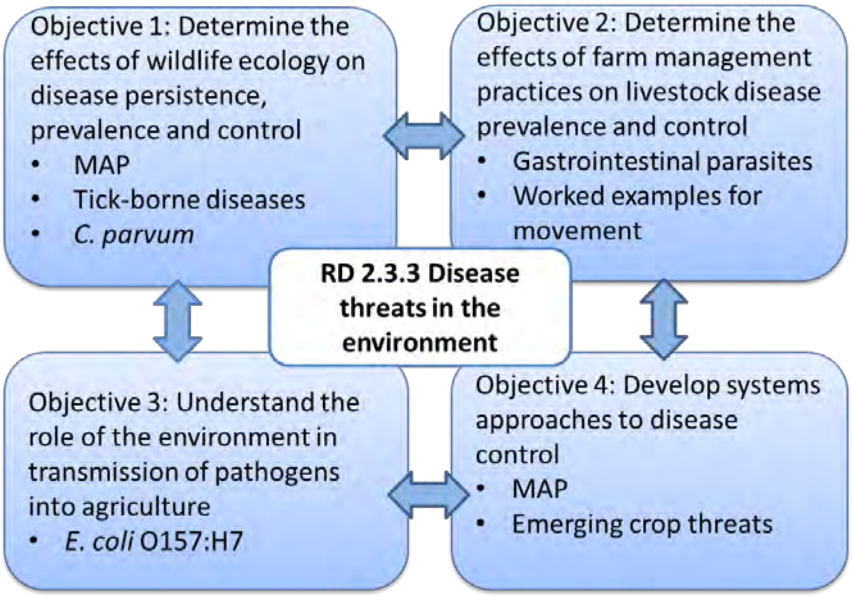
Research aim and key drivers

The One Health initiative is a global movement that unites animal, plant and human health. Our role in this initiative is to investigate the importance of the environment in disease transmission and host susceptibility to improve risk prediction and ultimately disease control. This aligns with the UK Animal and Plant Health Agency (APHA) strategy and will contribute towards the vison for capacity building and further integration. A disease systems approach will focus on biological processes and management practices that drive disease dynamics, persistence and spread, and is particularly relevant for parasites and pathogens with an environmental element to their lifecycle. Pest, parasites and pathogens of plants, animals and humans will be included, all of which are priorities of the stakeholder community. We will bring together science disciplines and stakeholders for improved understanding of the patterns of infection seen in agricultural environments. In doing so, we highlight the contribution of disease control by addressing the global grand challenges of:

- Climate change: contribution to & consequence of animal health
- Food Security: protecting production efficiency
- Disease Control: from emergence to emergency

Summary of the proposal:

Disease dynamics are determined in part by host-pathogen interactions and demographics of host populations (livestock / wildlife). Predictive mathematical models of disease dynamics are particularly sensitive to these factors when disease prevalence is low (e.g. when simulating disease control). Thus understanding contributions of wildlife and livestock management to disease persistence and prevalence is essential to inform control options and to model impacts of infection, environment and host population management on disease risk.



Four specific Objectives will be addressed in a number of activities, covering a range of pests and pathogens of strategic relevance (see figure, right). The common thread to each objective is the environmental component that impacts or affects the disease outcome.

The work proposed builds and extends on work in the current Work Packages (cWP) on ecological impacts on disease persistence and control. For example, the 'perturbation effect', a counter-intuitive increase in disease following population reduction. Here we will use modelling to better understand and parametrise the effect for use in operational models of disease control. Other examples include obtaining samples to test the dilution effect hypothesis for tick-borne diseases; testing recent models for parasite control; identification of the genetic basis to colonisation of plant hosts by food-borne pathogens in order improve food safety; and improved screening and control for *Mycobacterium avium* sub-species *paratuberculosis* (MAP), the causative agent of Johnes disease. The work has wide relevance to those in animal, public and plant health and will link to the Centres of Expertise for epidemiology (EPIC) and Plant Health. Disease that affects wild plants such as tree health but does not spread to agriculture is considered elsewhere, e.g. in RD1.3.3.

Key deliverables include: simulation outputs from models to test the perturbation effect, the dilution hypothesis for tick-borne diseases and movement between farms; a review of crop health status in Scotland; a better understanding of the presence of MAP in cattle and the wider environment; identifying the genetic component of verocytotoxigenic *Escherichia coli* (VTEC) that allows colonisation of plant hosts. (Numbering system for deliverables relates to the Gantt Activities chart listing Deliverables (D#), Milestones (M#) and KE/impact events (KE#) for Y1-2 only).

Objective 1: Determine the effects of wildlife ecology on disease persistence, prevalence and control, for a range of pathogens and vector-borne diseases.
1.1 Perturbation effect (PE): Work in the cWP initiated characterisation of the perturbation effect (Prentice et al. 2014). This effect has profound implications on disease control where there is an environmental component. Therefore, it is necessary to now assess the efficacy of wildlife population reduction strategies to control disease and their potential for a non-commensurate reduction or increase in prevalence.
1.2 Ecological impacts on disease persistence, prevalence and the efficacy of surveillance. Ecological factors (e.g. demography & population structure) and their impacts on wildlife disease persistence, prevalence and the efficacy of surveillance will be identified to parameterise modelling frameworks used to develop operational models of disease control. This generic work (including the PE in 1.1) will inform specific analyses and model development for *Mycobacterium bovis* in badgers as a proof of principle worked example. Specifically, new inference schemes and methods of implementation (from **HEI bid 4/**RD2.2.3) will be used to fit models to data to estimate demographic and transmission rates for *M. bovis* in badgers using existing long term datasets. This activity links this RD with **HEI bid 4/**RD2.2.3 and EPIC on the topic of inferring individual variation in population level models and is a test of the new methods to extract epidemiological information from data.
1.3 Tick-borne diseases: Ticks (*Ixodes ricinus*) are vectors for several pathogens including *Borrelia burgdorferi* (the cause of Lyme disease), louping ill virus (LIV, which kills red grouse and sheep) and *Anaplasma phagocytophilum* (causes death and abortion in livestock), and can infest multiple hosts including deer. The "Scotland's Wild Deer: a National Approach" (WDNA) Action Plan 2015-2018 specifies the need to address deer management in relation to disease risks, especially Lyme disease, and the ITGF requested work on how deer affect tick-borne diseases.Therefore, we aim to determine the relationship between deer density/management and tick-borne pathogens in contrasting habitats/land uses (links to RD1.3.3 and EPIC). Previous work has identified the effect of deer density and deer management on tick density but, crucially, this has not included pathogens or alternative host densities. This research is therefore novel yet low risk as it builds

on previous work, and will deliver much needed information on deer impacts on tick-borne disease, with clear use for land and deer management policy decisions.

1.4 Wildlife reservoirs of *Cryptosporidium parvum*. *Cryptosporidium parvum* infects calves within the first few days of life and other than from direct contact with their dams, may involve wildlife species such as deer, rabbits and rodents, as implied by our preliminary molecular species data for deer and rabbits. However, the importance of these wildlife reservoirs, as risk factors for cryptosporidiosis in calves, has yet to be assessed. Thus, source attribution and determination of key transmission routes will be established through broad sampling regimes on/around farms with known cryptosporidiosis to include resident wildlife, using our molecular speciation and genotyping techniques. Understanding origins and reservoirs of *Cryptosporidium parvum* will help to inform risk assessments that influence recreational and drinking water quality (RD1.2.1, RD1.2.3), animal health (RD2.2.6) and the management of catchment habitats (RD1.3.2).

Objective 2: Determine the effects of farm management practices on livestock disease prevalence and control, for parasitic, bacterial and viral diseases.

2.1 On-farm gastrointestinal parasite control. Existing models of livestock-parasite interactions will be used to assess alternative on-farm control strategies for gastrointestinal parasites (e.g. *Teladorsagia spp, Trichstrongylus spp, Nematodirus spp*),. The modelling will inform and be informed by the organic farm parasite control trials run in Scotland under the EU ERA-NET Core Organic Plus project PrOPara, coordinated by SRUC. The modelling and ProPara project outputs will feed in to a focal socio-economic study within RD2.3.12 on best practice.

2.2 Between farm livestock movements and disease control. Two modelling approaches will be used to characterise and quantify the role of between farm livestock movements in disease persistence, spread and control, using generic models of farmer behaviour and worked examples (Johne's disease, *E*. *coli* O157:H7 and bovine viral diarrhoea virus (BVDV): included as a comparison to current disease control activity that provides information on the sensitivity of the disease system to national control strategies). This activity will include explicit linkages with the continuation of the SPASE project on systems approaches to *E*. *coli* O157:H7 control and EPIC.

Objective 3: The role of the environment in transmission of pathogens into agriculture.

3.1 Colonisation of plant hosts by *E. coli* O157:H7. cWP6.2-supported work established that zoonotic pathogens including *E. coli* O157:H7 can utilise plants as secondary hosts from where they can enter the food chain in raw or minimally-processed fruit and vegetables. Specificity in the potential for *E. coli* to colonise plants is in part, dependent on the presence of certain bacterial genes. Functional analysis of the genes will help support enhance risk analysis for food safety. Key aims will identify functional roles for *E. coli* O157:H7 genes associated with plant colonization and determine whether *E. coli* O157:H7 secretes proteins that counteract the plants defensive response. Candidate genes will be collated from existing data (cWP6.2.5), genome analysis in RD2.2.6 (animal epidemiology) and by obtaining bacterial proteins that are secreted *in planta* to potentially counteract the defensive response of plants. The results will inform risk analysis for producers and public health.

Objective 4: Develop systems approaches to disease control

4.1: A systems approach to Johne's disease control in Scotland. The Johne's disease system will be characterised in Scotland and inform disease control strategies by bringing together the ecological, environmental and farm management research with new diagnostic tools and industry control schemes. This activity builds on previous RESAS funded research in to Johne's disease control Screening for MAP will be assessed from longitudinal livestock samples using existing and novel diagnostics (**4.1a**) and also from the National Soils Inventory of Scotland DNA archive (**4.1b**), to enable mapping national-scale distribution in the soil and routine testing outcomes (e.g. BioBest and Premium Cattle Health Scheme (PCHS) data). This information will form the basis of a statistical analysis to explore links between pathogen prevalence and soil types/land uses/livestock densities. Screening will be aligned with the genomic analysis of the NSIS samples being planned within RD1.1.3 and links to the PARABAN project.

4.2: **Existing and emerging issues affecting crop health**. The aim is to identify the existing and emerging issues affecting crop health and link to other parts of the RESAS Strategic Research Programme which are examining long term trends, control options, detection methods and the development of diagnostics. This will link to crop health research to Scottish Government Veterinary Advisory Service (VAS) funded crop health monitoring and to annual intelligence gathered through the SRUC crop clinics and staff advisory contact with growers. A key KE link will be established with the proposed Centre of Expertise for Plant Health.

4.3 New pests, pathogens and vectors of Scottish soft fruit. New risks to the soft fruit industry will be assessed. Blueberry aphid (*Ericaphis scammelli*), the vector for Blueberry Scorch Virus, a quarantine pest, was first reported in Scotland in 2013 at Hutton and confirmed by Science and Advice for Scottish Agriculture (SASA) who subsequently recommended monitoring for the virus and control of the aphid to prevent an outbreak. Although not listed as occurring in vacciniums in the EPPO region, the virus is a potential risk to the blueberry industry in Scotland from imported material. Another potential problem is *Erwinia pyrifoliae*, which causes blackening and oozing of fruit and stem in strawberry and possibly also infects raspberry, blackberry and other Rubus species. *E. pyrifoliae* was identified in The Netherlands in 2013 but has not yet reported in the UK. Both these pests need monitoring using diagnostic testing and soft fruit samples will be tested for their occurrence. In addition we will assess for the presence of other possible pests and pathogens such as Zebra Chip, transmitted by a psyllid vector.

Technical approach

Objective 1: Effects of wildlife ecology on disease persistence, prevalence and control:

1.1 Perturbation effect (PE): The impact of the PE on disease control strategies will be assessed by using existing spatial stochastic simulation models to determine the efficacy of different methods and spatial and temporal patterns of of wildlife population reduction (e.g. simulations of random vs rule based removal of individual animals or social groups) and their potential to lead to a PE (Y1, D1). This research will inform activities in sub-objectives detailed below on MAP and TB (*M. bovis*) in wildlife and cattle and the results inform the development of operational models of disease control developed under a Defra funded project.

1.2 Ecological impacts on disease persistence, prevalence and the efficacy of surveillance: Initially, wildlife demographic structures that affect disease persistence & prevalence and the efficacy of surveillance will be identified (Y1, D2). In the first instance, this generic work will inform specific analyses and model development for

M. bovis in badgers as a proof of principle worked example. Specifically, new inference schemes and methods of implementation, from **HEI bid 4**/RD2.2.3 will be used to fit the simulation models to data to estimate demographic and transmission rates for *M. bovis* in badgers using existing long term datasets (Y2, D4).

1.3 Tick-borne diseases: To determine how deer affect tick-borne pathogens under different land management scenarios (as requested in the ITGF), cross-sectional tick and pathogen surveys will be conducted. Previous studies suggest that the effect of deer on pathogens depends on deer densities relative to densities of competent transmission hosts (small mammals and birds for *B. burgdorferi*; red grouse, sheep and mountain hares for louping ill virus). We aim to quantify this effect of deer on tick-borne pathogens in Scotland for the purposes of informing deer management and disease control policy. Sites will be selected to encompass a cline of deer densities, from very low to very high (JHI holds deer density data, and we will co-develop the selection with land managers for refining site selection). Contrasting land uses will reflect contrasting densities of transmission hosts, i.e. moorland (known to have few transmission hosts for *B. burgdorferi* but several for LIV) will be contrasted with woodlands (known to have many transmission hosts for *B. burgdorferi* but few for LIV). This simple design allows us to quantify deer effects on different pathogens between habitats. .

Detailed Workplan:

1. Years 1-4 collect ticks (n=70 ticks / site / visit) from 16 sites selected (using existing information held by JHI) to have contrasting deer densities (8 woodland sites, 8 moorland sites). Sites surveyed 3x per season.
2. Develop and validate PCRs for *B. burgdorferi* and *A. phagocytophilum* (already validated for LIV) (Y1, M1); feasibility of multiplexing (Y2, M6). If multiplexing fails, we will continue to use standard PCRs.

Y3-4: DNA extractions and pathogen evaluations (standard or multiplex PCRs) of pools of 5 ticks (20 pools per site per visit).

3. Y2-4: Run multivariate statistical models to test the effect of (i) deer density and (ii) land management on tick abundance and pathogen prevalence; KTE to disseminate results.

1.4 Wildlife reservoirs of *Cryptosporidium parvum*. In order to assess the importance of wildlife reservoirs, the following activities will be undertaken, with a focus on cattle and calves.

Detailed Workplan:

1. Optimisation of parasite separation, purification and concentration from different wildlife faecal samples (Y1, M2).
2. Collection of samples and parasite concentration (Y2, M7).

Beyond Y1-2, the following activities will be completed: DNA extraction and detection of *Cryptosporidium* positive samples; Speciation of *Cryptosporidium* positive samples; Genotyping of *C. parvum* positive samples.

Objective 2: Effects of farm management practices on livestock disease prevalence and control.

2.1 On-farm gastrointestinal parasite control. Modelling approaches will be used to assess two different aspects: control of parasitic colonisation of livestock (*Teladorsagia spp, Trichstrongylus spp, Nematodirus spp*); and to model the effect of livestock movement between farms for the control of well-characterised diseases.

Detailed Workplan:

1. The effect of the potential for the composition of physiological states of livestock groups to affect disease risk (Smith et al., 2010) on the parasite population dynamics

will be quantified, informed by previous RESAS funded research. (Y2, A8).
2. Existing mathematical models of parasite population dynamics in livestock grazing systems funded by RESAS (see Fox et al. 2013) will be used to compare the efficacy of alternative parasite control strategies using anti-parasitic forages. Anti-parasitic forages e.g. chicory (to include both the direct antiparasitic effect and the effect of plant structure on parasite larval migration, in isolation and in combination) and the use of anti-parasitic plant extracts as drenches will be compared. Model parameters will be estimated from previous RESAS funded research on plants with anti-parasitic properties (Y2, D5) and the effects of parasite control will be tuned with grazing management to identify best practice.
2.2 Between farm livestock movements and disease control:
Two modelling approaches will be used to characterise and quantify the role of between farm livestock movements in disease persistence, spread and control. Firstly, the current research in to the potential for patterns of animal movement to enhance the performance of livestock health schemes (using the worked example of Johne's disease control within the PCHS and cattle movement patterns from the Cattle Tracing System) will be extended to consider other cattle infections as worked examples (*E. coli* O157, Bovine viral diarrhoea virus BVDV, Bovine herpes virus BHV-1) (Y2). Secondly, generic modelling work on characterising the role of between farm variation in disease susceptibility and infectivity on disease prevalence and persistence will be used to underpin the worked examples (beyond Y1-2).

Objective 3: Understanding the role of the environment in transmission of pathogens into agriculture
3.1 Colonisation of plant hosts by *E. coli* O157:H7: The functional role of candidate *E. coli* O157:H7 genes that may enhance the colonisation of plants will be determined. A combination of plant science, microbiology, proteomics and bioinformatics will be used.
Detailed Workplan:
1. Candidate *E. coli* O157:H7 genes will be assembled from RD2.2.6 and other sources for functional analysis (Y1-2, M9).
2. Apoplastic extracts (the fluid that fills the space between plant cells) will be inoculated with *E. coli* O157:H7 to obtain bacterial secreted proteins (Y1, M3).
3. *E. coli* O157:H7 secreted proteins will be identified using proteomics approaches developed by MRI (Y1-2, M4)

Beyond Y1-2, additional work will involve making a series of gene knock-out mutants and/or over-expression constructs as necessary; functional assays for growth, colonization and plant defense response; incorporation of data into risk analysis.

Objective 4: **Developing systems approaches to disease control**
4.1a: A systems approach to MAP control in Scotland: The potential for this more holistic systems approach to inform Johne's disease control will be demonstrated by determining the potential contribution of novel MAP diagnostics to livestock disease control.
Detailed Workplan:
This sub-objective has longer term returns that are likely to be realized beyond Y1-2. They include: Two novel MAP diagnostics will be used; a phage based assay and a MAP-specific IFN-γ ELISA. Longitudinal testing and comparison of the new with existing diagnostics will be used to quantify their abilities (e.g. Se and Sp). This will inform the mathematical models of disease dynamics and control.
4.1b: Surface soil samples from the National Soils Inventory of Scotland are being

re-extracted for genomic analysis as part of RD1.1.3. A test that was developed as part of the Scottish Enterprise PARABAN project will be used to screen the extracted DNA for presence of MAP.

Detailed Workplan:

1. Apply test developed as part of the PARABAN project to DNA extracted from the NSIS surface soils. This test only considers ‘in-tact’ or ‘within-cell’ DNA and as such can be used as a proxy measure for living bacteria and can provide an indication of where MAP are surviving in the soil (M5).
2. Conduct a GIS-based statistical analysis of MAP presence vs. other landscape-scale characteristics such as soil type:land use combinations, climatic variables, etc. A hypothesis developed during the PARABAN project that soil available iron correlates with presence of viable MAP, will be tested (A10).

Beyond Y1-2, additional work will be undertaken to: Plot the locations of reported/published cattle health scheme test results and undertake a further statistical analysis to see which environmental variables (if any) can predict where positive tests are most likely to occur, and what degree of accuracy these predictions provide; Undertake a national-level meta-analysis, to make inferences about where in Scotland environmental aspects of MAP (i.e. re-infection of cattle of environmental reservoirs of MAP, whether survival of MAP is related to soils types, land-use, climatic factors, etc.) is most likely to be an issue.

4.2 Existing and emerging issues affecting crop health: Detection, surveillance and monitoring for crop health issues will be taken into account. An initial objective is to review available data in the Veterinary and Advisory Services Crop Health data and long term analysis undertaken in current WP4 Capacity Building project sources, so that the current of crop health intelligence can be presented (Y2+, D6). Links to commercial crop monitoring carried out by industry (HGCA) will also be made. Discussions on key findings with SASA and relevant Scottish Government departments will be planned. The need for the development and implementation of detection methods for new and emerging pest and disease threats will be identified through regular contact with RD2.1.5 (O7) and RD2.1.4, SASA and the Centre of Excellence for Plant Health and informed by the new Pest Risk Analysis for Scotland (KE1). Including linkage to RD2.1.6, diagnostics, spore trapping from environmental samplers, crop surveys and Integrated Crop Management tools to manage crop diseases will be evaluated to estimate what these can add to established crop monitoring methods. Joint methods of working with animal surveillance RDs will be considered for applications to plant health.

4.3 New pests, pathogens and vectors of Scottish soft fruit: Monitoring for emerging threats of soft fruit with an environmental component will make use of established industrial links and is relevant to the High Health Stock Collection for soft fruit.

Detailed Workplan

1. Collect and test strawberry samples from growers for the presence of *Erwinia pyrifoliae*.
2. Produce an annual report on incidence *Erwinia pyrifoliae* in strawberry (Y1 and 2, D3, D7)
3. Visually assess for disease and collect leaf samples in blueberry plots at the James Hutton Institute for blueberry scorch analysis in the laboratory. If discovered in Scotland in Y1-2, further work will be done to improve testing methods.

Beyond Y1-2, an annual report on incidence of blueberry scorch virus and other emerging threats will be published.

Expertise

The staff leading this RD all have a high degree of expertise in their chosen area, of international standing. The work has been designed in a collaborative manner maximising the strengths of each of the MRPs. All work will conform with regulations for use of GMOs (the Genetically Modified Organisms (Risk Assessment) (Records and Exemptions) Regulations 1996 and the GMO (Deliberate Release and Amendment) Regulations 1997); any plant pathogens/imported soils/plant materials is governed by the Plant Health (Scotland) Order 2005, regulated by SASA.

Key linkages, interdisciplinarity & collaboration

By their nature, many if not all of the areas involve a component of interdisciplinary work. They have important and in some case inter-dependent links with other RDs. Some parts of the work will also link to Centres of Expertise, especially EPIC and Plant Health. Examples of some key linkages are listed below.

1. Work on ticks as vectors of disease combines ecology, genetics, chemistry and modelling. It has integral links with RD1.3.3 (Resilience of ecosystems and biodiversity to environmental change) and will also inform other parts of the RESAS program via EPIC. It links with RD2.2.5, O6A24 in particular (Vaccine production and delivery strategies to improve efficacy and economic viability – a novel Louping ill virus) through use of a viral vaccine delivery mechanism to control a tick-borne virus. It is an exemplar for cross-MRP collaboration, with MRI (pathogen diagnostics), Hutton (upland ecology) and SRUC (livestock management and disease). Where relevant data is generated in RD2.3.3 for tick-borne diseases and paratuberculosis, it will be used to inform the analysis in RD2.2.2.
2. Research on Johne's disease brings together different areas of research from **HEI bid 4**/RD2.2.3 (novel inference methods); RD2.2.6 (longitudinal herd testing for MAP), EPIC (livestock management & disease control)and benefits from the long established link between SRUC (Disease Systems), MRI (Diagnostics), Hutton (soils) and BioSS (Mathematical modelling and analytical techniques). The research will continue to inform and be informed by the Johne's disease control element of the PCHS and the Islands wide Johne's disease control initiative of the Shetland Islands Council (e.g. for access to farm data on control efficacy). It also links to the DairyCo Control plan towards monitoring.
3. Functional analysis of *E. coli* O157:H7 genes required for colonisation of plant hosts is dependent on the findings from RD2.2.6 (Animal Epidemiology). The work is run jointly between Hutton for function analysis and MRI for proteomics. It will contribute to the identification of risk factors, in RD3.1.3 (Food Safety). It links to the SG VTEC *E. coli* O157:H7 Action Plan for Scotland, where a related FSA-funded project delivers to the action plan (RS5). The work also links to an ongoing HEI partnership with SPASE partners (via Glasgow University), using a systems modelling approach for the persistence and control of VTEC.
4. Work on the plant pest and pathogens is extensively inter-linked with related RD in WP 2.1. Links will be maintained with the Environmental Change Network (ECN) and active collaborations with Forest Research, SASA, and the horticultural and soft fruit industry. Identification of current and emerging pests is integral to maintaining the High Health status of crops and encouraging continual trade with Scotland. It also connects with RD1.3.3 (ecosystem and biodiversity resilience) where there is an environmental component, e.g. work on plant pests of wild plant species, including

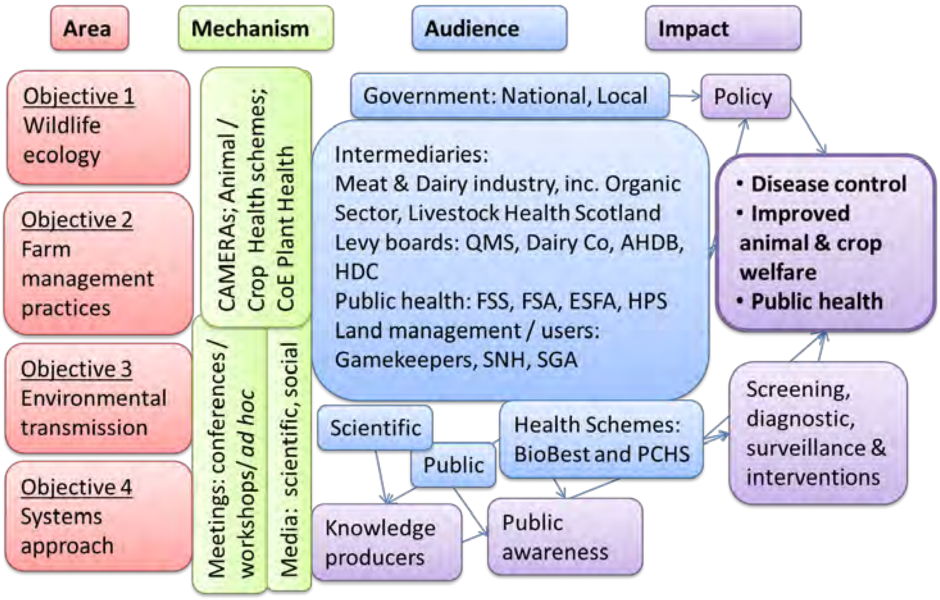
trees.
5. Work on plant pests and pathogens, and to a lesser extent on *E. coli* O157:H7, is directly relevant to the new Plant Health CoE, in the context of disease reduction and the plant defence response.

Added Scientific Value

- Work on MAP has established links with Glasgow University, the Royal (Dick) School of Veterinary Studies, Edinburgh and a number of veterinary practices across Scotland, with wider links to groups in other countries where Johne's disease is prevalent (Denmark, the Netherlands, USA and Australia).
- The proposed research on tick borne pathogens will be the first to actively test the dilution hypothesis for tick systems.
- Work with zoonotic bacteria will add value to quantitative risk analysis and is relevant to Food Standards Scotland (FSS), Food Standards Agency (FSA), Health Protection Scotland (HPS) and European Food Safety Authority (EFSA). The findings will inevitably inform on more detailed analysis of genes used for screening VTEC and support funding applications (e.g. RCUK, EU). N. Holden holds an FSA-funded project on the relevance of internalization of VTEC into produce crops, and work on VTEC is relevant to IFR-based research on environmental persistence of *E. coli* in crops.
- Research on gastrointestinal parasites informs and is informed by the EU ERA-NET Core Organic Plus project PrOPara (6 farms, coordinated by SRUC), to improve parasite control in organic production systems.
- The capabilities of the new tools for bovine tuberculosis contributes to tackling a current UK disease threat and will access data from the Defra-funded project in the Development and testing of Operational Models of Bovine Tuberculosis in British Cattle and Badgers (SRUC & BioSS).
- Work on crop health will be relevant for SASA and Plant Health policy work.

KE, Audiences and Impact

In preparing the work package a summary of each RD was circulated to a wide range of policy and industry stakeholders and general feedback incorporated. Acknowledgment of the impact of the wider environment on the well-known pests and pathogens has revealed many important and wide-ranging knowledge gaps in the area. In addition, there are limited examples of holistic systems approaches to disease control. Consequently the proposed research is expected to receive interest from a range of audiences from scientific, policy and industry, informing disease control strategies (see below). Arrows show the key linkages between target audience and impact and/or outputs. Topics feed into all of the audiences in varying degrees with some specificity, e.g. the parasite work is relevant to the Organic sector; tick-borne disease is relevant to land management and use, etc. Pathways to impact will be through the different mechanisms listed and is dependent on when meetings will be held with each group. Where appropriate we will make use of the facilities and services provided by the new KE and Impact centre. Success will be measured by acknowledgement of the work by stakeholders and where appropriate, uptake of the outputs.



Acronyms

AHDB:	Agriculture and Horticulture Development Board	HPS:	Health Protection Scotland
FSA:	Food Standards Authority	PCHS:	Premium Cattle Health Scheme
ESFA:	European Food Safety Authority	QMS:	Quality Meat Scotland
FSS:	Food Standards Scotland	SGA:	Scottish Gamekeepers Association
HDC:	Horticultural Development Company	SNH:	Scottish Natural Heritage

RESEARCH DELIVERABLE NUMBER: 2.3.3

Work planning and timetable for Year 1: Key milestones (M), deliverables (D) and KE/impact events (KE) have been provided for the major research activities, with their timing for delivery of each item.

Year 1: 2016/17 **KE events & outputs**	**Period 1** **(April-July)**				**Period 2** **(August–November)**				**Period 3** **(December –March)**			
O1.1 Estimation of perturbation effect in control scenarios										D1		
O1.2 Impact of demographic structures on prevalence												D2
O1.3 PCR validation				M1								
O1.4 Optimisation of Crypto. purification												M2
O3.1 Obtain *E. coli* secreted proteins										M3		
O3.1 Initiate proteomics on *E. coli* secreted proteins												M4
O4.1b Extracted DNA test for MAP						M5						
O4.2 Joint meeting with RD2.1.5, 2.1.4 to ID new threats										KE1		
O4.3 Screen and formulate Incidence reports										D3		
Activity: KE event, e.g. RHS					KE2							
Annual report (Y1)												R1

RESEARCH DELIVERABLE NUMBER: 2.3.3

Work planning and timetable for Year 2: Key milestones (M), deliverables (D) and KE/impact events (KE) have been provided for the major research activities, with their timing for delivery of each item.

Year 2: 2017/18	**Period 1 (April-July)**				**Period 2 (August–November)**				**Period 3 (December –March)**			
O1.2 Impacts of group composition on control potential					D4							
O1.3 Multiplex PCRs				M6								
O1.4 Sample collection and Crypto concentration						M7						
O2.1 Quantify demography effects on parasite control										M8		
O2.1 Efficacy of alternative control strategies												D5
O3.1 Collate candidate *E. coli* genes												M9
O4.1b GIS-based analysis of MAP							M10					
O4.2 Crop Health Review									D6			
O4.3 Incidence reports									D7			
KE event, e.g. CoZEE workshop								KE3				
Annual Report (Y2)												R2

Name of RD: 2.3.4. Sustainable soil and water management
Research aim and key drivers Optimal functioning of soil is crucial to the long-term production and sustainability of agriculture on a global, European and Scottish scale, with well managed soils providing ecosystem services addressing societal grand challenges. Conventional agriculture and future environmental change impose pressures on soil functions and quality. Soil degradation, in a range of forms, is a major threat to crop productivity and yield stability, profitability and sustainability. Consequently, soil and water resources need to be managed to be increasingly competitive and productive, while also improving soil function and quality. This RD will focus on the application of existing and novel models, soil management interventions, plant genotypes and soil quality indicators to enhance sustainable use and management of soils and water in agricultural systems whilst reducing environmental impact. The following threats to soils, water and atmosphere will be considered: soil erosion, compaction, eutrophication of water, greenhouse gas (GHG) emissions, declining fertility, declining organic matter and pollution from alternative fertiliser sources. The work will use manipulative experiments in both controlled environments and field with soil and vegetation management interventions including reduced tillage, minimised traffic, management of soil pH, fertiliser recommendations, use of bulky organic fertilisers (BOFs), novel genotypes and novel cropping systems. The work will utilise existing field experiments and platforms, with new trials on reduced tillage/ traffic. Novel indicators for soil quality will be validated and wider impacts on water and atmosphere quality will be monitored on these experiments. This RD will deliver improved management packages that will optimise productivity with reduced inputs of energy, traffic and agrochemicals, while maintaining and enhancing soil quality and function and reducing diffuse pollution from agriculture. These management packages will include improved soil management techniques and crop genotypes to optimise 1) alternative land management strategies (including reduced tillage) and 2) use of degraded and contaminated land. This will enhance sustainable production and promote soil quality, fertility and ecosystem service provision from agriculture in the future. The RD will also deliver a tool for land managers enabling rapid and effective assessment of soil quality (physical, chemical and biological) in all agricultural and semi-natural systems including grasslands and allow the management of soils across Scotland for productivity and other essential ecosystems service. Finally, insight, innovation and intellectual property generated will influence opinion in public, industry and policy arenas to maximise the potential of the RD to have a positive impact on the future sustainability of agriculture in Scotland and beyond.
Summary of the proposal: Agricultural systems need to be established that, while being competitive and productive, improve soil function and quality and meet greater standards of environmental performance. This deliverable draws together the skills of a highly inter-disciplinary team of biophysical scientists to address this goal. A healthy soil system is a pre-requisite for sustainable agriculture as soil biota and their interaction with physico-chemical conditions are responsible for many critical soil services. Soil function is driven by complex interactions between biology,

chemistry and physics all of which are affected by changes in the integrated management of both soils and vegetation. Our understanding of the linkages between management and soil function remains incomplete, but is critical to allow the development of a sustainable agricultural system. To establish the impact of changes in management on soil function it is essential to have sensitive indicators of soil quality and to apply these to test the potential of mitigating against threats to soil, water and atmospheric quality as a consequence of the agricultural system. This RD will take the form of four objectives (O) to address this critical need. **O1: Soil management impacts on soil function**: Soil management options potentially including (but not exclusive to) tillage, minimised traffic, drainage, cover crops, management of soil pH, and precision farming techniques will be assessed for their impacts on soil functions including nutrient cycling, water availability, provision of favourable rooting environments and protection against pest and pathogens in both arable and grassland systems. **O2: Plant management impacts on soil function**: Management of vegetation including selection of genotypes with enhanced root traits, selection for optimal growth in mixed systems, design of optimised rotations, cover cropping and management of plant communities will be assessed and modelled for their impacts on soil functions including nutrient cycling, water availability, provision of favourable rooting environments and protection against pest and pathogens in both arable and grassland systems. **O3: Developing assessment of soil quality**: Methods of assessing and indicators for soil quality will be developed and extended beyond arable soils, to integrate soil biological, chemical and physical characteristics and enable assessment of the ability of a soil to deliver vital soil functions and ecosystem services in a range of agricultural and semi natural systems. These indicators will then be used to assess the impact on soil quality of the management tools being tested in this deliverable and elsewhere. **O4: Land management mitigating threats to soil, air and water quality**: Assessment will be made of how the integration of soil and vegetation management options can be used to maintain soil function and soil quality while preventing degradation of soils in the face of threats including erosion, compaction, land contamination, loss of organic matter, loss of fertility, acidification and eutrophication and loss of biodiversity. As a whole, the research will use manipulative experiments in both controlled and field environments for both arable and improved grassland systems, with treatments defined by changes in soil and vegetation management. The work will rely on existing field experiments, arable and grassland platforms and the creation of novel field experiments, including novel trials on reduced tillage/reduced traffic.Soil functions will be assessed including nutrient cycling, water availability, provision of favourable rooting environments and protection against pest and pathogens. Novel indicators for soil quality developed from research in the current RESAS portfolio will be validated on these experiments, extended to non-arable soils and used to monitor the performance of the longer term platforms. Evaluation of the responsiveness of proposed indicators of soil quality will be undertaken on common samples from manipulative experiments or “real world” land use gradients to produce a greater understanding of the value of these tools to assess system function. Threats to soil quality and function will also be assessed, both when posed by changes in land management and when mitigated against by these changes. This will enable the RD to provide recommendations on integrated management solutions linking to key policy drivers which aim to legislate the management of soils and water. This RD will require significant statistical and potentially modelling input in which BioSS will be supportive via funding for Underpinning Capacity Function 7. We will link with other RDs to specifically address the socio-economic questions raised here through work performed in RDs 2.3.8 and 2.3.12 and interface with RDs in Theme 1 (RD1.1.1 and 1.2.1) to deliver added value with respect to soil and water management, respectively.

This work will have impact by identifying alternative land management systems, providing indicators for monitoring soil quality and in developing sustainable farm management practices where threats are identified and require mitigation against. Generally, this will deliver a more productive and sustainable agricultural system for Scotland, but specifically key deliverables from this RD will include: D1) Provision of insight and knowledge that can be used to leverage funding from other sources (Research Councils UK [RCUK], Agriculture and Horticulture Development Board [AHDB], Technology Strategy Board [TSB], European Union [EU]) (year 1 onwards; M1-5, M10). D2) Dissemination and exchange of knowledge to relevant stakeholders including the science community, land managers, industry, policy makers and the public (year 1 onwards M7, M11, M14). D3) Contribution of field demonstration plots to KE demonstration hubs for arable systems (Balruddery) and grassland systems (Hartwood) (year 1 onwards M7). D4) Production of scientific highlights of key issues raised by the research, technical notes to inform land managers and policy briefings to inform government (year 2 onwards M8, M15). D5) Integration of soil and vegetation management to produce novel integrated management systems to optimise function and mitigate against threats to sustainability (year 2 for other RDs M9, M13; year 4 onwards for land managers and policy makers). D6) Development and release of an on-farm tool (neo-Visual Evaluation of Soil Structure (VESS)) for the assessment of soil quality that links both soil structure and soil quality (year 2 onwards, M6, M12). D7) Assessment of crop and soil management impacts on soil function, quality and ecosystem services (year 3 onwards). D8) Contribution to workshops aimed at engaging with politicians organised at a WP or theme level (year 3 to 4). D9) Scaling of understanding of land management impacts on soil from single plants through to field scale (year 4 onwards). D10) Development of soil quality indicators which integrate soil biological, chemical and physical characteristics on a relevant scale to provide assessment of soil capability to provide ecosystem services (year 5). and D11) Development of optimised integrated management solutions linking to key national policies such as Zero Waste Scotland, Climate Change Legislation and the Scottish Soils Framework (year 5).

In order to achieve these deliverables, a strong multidisciplinary team has been assembled which has experience in developing research, disseminating it and exchanging information to a range of stakeholders at local and international scales. Dissemination of this integrated package of work will be performed in close collaboration with other RDs through the CKEI and will engage the relevant stakeholders through an innovative dissemination package including presentations, publications, policy briefings, technical notes, technology, demonstrations and workshops.

Technical Approach

O1: Soil management impacts on soil function. Soil management options potentially including (but not exclusive to) tillage, cover crops for pre-condtioning soil prior to cultivation, minimised traffic, drainage, management of soil pH, fertiliser recommendations, and precision farming techniques will be assessed for their impacts on soil functions including nutrient cycling, water availability, provision of a favourable rooting environments and protection against pest and pathogens in both arable and grassland systems. Controlled field-based testing of long term experiments will be supplemented with new platforms to test hypotheses on agricultural soil management. Sites will include current platforms in both arable and grassland systems which have a range of agricultural management systems (including tillage, traffic, fertiliser source and pH) and possible new precision farming and agroecology experiments. Activities will focus on best management and on novel practices or alternatives to deliver improved productivity and environmental protection. Soil quality assessments will combine laboratory (e.g. gap filling experiments focussed on soil type and degradation level) and in-field approaches, including those developed in this RD to specifically assess the soils impact on crop rooting and water and nutrient movement through the landscape. Specifically: water retention, Least Limiting Water Range (LLWR), VESS and supplementary soil physical properties (bulk density and cone resistance). Re-sampling well documented and completed soil management experiments (e.g. Bush long-term tillage experiment) will test the recovery of soil function from previous damage.

Plot scale experiments will supplement the long term experiments to test mechanisms of soil management on environmental impacts such as erosion including run-off, sediment generation, nutrient movement and measures of bio-diversity, linking closely with work on water management in RD1.2.1. Improvements in the accuracy of information used to underpin fertiliser recommendation for phosphorus (with possible expansion to potassium and sulfur) will be developed alongside risk assessments for phosphorus leaching loss and potential trace element deficiencies.

O1 Detailed work plan: Existing field trials will provide unique resources for field measurements and soils for controlled studies, and are supported by ongoing research and monitored data. With weed and other pest burdens and pH declines after long term monoculture limiting productive yield we will undertake sampling of Mid-Pilmore on multiple dates, including after harvest, in 2016 and determine soil quality by methods described above for multiple depths and for each tillage regime (O1.1). It is also proposed to initiate a new tillage platform at Balruddery (O1.2). This will commence with an assessment under Scottish conditions of the establishment and efficacy of cover crops to pre-condition soil prior to tillage (O2.1). Tillage treatment (deep, shallow, chisel ploughing, direct drill) plots from the Bush long term tillage experiment will be re-identified and soil quality determined by the methods described above (O1.3). Re-sampled data from former plots will be compared to study recovery between treatments and compared with historic soil measurements (1967 to 1996) to investigate the current soil state and recovery of soil function from previous tillage treatments (O1.4). Farm nutrient budgets and agricultural soil pH management will be reviewed. The potential use of focused applications using precision agriculture to decrease nutrient losses and reduce diffuse pollution will also be investigated. A dynamic mechanistic phosphorus model will be validated and used to assess the impact that different management strategies and extreme weather patterns have on phosphorus losses (O1.5).

O2: Plant management impacts on soil function. This objective focuses on application of an integrated suite of biological, physical and chemical approaches to quantify impacts of agricultural management and genotype selection on soil functions, productivity and other ecosystem services. The research will apply established methods in combination with novel approaches from RDs 1.1.1, 2.1.7. The research will exploit field-scale trials of management practice, that are the focus of RDs 1.3.1, 2.3.8, and also the emerging understanding of genotype-specific interactions between crops and the soil environment from RD2.1.7. Experimentation will scale from individual plants, through to process measurements and application of indicators of function in field trials.

Root-soil interactions will be studied in the context of conventional management and potential alternative management options focused on in RD2.3.8. Impacts of management on plant-mediated nutrient cycling, soil carbon fluxes and soil physical properties will assess impacts of plants at the soil water interface. Initially experiments at the single plant and mesocosm scale will focus on both arable and grassland species impacts on water and nutrient dynamics. These measurements will be coupled with those on field plots (e.g. trajectories of soil physicochemical properties and biological indices) and with the development of models of the interaction. Subsequently, the research will utilise outputs from RD2.1.7 identifying beneficial root traits (ideotypes) for root-soil interactions, and will assess these ideotypes in the context of different management practices. Controlled experiments will allow identification of where functionally distinct root traits (e.g. for root penetration and enhanced nutrient cycling) are co-incident or segregate within plant populations, and will be used for initial selection of genotypes adapted for specific managements. These optimal varieties will be used alongside current elite varieties in years 4 and 5, and impacts on soil and water quality will be assessed with the functional indices applied previously.

O2 Detailed work plan: Existing arable and grassland field trials including reduced tillage, BOFs, novel crop rotations, inter-cropping and integrated sustainable practice will be used for the research (O2.2), providing unique resources for field measurements, and supported by a wealth of ongoing research and monitoring data. In addition, we will contribute to the setting-up of novel tillage trials (described in O1). Controlled environment experiments investigating crop effects on soil physical, chemical and biological functions and there impacts on water will use common soils, genotypes and where possible common experimental systems. Steady-state ^{13}C-labelling will be used to quantify root-derived inputs to soil, trace flux through biological components, and concurrent impacts on mineralisation of native and applied soil organic matter (O2.3). Plant and soil solution analyses will be used to quantify availability and uptake of N, P and micronutrients, as functions of genotype and soil management. Models will be applied both at single root and plant scale to analyse the links between root traits and the acquisition of N and P. Stable isotope approaches will further resolve soil N (nitrification and denitrification) and P (^{18}O isotope dilution) cycling processes leading to plant uptake and to losses from soil (O2.4). Root elongation and N uptake efficiency assays will assess genotypic variation in tolerance of soil physical constraints. Understanding of the dynamics of N and C in agricultural soils will link directly with work on greenhouse gases in RD2.3.5.

Measurements on field soils will include bulk density, water retention curves and soil strength determinations, allowing assessment of management impacts on the capacity of soils to provide a physical environment supporting root growth and effective management of water in the landscape. These will be combined with analyses of soil solution chemistry to assess nutrient availability and potential for leaching losses to water resources (O2.5). Soil C stocks will be quantified and stability will be assessed in relation to organo-mineral associations and physical protection. Further, soil and root samples will be collected to perform metagenomic assessment of the root-associated microbiomes, and to validate microbial and nematode indicators of nutrient cycling processes against the C and N process rate measurements (RD1.1.1) (O2.6).

O3: Developing assessment of soil quality. In this objective we will develop indicators for soil quality which integrate soil biological, chemical and physical characteristics and enable assessment of the ability of a soil to deliver vital soil functions and ecosystem services. We will then use these indicators to assess the impact, on soil quality, of the range of soil and vegetation management tools being tested elsewhere in the WP and programme as a whole. Specifically, we will develop tools for on-farm assessments of soil quality.

There is a strong background of research into soil indicators from previous RESAS, UK and EU funded projects. Current national and regional schemes looking at biological soil quality tend to use a large number of indicators which makes practical (i.e. farmer-led) implementation difficult, as does the relative, rather than absolute, scale of most studies. An important constraint to the application of a soil quality tool (*i.e.* a selected suite of indicators) is the lack of background knowledge of the range of soil values for a given pedo-climatic zone and land use. One method to calibrate the tool for local conditions will be to determine the normal operating range, such that deviations from the normal operating range indicate that the system is in a condition of stress (A6.1). Another method will be to define relevant reference soils against which soil quality can be judged. Ultimately land managers are looking for soils that are stable to disturbance (*i.e.* with resistance and resilience – link to RD1.1.1 where the underlying processes will be studied) and more likely to support stable yields allowing advice on the nature and practicality of on-farm decisions e.g. around rotations, cultivations, cover crops (link to RD2.3.8 where the approach will be tested in a participatory setting and with socio-economic evaluation of acceptability).

O3 Detailed work plan: Initially, the VESS, a well-established “farmer friendly” indicator for soil physical structure in grassland and arable systems, will be extended to include assessments of other important soil biological and chemical conditions to provide an overall assessment of soil quality (O3.1). A linkage of VESS to water loss/storage will be addressed by refining the test to improve estimation of macroporosity and faunal activity across layers of differing structure. This will be helped by relating VESS to field measurements of soil water flow and storage and other soil functions. The normal operating range of VESS will be tested against a range of soils (O3.2). Utilising ongoing field experiments at Hutton (Balruddery and Glensaugh) and SRUC (Tulloch, Bush and Crichton) this objective will demonstrate and quantify improvements in ecosystem services, including yield and GHG emissions, that can be made with improved soil quality (O3.3). A farmer friendly tool will be developed and results will be disseminated to stakeholders such as consultants and farmers through demonstration/monitor farms and open days (O3.4).

O4: Land management mitigating threats to soil, air and water quality. This work will focus on the restoration of degraded and/or marginal land where prohibitive threats to soil quality and function and antagonisms between 'value' (trace nutrients) and 'risk' (contaminants) exist. Scalable experimental approaches will be used in the field and laboratory, with reference to O1/2 to determine the impacts of a variety of combined soil and vegetation management methods on soil functionality and water quality. The outcomes of this O will include practical measures for restoring degraded land and adding value to marginal land using combined soil-vegetation management therefore it will primarily study antagonisms existing such as nutrient and contaminant uptake to crops, linked closely with RD2.1.7 and RD2.3.4.

O4 Detailed work plan: We will investigate novel land management options to reduce the burden of existing and emerging organic and inorganic contaminants. Burdens of 'classic' (heavy metals, Polycyclic Aromatic Hydrocarbons [PAHs]) and 'emerging' (endocrine disrupting compounds; EDCs) contaminants exist in some agronomic soil amendments applied as part of land management (O1), which may result in threats to soil and water quality and functionality (O3). *In-situ* soil pore water monitoring and solid phase analyses will firstly (Yr 1 & 2) determine baseline concentrations of contaminants (O4.1), nutrients and other trace elements at existing study sites, including grassland sites at Hartwood and Auchincruive long-term plots (heavy metals) and Glensaugh compost, manure and slurry trials (EDCs). Secondly (Yr 2-5) manipulative mesocosm studies will evaluate a range of novel soil amendment and vegetation combinations specifically aimed at restoring soil functionality and protecting water quality at existing degraded sites, reducing phyto-toxicity and preventing leaching of contaminants to waters (O4.2). A range of wild arable plant species/types will be tested as novel understorey or pre-crops, to optimise legume-supported arable system (linked to RD 1.1.1). Special attention will be paid to the interactions of mineral and organic constituents of soils and water have on the role of dissolved organic carbon (DOC) in the fate of nutrients and contaminants; this work will be strongly linked to that of RDs 1.2.3 and 2.1.7. A degree of modelling of key antagonisms between nutrients and contaminants [and DOC] as a result of soil and vegetation manipulation will be included (O4.3).

In addition, we will investigate the physical and biological improvements from the restorative measures trialled above, in grassland and arable soils and the effect of controlled traffic in reducing yield loss in grassland soils from tillage and sowing through a number of growing seasons (O4.4). Comparison between grassland and arable crop soil stability and resistance to compaction and surface erosion from the incorporation of organic material compared to inorganic fertilisers will be made. Measurement of changes in soil quality will be achieved by applying indicators developed in O3. This work will be closely linked to 2.3.8 and will follow the effects of establishing a sward of perennial ryegrass from tillage and sowing across three years of silage cuts using controlled traffic wheeling lines compared to uncontrolled 'normal' management. Yield differences will be measured and economic benefits in any yield improvement calculated (O4.5).

The experimental work in this objective will harness advances in analytical technology, including rapid, cost effective and portable screening methods for a range of elements (Portable X-Ray Fluorescence [P-XRF], Fourier Transform Infrared Spectroscopy [FTIR]) developed in theme 1 and such methods will be underpinned by the National Soils Inventory of Scotland [NSIS]. Where appropriate access to new study platforms, such as urban and peri-urban sites,

will be considered.
Key linkages, interdisciplinarity & collaboration Key linkages to this RD will bring additional benefits including interdisciplinarity, scaling, dissemination and translation of the research, while also leveraging further funds. **1) WP 2.3 Productive and Sustainable Land Management and Rural Economies** (RDs 2.3.5, 2.3.6, 2.3.8, 2.3.9, 2.3.11, 2.3.12). Interdisciplinary and inter-MRP projects will be created which span the RDs within and across workpackages, these projects will share field experiments, field platforms, land management treatments or crop genotypes. Specifically, understanding on the N cycle in both arable and grassland systems will link directly to RDs 2.3.5 and 2.3.6, while integrating soil and crop management into single translatable alternative land management will be tested in RD2.3.8 and further assessed in RD 2.3.9 where the mechanistic understanding generated here will be tested in functioning agricultural systems. In addition, specific links will be forged which take the biophysical information produced in this RD and apply socio-economic analyses to it to assess any barriers to uptake and socio-political impediments to translation of the research (RD2.3.11 and RD2.3.12). **2) WP 2.1 Crop and grassland production and disease control** (RDs 2.1.1, 2.1.2, 2.1.7, 2.1.8) Research performed in WP2.1 will feed directly into RD2.3.4. Genetic populations of crops identified, maintained and genotyped in RDs 2.1.1 and 2.1.2 along with novel crop species identified in RD2.1.8 will be phenotyped and physiologically described in RD2.1.7. These along with models developed in RD 2.1.7 will select genotypes of crops to be used here. Field based experiments with these genotypes in association with RDs 2.3.8 and 1.1.1 will act as both field validation and demonstration to industry stakeholders. **3) Theme 1 Natural Assets** (RDs 1.1.1, 1.1.2, 1.1.3, 1.1.4, 1.2, 1.3). Many of the soil functions and indices of soil quality tested here in agricultural soils and with agricultural management, will also be applied in WP1.1 in natural and semi-natural ecosystems. In addition, work performed here will directly inform the Water Resources WP 1.2, by providing information on the loss from arable soils of nutrients, toxic elements and eroded soil. Some common field based experimental platforms will be used between the two packages of research. There are also strong interactions on research in plant impacts on soil microbial diversity and function and impacts on ecosystem services. Integration of the high impact work performed on soil function and ecosystem services in both natural and agricultural systems is unique. **4) Wider RESAS Programme** (Climate X Change, Underpinning Capacity). We will link with ClimateXChange to help it inform Scottish Government policy teams in addressing issues including 1) locking carbon into the soil and vegetation and 2) optimising the application of fertiliser and manures. The RD will also make extensive use of underpinning capacity provided by RESAS, including plant genetic populations, field platforms such as Balruddery and NSIS archive and database. **5) Other Funding Bodies** (RCUK, AHDB, TSB, EU). The primary aims of our deliverable are well aligned with the priorities of a range of funders from levy boards through UK Research Councils to the European Union. Therefore, the work proposed in this RD is extremely complementary to a number of funded projects from this range of funders held by the key researchers in this RD.

Added Scientific Value This RD builds heavily on a foundation provided by work commissioned by RESAS in the previous programmes of work. Specifically it will rely on the sampling and resampling of field based platforms in both arable and grassland systems instigated in previous programmes of research. It will also further develop tools and indicators first conceived in previous programmes. Notwithstanding this, the large range of novel research proposed has strong links to research already funded by levy boards, RCUK and the European Community, which will allow this research to leverage further funds from such sources. Beyond this the insight gained in this RD has potential to allow participation in multilateral international funding opportunities such as Newton Funds with China, India and Brazil and joint RCUK/National Science Foundation [NSF] funding with the United States. The research is complementary and well interfaced with research that occurs at a number of UK institutions which have complementary themes of research looking to increase the sustainability of agriculture, through improved management of soil, plants and water. One tangible way in which we will interface with other UK institutions is through AgriTech Innovation platforms. Beyond the UK, we will integrate well with projects and project partners priorities across Europe funded through Horizon 2020 calls.
KE Outputs, Audience and Impact A range of KE outputs will be produced in the RD and will be integrated into a wider WP, Theme and Programme KE strategy determined by the CKEI. Audiences for the outputs of this RD will range from scientific peers, through industry and commercial representatives to land managers, the public and on to policy makers.These interactions will have impact at local, national and international scale which will be monitored in a number of ways including metrics of use, direct and indirect feedback and various research excellence exercises performed by the contributors. The researchers proposing the work in this RD have had interactions with the range of multiple actors mentioned here in the past, but in the new programme this will be better integrated and interactions with new stakeholders in all the sectors have been sought within the proposal process. By the end of the programme we hope that our KE will have an impact by having Influenced opinion in public, industry and policy arenas to maximise the potential of the knowledge generated in the RD to have a positive impact on the future sustainability of agriculture in Scotland and beyond**.** **Specific examples of the KE planned include:** **1) KE Demonstration Sites:** Tours of demonstration sites for visitors, organised tours and open days with the aim of reaching hundreds of people each year. **2) Science/Policy Workshop**: Workshops organised in Edinburgh will target Scottish Government and MSPs and have impact in policy related to sustainable land management this will happen in the second half of the programme and would be hoped to inform tens of MSPs and civil servants. **3) Tools for farmers:** the new VESS soil quality indicator tool will be rolled out to industry representatives through engagement events and the VESS website (http://www.sruc.ac.uk/info/120625/visual_evaluation_of_soil_structure**)** with a view to the tool being useful to more than 20% of farmers in Scotland and extension to an international audience by the end of the programme. **4) Contribution to EU COST Networks** (KE2) including 'Industrially Contaminated Sites and Health Network (ICSHNet)'. **5) Public and industry Stakeholder engagement events** (KE1) Including i) Cereals in Practice, Potatoes in Practice,

Fruit for Future, ii) LEAF Open Farm Sunday/LEAF Technical days, iii) Open days at SRUC Monitor Farms and iv) James Hutton Institute and SRUC Open days. All of which engage tens to hundreds of stakeholders**. 6) Science Presentations** Including i) Presentations at relevant scientific conferences and seminar series, ii) Presentations to visiting scientists and industry consortia.and iii) Organising a session within the Annual Meeting of The Scottish Society of Crop Research in year 2 to publicise the research to farmers and land managers, and to solicit involvement in trialling of developed indicators of soil quality in years 4 and 5. These events will interact with tens to hundreds of peers and stakeholders. **7) Publications** Reviews on a) Soil and vegetation management impacts on soil function; b) Development of effective indicators for soil quality; c) Threats to soil quality and function: 10 years on from the Scottish Soil Framework (KE3) and Peer reviewed science papers. **8) Policy Advice.** a) Call down advice and response to government committees concerned with **Sustainable soil and water management.** b) Comment on EU Policy documents concerned with **Sustainable soil and water management.** c) Policy briefing documents e.g. “Threats to soil quality and function: 10 years on from the Scottish Soil Framework”

RESEARCH DELIVERABLE NUMBER 2.3.4: Work planning and timetable for Year 1:

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1: Final sampling of existing tillage trial									M1 (D1): Data to leverage funds from AHDB			
O1.2: Cover crops assessed as treatments in new tillage trial												→
O1.3: Resampling of historical tillage plots												
O1.4: Comparison of resampling with historical data									M2 (D1): Data to leverage funds from AHDB			
O2.1: Initiation of novel reduced tillage field trials												→
O2.2: Existing field trials will sampled for nutrient assessment											M3 (D1): Data to leverage funds from EU H2020	
O2.3: Studies on the dynamics of C in the rhizosphere											M4 (D1): Data to leverage funds from EU H2020	
O2.4: Studies on the dynamics of N, P											M5 (D1): Data to leverage	

in the rhizosphere				funds from EU H2020								
O3.1: Extension of VESS to grasslands and other soil functions												→
O3.2: Definition of normal operating range for VESS	M6 (D6): Normal operating range for VESS											
O4.1: Baseline contaminant monitoring												→
O4.2: Soil quality monitoring of degraded sites												→
O4.4: Assessment of erodability of grassland and arable soil												→
KE1: Stakeholder Events		M7 (D2, D3): Dissemination of findings to stakeholders via field demonstrations										
Annual Report to RESAS												**R1**

RESEARCH DELIVERABLE NUMBER 2.3.4: Work planning and timetable for Year 2:

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O2.1: Continuation of novel tillage trial												→
O1.5: Dynamic P model to predict P losses from agricultural soil												M8 (D4) Production of reports/papers/ briefing on output of the model
O2.3: Field Assessment of soils for root penetration and water movement							M9 (D5) Management recommendations for soil physical conditions					
O2.5: Activity 4.3: Metagenomics of C,N,P Cycle									M10(D1) Data to leverage funds from RCUK			
O3.2: Development of soil indicators for ecosystem services						M11 (D2) Session at SSCR annual meeting on soil quality indicators						
O3.4: Development of Farm Tool and release of updated VESS												M12 (D6) Release of new VESS tool for farmers
O4.2: Management to restore function in degraded soils							M13 (D5) Management recommendations for degraded and contaminated sites					
O4.3: Modelling of key antagonisms nutrients vs contaminants												→

KE2: EU COST Networks							M14 (D2) Input to EU policy					
KE3: Threats to Soil – Update						M15 (D4) Policy briefing Threats to soil						
Annual Report to RESAS												**R2**

Name of RD: 2.3.5 Improving existing GHG reduction measures
Research aim and key drivers The global challenge of climate change requires societal responses, both to avoid dangerous levels of climate change and to adapt human activities to the changing climate. Greenhouse gas (GHG) mitigation and climate change adaptation have become important policy drivers in all sectors, including agriculture. Due to the biophysical, economic and social particularities of this sector, mitigation and adaptation efforts in cropping and livestock activities so far have primarily been delivered through voluntary uptake with regulatory support and incentive schemes playing a secondary role. Significant barriers to more widespread uptake span from the farm level to international governance arrangements. Consequently, the penetration of low emission farming practices in the agricultural sector is still limited. A considerable amount of scientific and practical knowledge on low carbon farming practices has been accumulated over the past few decades. The costs and mitigation potential of a range of measures and their wider environmental and social effects, including adaptation synergies, have been assessed. A number of mitigation measures have been identified to be "win-win" options, providing GHG mitigation and cost savings at the same time. However, a combination of financial, technical, policy and behavioural barriers hinders the wider uptake of the win-win and low-cost practices; this poses challenges for the development of efficient mitigation policies. Barriers faced by farmers include the cost and time required to implement mitigation measures, the limited availability of farm decision-support tools and climate-related advisory services. Barriers for policy formulation include the lack of objective, practical and cost-effective monitoring and evaluation mechanisms, lack of information on current farm practices and limited information on farm-specific effects of policy instruments. The work in this RD will address these key farm-level and policy-level issues to help develop policies in Scotland (e.g. the forthcoming versions of the Review on Policies and Proposals), in the UK (e.g. the Carbon budget period documents of the third period and beyond) and in Europe (e.g. the Common Agricultural Policy (CAP) beyond 2020). The research will include a combination of survey work, environmental economic modelling and development of monitoring and evaluation tools and approaches. Specifically, the Research Deliverable (RD) will: • Improve our understanding of the financial and time-related barriers of the most promising mitigation measures on farm, exploring opportunities to reduce these barriers, Objective (O) 1, • Strengthen existing monitoring and verification tools and farm decision support tools while providing deeper insight into the resource efficiency and emission intensity of individual farms and farmers' decisions on mitigation and adaptation measures' uptake (O2), • Develop new monitoring and verification approaches for soil related GHG emissions and mitigation measure implementation on farms (O3), • Provide *ex-ante* assessment of agro-environmental policies in the light of changing climate, with a particular emphasis on soil-related farm practices and the adaptation capacity they can provide (O4).

In preparing the work package a one page summary of each RD was circulated to a wide range of policy and industry stakeholders (e.g. Scottish Government, National Farmers' Union Scotland, Scottish Environment Protection Agency) and general feedback incorporated. Research in this RD by nature will involve farmers and farm advisors who will be actively involved in the study design and in creating knowledge which is relevant to them.

Summary of the proposal:

The multi-level barriers to the uptake of mitigation and adaptation measures in agriculture have to be overcome in order to increase the mitigation potential and adaptive capacity of the sector. A reduction in the cost of implementation, better adjustment of measures to farm-specific barriers such as labour and time constraints and improved decision support tools might increase farmers' willingness to implement mitigation measures. At the same time, the development of monitoring and verification tools will equip policy makers with opportunities to further develop agri-environmental policies and carry out *ex-ante* assessments of the policies to inform the decision makers about their effects on the sector's mitigation potential and adaptive capacity. This RD will advance research via four Objectives:

Objective 1: Drivers of mitigation costs on farms and farmers' utility of time

O1 The identification of 'win-win' mitigation options has thus far been based on assumptions about "average" farms. Therefore, variation in cost, and additional non-financial barriers to uptake at the farm level, have mostly been ignored. Furthermore, costs elements that are relevant to only a sub-set of farms might remain hidden in the aggregation process of economic models. To robustly identify 'win-win' (providing GHG mitigation – both per ha/livestock and in emission intensity – and increasing farmers' profit) mitigation options and encourage their uptake, research under this objective will investigate heterogeneity of farm-level costs of the implementation of selected mitigation options (previously identified 'win-win' options with low current uptake) and the hitherto unexplored value of time.

In this Objective selected cost elements of mitigation options will be explored through a desk-based study. The aim is to investigate how variation in cost elements depend on farm characteristics such as farm structure, farm size, involvement in farming co-operatives, or location, and how this variation affects the cost-effectiveness of mitigation measures. Some of these relationships will have been explored in the previous Programme (RD2.4.1) and in RD2.3.12 – these results will be utilised in the cost-effectiveness analysis. The work in O1 will focus on further important cost elements, analysing available datasets (e.g. Farm Accounts Survey, industry benchmarking data).

Although cost of time is sometimes factored in economic analysis using the wage rate, this is not necessarily a good approximation of the value of time of farmers, and therefore time-related constraints might be misrepresented. Thus far, there is limited evidence on the value of time for farmers in developed countries, although the literature highlights the importance of time constraints and time savings in relation to uptake and implementation of new farming practices. The work will investigate farmers' value of time, and how this is acting as a barrier or incentive to the adoption of mitigation options.

Findings from O1 on mitigation costs and value of time will also feed into economic and bio-economic modelling work in O4 and RD2.4.2.

Key deliverables:

- D2.1. Report on the cost elements of selected mitigation options and their likely drivers (Y1)
- D2.2. Analysis of the relationship between farm characteristics and mitigation cost elements and development of cost functions from existing datasets (Y3)
- D2.3. Report on the variation in GHG mitigation cost-effectiveness as influenced by the variation in costs (Y4)
- D2.4. Analysis of the characteristics of the value of time in agricultural production (Y2)
- D2.5. Report on farmers' value of time and its effects on mitigation measure uptake (Y5)
- D2.6. KE activities joint with RDs 2.3.6 and 2.3.7: Y2 m18 (KE1), Y3 m30 (KE2), Y5 m54 (KE3)

Objective 2: Resource efficiency and emission intensity assessment of Scottish farms with AgRECalc

O2 Low penetration of GHG-mitigation practices in the farming community necessitates the further development of policy instruments, farmer decision-support tools and advisory services. In this process a carbon accounting tool and a related database are invaluable, as they gather statistics on current practices on an on-going basis, provide a monitoring instrument for on-farm and supply-chain (Life Cycle Assessment) based emissions, serve as a knowledge exchange tool at the science-practitioner interface, and, importantly, support farmers' decision making. Additionally, they enable research to use up-to-date information when looking at further opportunities in GHG reduction.

This project will utilise and further develop emission calculations in the carbon accounting tool Agricultural Resource Efficiency Calculator (AgRECalc) and conduct resource economics research using the database. The data collection for the economic analysis will build on existing data (e.g. Farming for a Better Climate's Climate (FFBC) Focus Farms) and on-going and future projects. Farms will be analysed from the resource efficiency and emission intensity perspective, exploring the heterogeneity amongst the farms and highlighting potential factors behind the differences between farms.

Key deliverables:

- D2.1. Report describing the implementation of soil N_2O and enteric CH_4 emission factors in AgRECalc (Y2)
- D2.2. Report on farms' resource efficiency and emission intensity (Y5)
- D2.3. KE activities joint with RDs 2.3.6 and 2.3.7: Y2 m18 (KE1), Y3 m30 (KE2), Y5 m54 (KE3)

Objective 3: Minimising GHG emissions and loss of carbon from managed soils

O3 Human-driven land use and management activities such as tillage operations, grazing intensity, and fertiliser application have an influence on soil C storage, GHG emissions and nutrient leaching. At the same time, soil structure and properties also have a major influence on these emissions. Poorly-managed soils are often associated with a decline in organic matter, high emissions of N_2O, low uptake of CH_4, and poor nutrient retention. Promoting and maintaining the physical condition of the soil is an effective means of increasing C storage and reducing GHG emissions.

This research will use experimentation and modelling approaches to investigate

GHG emissions from soils under different vegetation and soil management (including soil amendment). Farmer friendly soil structure/quality scoring systems and visual soil assessment tools (e.g. Visual Evaluation of Soil Structure (VESS)) will be used to test soil management GHG mitigation options in order to identify the best options available for minimising soil GHG emissions and loss of carbon from managed soils. Extension of the use of soil structure/quality scoring systems developed as part of RDs 2.3.4 and 2.3.8 will be used alongside targeted experimental measurements of GHG emissions to test their use as proxies for GHG emissions and soil quality status and improve models.

Key deliverables:

- D3.1. Draft score sheets for N_2O emission and C status (Y3)
- D3.2. Report on local management interventions to mitigate GHG emission and compaction damage (Y4)
- D3.3. KE activities joint with RDs 2.3.6 and 2.3.7: Y2 m18 (KE1), Y3 m30 (KE2), Y5 m54 (KE3)

Objective 4: Soil management and GHG mitigation: environmental and economic impacts of policy instruments under climate change

O4 A range of economic models are available to carry out impact assessment of climate change effects and mitigation. However, most of them use crop yield shifters to represent the impacts on crop production. This removes the variability between farm management practices, which can have an important effect how crops react to changed climate.

Additionally, there has been a lack of effort so far in the economic analysis of soil management measures, particularly with regards to the synergies and trade-offs with climate mitigation and adaptation on farm.

An extension and development of a dynamic farm level economic model will be a very useful tool to improve environmental and economic assessments of farms, particularly climate change effects (e.g. impacts of climate change on crop yields in a whole farm perspective, risk in crop yield arising from weather variability). The modelling cluster will be used to assess mitigation, adaptation and agri-environmental policy instruments for Scottish farms under climate change and to identify the uptake of best climate and soil practices by the farms.

Key deliverables:

- O4.1. A report on model linkages (Y2)
- O4.2. A report on the emulator (Y3)
- O4.3. A report on the selection of the soil management, mitigation and adaptation techniques and policy instruments as discussed with stakeholders (Y2)
- O4.4. A report detailing the effect of soil management practices of GHGs emissions, C sequestration and yield for a range of cropping systems and soils (Y4)
- O4.5. A report on the integrated assessment in the modelling cluster (Y5)
- O4.6. KE activities joint with RDs 2.3.6 and 2.3.7: Y2 m18 (KE1), Y3 m30 (KE2), Y5 m54 (KE3)

The work proposed will maximally utilise linkages with recently finished and on-going projects, and will provide a robust platform to attract further funding both nationally and internationally. These linkages will span from long-term research projects (e.g. Horizon 2020 or Research Council) through medium term synthesis research (e.g. Directorate General (DG) Clima, DG Agri, Joint

Research (JRC), Defra, Committee on Climate Change (CCC) and ClimateXChange (CxC)) to short response time policy projects (Organisation for Economic Co-operation and Development (OECD), European Parliament, CxC).

Technical approach

Objective 1: Drivers of mitigation costs on farms and farmers' utility of time

O1 Cost elements of GHG mitigation options, and the value of time for farmers will be explored in this Objective. The research will focus on selected mitigation options and selected farm types (e.g. dairy and mixed cropping), and will utilise data available in statistical databases and data collected via focus groups and a survey.

Research plan:

1. Selection of mitigation measures to be studied, comprising of previously identified 'win-win' options (GHG mitigation with financial savings) with low current uptake (A11, Y1). Desk-based analysis of their cost elements and available information on their variation (A12, Y1). Focus group with farmers to verify cost elements of the mitigation measures (A13, Y1).
2. Analysis of existing datasets to explore the relationship between farm characteristics and cost elements. Drawing up cost functions. (A14, Y2)
3. Assessment of the variation in the cost-effectiveness of the selected mitigation measures (A15, Y3).
4. Literature review (A16, Y1-Y2) and focus groups (A17, Y2) to explore how time requirements change throughout the year and what the main drivers of the value of time are.
5. Survey to explore the marginal value of time using experimental games (e.g. exchangeability method; choice experiments) that include a time-money trade-off (A18, Y3-Y4). Assessments of the impacts of the value of time on the uptake of mitigation measures (A19, Y4).

The cost variation data will be compiled into a database relating mitigation options, cost elements and farm characteristics. The survey data will be stored in electronic format (e.g. xls files), focus group information in audio files.

Objective 2: Resource efficiency and emission intensity assessment of Scottish farms with AgRECalc

O2 The work will consist of econometric analysis of data using the AgRECalc carbon calculator. (AgRECalc considers on-farm and off-farm emissions, resource use efficiency and economics of possible GHG reductions on farm; further information is available here: http://www.sruc.ac.uk/info/120355/carbon_and_climate/1333/agricultural_resource_efficiency_calculator_agre_calc.)

Research plan:

1. Emission factor refinement for soil N_2O based on the GHG Platform and other relevant projects (links with RD2.3.7) (A21, Y1).
2. Emission factor refinement for enteric CH_4 based on the GHG Platform and other relevant projects (links with RD2.2.9, RD2.3.6 and RD2.3.7) (A22, Y1-Y2).
3. Resource efficiency and emission intensity analysis to examine farms' technical and environmental efficiency, using production frontier analysis (e.g. Data Envelopment Analysis). The research will explore the heterogeneity amongst the farms and highlight potential factors behind the differences between farms. (A24, Y5)

The data collection will build on the on-going FFBC project, whereby 60 Climate Change Focus Farm cohort farms will be assessed from the biophysical viewpoint in 2015/2016. These farms represent the main farming sectors across Scotland i.e. beef, sheep, dairy and arable. Physical data about the land and crops, livestock, energy and waste will be collected in 2017 and 2018, along with financial information (subject to availability) and information about implemented mitigation actions. Twenty of these farms will be re-assessed in 2017 and 2018 as part of a CxC project (subject to final approval), with the financial elements added. Further farm data might become available via the potential delivery of carbon assessments using AgRECalc under the CAP Pillar 2 Advisory Service.

The newly developed AgRECalc parameters will be stored within the AgRECalc parameter files, while farm data will be stored in the AgRECalc database.

Objective 3: Minimising GHG emissions and loss of carbon from managed soils

O3 Soil structure has a major influence on soil GHG emissions and soil C storage. Key soil properties regulating these functions include soil texture, clay content/mineralogy, organic matter content, supply and availability of soil plant-derived inputs of C, pH, temperature, water content, soil biology and habitat, compaction/packing density, gas diffusion, water infiltration and plasticity. Human-driven land use and management activities such as tillage operations, grazing intensity, application of inorganic and organic fertilisers and lime have an influence on soil C storage, GHG emissions and nutrient leaching too. Promoting and maintaining the physical condition of the soil is an effective means of increasing C storage and reducing GHG emissions. Management practices such as the addition of OM and use of organic fertilisers contributes to the overall capture of organic C in the soil, enhances nutrient uptake and agricultural productivity whilst reducing soil GHG emissions (particularly when quantified in terms of yield-scaled emissions).

Work will include activities such as the quantification of GHG emissions from soils under different agricultural land use and management (A31, Y1-Y2) using 2.3.4 and 2.3.8 field experiments (e.g. use of soil amendments, reduced tillage, compaction mitigation, alternative fertilisers, low-input systems and organically managed rotations).

Extension of the use of soil structure/quality scoring systems developed as part of 2.3.4 to specifically test the use of visual tools as proxies for GHG emissions will be investigated (A32, Y1). Soil visual scoring (VESS and Visual Soil Assessment) and soil surveys/monitoring activities will be undertaken (with open days for farmers, KE31, Y2 & Y3) alongside direct measurements of GHG emissions from soils under different vegetation and soil management (including soil amendment). Visual tools and targeted GHG experimental measurement data will be used to test the use of simple visual assessment tools as proxies for soil quality (A33, Y2-Y3). Simple soil modelling (e.g. N_2O boundary line model, regression approaches) will be used to test GHG mitigation measures using experimental data (A34, Y4).

Objective 4: Soil management and GHG mitigation: environmental and economic impacts of policy instruments

O4 In this Objective a farm-level bio-economic assessment will be carried out based on developing linkages between ScotFarm (economic farm level model) and Landscape/SPACSYS (soil carbon and GHG and crop model), utilising an

emulator approach.
Model farms of different types will be developed using the Farm Accountancy Data Network (FADN) dataset, complemented with more detailed management data based on expert knowledge. The set of soil management, adaptation and GHG mitigation measures and policy instruments will be selected based on the literature and on the preferences of policy makers (KE41). Price projections will be sourced from macroeconomic models, like FAPRI/CAPRI/AgLink COSIMO. Specific attention will be paid to soil carbon thresholds and yield variability and the importance of soil carbon for climate change adaptation (drought resistance).
The soil qualities, soil C stock changes and GHG emissions and crop responses will be modelled in Landscape/SPACSYS, based on expected future weather and climatic parameters. ScotFarm will model the farm management changes and the related cost and income changes through linear programming. A comparison of model runs under policy measure scenarios with a baseline scenario (no policy changes) will provide a measure of financial impacts as well as determine farm responses.
The model chain is computationally intensive and a statistical emulator will be developed in order to provide a mechanism for exploring the behaviour of the model across a range of parameter values and for quantifying uncertainty in the model output. The development of an appropriate emulator is expected to require the development of novel statistical methodology, probably based on Gaussian processes. Gaussian process emulators are particularly useful as they provide both a prediction for the output at points that have not been simulated and an estimate of the uncertainty in that prediction, but other approaches to emulation (including training of neural networks) will also be explored.
Modelling plan:

1. Reviewing and modifying the models (assumptions, time frame, baseline scenario, linkages) (A41, Y1-Y2); model farm development (A42, Y2-Y3).
2. Developing an emulator for yield, soil GHG emissions and N leaching based on climatic, soil and management parameters (A43, Y2-Y3). It will propagate the uncertainty in the crop models and the weather-related risk in the crop yield to the economic model.
3. Identifying soil management, adaptation and mitigation measures (A44, Y1-Y2).
4. Identifying policy instruments and their effects at the farm level (A45, Y2).
5. Crop and soil modelling under various climate scenarios (A46, Y2-Y3).
6. Running ScotFarm – using scenario specific soil, crop and GHG parameters from the emulator – to explore the integrated environmental and economic aspects (A48, Y4).

Key linkages, interdisciplinarity & collaboration
An exchange of research approach, methodologies and results will be facilitated between O1 and RD2.3.12. In particular, results from the work on the economics of sustainable and conventional farming practices in RD2.3.12 can be utilised and built in the cost-effectiveness analysis. Findings from O1 will feed into economic and bio-economic modelling work in RD2.4.2.
O2 will benefit from RD2.3.7 (soil N_2O emissions, enteric CH_4 emissions), RD2.3.6 (animal health and GHG), RD2.2.9 (livestock emissions) and RD2.3.8 (soil C) in the form of emission factors provided by shared team members and

by internal workshops. O2 has also has a strong link to proposed CxC work, where AgRECalc is going to be used to survey farms, and to SRUC's potential delivery of CAP Pillar 2 advisory services (key staff: Gillian Reid).
O3 utilise existing field experiments and platforms and build on work being done in RD2.3.4 and RD2.3.8 but focussing specifically on GHG emissions. O3 will link to soil C storage tools developed at the Hutton and will get data from the Centre for Sustainable Cropping at Balruddery on the GHG effects of soil improvement actions (RD2.3.6).
O4 will be strongly linked to modelling of economic resilience and adaptation (RD2.4.2, key staff: Shrestha), and will capitalise on biophysical and agronomic research soil management (RD2.3.4), novel GHG reduction measures (RD2.3.6) regarding GHG emissions and yield effect of measures, and livestock health (RD2.3.1). This joint development will build on collaboration started in the current Strategic Research Portfolio.

Added Scientific Value

International and national policy objectives have created a deepening scientific interest on the farm scale and policy scale barriers of the implementation of mitigation measures. The increased activity is also reflected in funding opportunities in the area. The proposed four Objectives will advance internationally relevant questions via Scottish examples, maximising mutual benefits with current UK and European projects (e.g. INCOME (Joint Programming Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI), 2015-2018), Climate Change Adaptability of cropping and Farming systems for Europe (FACCE-JPI, 2015-2018), Generating Regional Emissions Estimates with a Novel Hierarchy of Observations and Upscaled Simulation Experiments (Natural Environment Research Council (NERC), 2013-2017), Improving efficiency and reducing waste in the beef supply chain (Innovate UK, 2013-2017)), European and global research networks (e.g. AgMIP (UK, US and CGIAR funding), MACSUR (FACCE-JPI, 2015-2017), Global Research Alliance on Agricultural Greenhouse Gases (GRA) (international funding)) and PhD studentships (on AgRECalc and on econometric modelling of CAP's effects on GHG emissions). A wider range of further collaboration is expected with key partners in Europe, like INRA (econometric modelling), JRC (CAPRI modelling), and globally, like Food and Agriculture Organisation of the United Nations (FAO) (GLEAM modelling), AgResearch (value of time) and International Livestock Research Institute (ILRI) (value of time).

KE, Audiences and Impact

<u>KE</u>

The Scottish and UK Governments, along with organisations such as CCC, CxC, DG Agri and DG Clima will directly benefit from the research findings, and a regular engagement (two KE meetings organised jointly with RD2.3.6 and RD2.3.7 and presentations at policy workshops) will ensure that the relevance of the research questions and the presentation of the findings will be maximised to the policy stakeholders. A side event at an international conference (Agricultural Economics Society) for industry and policy makers will also be organised together with RD2.4.2. The improved AgRECalc and visual soil assessment tools will be promoted at events targeting farmers, such as technical days, open days and FFBC Focus Farm events with topics on farm efficiency, soil management, sustainable practices and climate action. Knowledge exchange will also be facilitated through developing technical guidelines and regular discussions with farm advisors.

Impact

O1: Improved understanding of the costs of mitigation measures and the value of time and its impact to mitigation measure uptake will feed into farm-level bio-economic modelling (within the new Programme) and potentially to European level modelling (e.g. CAPRI) via international collaboration. These, in turn, together with the cost-effectiveness analysis proposed in O1, will inform policy decisions on climate action. The impact will be assessed as acknowledgement of the outputs by policy makers and industry representatives.

O2: AgReCalc is currently used by 14 consultants and 11 farmers and has 90 farm reports in its database. With the roll out of the new Farm Advisory Scheme in 2016, there is the potential for an additional 250 farmers to use AgRECalc. The improvements will enable an improved characterisation of GHG emissions in the tool and therefore improvement in the tool's suggestions on GHG mitigation possibilities on farms. Additionally, the findings from the farm efficiency and emission intensity analysis will be communicated with 80 SAC Consultants who are reaching out to farmers across the whole of Scotland.

O3: Farmer friendly soil assessment tools already widely used by the farming community will be further improved. The current VESS chart and training videos are freely available on the SRUC webpage (in 2014 over 1500 views), and feedback forms (between 7 and 40 per meeting) from recent farmers' meetings also indicate that the research and advisory effort is increasing farmers' awareness of the risk of soil structural damage. The VESS chart has been adopted internationally and translated into several languages. Impact will be measured from counting hits off the VESS web site (with the GHG-enhanced tool), from estimates of the take up from outreach activities and farmer-oriented KT booklets/videos, from feedback forms of farmers' meetings and via direct feedback from farmers via social media.

O4: The bio-economic analysis will feed into the policy process regarding soil management, sustainable agriculture and climate change at a national and likely at an international level. The parallel delivery of research synthesis projects for relevant government bodies will ensure that the research findings will provide scientific evidence for the decision making.

RD 2.3.5, Work planning and timetable for Year 1

Numbering system for deliverables relates to Gantt charts listing Activities (A#), Deliverables (D#) and KE/impact events (KE#)

Year 1: 2016/17	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 Inventory of cost elements	A11		A12					A13				D1.1
O1 Cost functions and cost-effectiveness												
O1 Value of time						A16						
O2 Emission factors	A21									A22		
O3 GHG emissions from soils												
O3 Soil scoring systems						A32						
O3 Testing the visual assessment tools												
O4 Model review and model farms	A41											
O4 Emulator												
O4 Management measures and policy instruments											A44	
O4 Crop/soil modelling												

RD 2.3.5, Work planning and timetable for Year 2

Numbering system for deliverables relates to Gantt charts listing Activities (A#), Deliverables (D#) and KE/impact events (KE#)

Year 2: 2017/18	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 Inventory of cost elements						KE1						
O1 Cost functions and cost-effectiveness	A14											
O1 Value of time	A16 cont.					KE1					A17	D1.4
O2 Emission factors	A22 cont.					KE1						
O3 GHG emissions from soils	A31 cont.					KE1						
O3 Soil scoring systems	A32 cont.										KE31	
O3 Testing the visual assessment tools							A33				KE31	
O4 Model review and model farms	A41					KE1		D4.1	A42			
O4 Emulator	A43											
O4 Management measures and policy instruments	A44 cont.			A45		KE41, KE1						D4.3
O4 Crop/soil modelling								A46				

Name of RD: 2.3.6 - Novel greenhouse gas reduction measures

Research aim and key drivers

The issue of greenhouse gas mitigation and climate change is of significant importance to the RESAS Strategic Research Programme, reflecting high level national and international policy concerns about the implications of climate change for agriculture and wider society. Building a low carbon economy is one of the five high level priorities identified in the Co-ordinated Agenda for Marine Environmental and Rural Affairs Science (CAMERAS) for which new research is recommended. The Scottish Government is committed to investment in the development technologies that will help deliver a low carbon economy. The Scottish and UK Governments have ambitious targets to deliver reductions in greenhouse gas emissions of 80% by 2050, and it is anticipated that the agricultural sector will make a significant contribution to this, supported by work undertaken in this RD. However, it is becoming apparent that current trajectories of agricultural intensification will be insufficient to meet policy objectives. It is inevitable that achieving increased greenhouse gas savings will require the development of new and innovative approaches to the management of agricultural systems. Such new approaches to greenhouse gas mitigation will need to be tested and assessed both for their mitigation potential and economic impact. An underlying principle of the design of new approaches to management of farming systems would be that technologies that reduce greenhouse gas emissions would also help to co-deliver other sustainability benefits such as increased resource use efficiency, reduced loss of pollutants (such as nitrates and ammonia) and improvements in soil quality. Work will be undertaken in the crop and livestock sectors, using cutting edge (precision management and new system designs) to deliver significant additional greenhouse gas savings to the sector. This work will be linked closely to other programmes of work in Theme 2, particularly RDs 2.1.7, 2.2.9, 2.3.5, 2.3.7, 2.3.8 and 2.3.12. In Theme 1 this work will deliver data for modelling and expertise to RD1.1.3.

Emissions of greenhouse gases from agriculture and land use result from the release of nitrous oxide, methane and carbon dioxide. Together they make up around 21% of Scotland’s total emissions, and therefore represent an important target for mitigation if Scotland is to achieve its ambition of delivering a low carbon economy. Nitrous oxide is the single largest component of agricultural emissions making up over 50% of total from agriculture (3,841 $ktCO_{2e}$ in 2012), although in future inventories methane will assume a greater significance as a consequence of the adoption of new IPCC guidelines. Nitrogen fertilisers and organic source of N are the main source, and the development of new mitigation approaches therefore focuses around the more efficient use of N within agricultural systems, which can also contribute to reduced water pollution. Methane is the next most important greenhouse gas with emissions of 2,664 $ktCO_{2e}$ in 2012. The main source is enteric methane production, and mitigation options include genetic and dietary manipulations as well as improvements in the efficiency of the production system. Direct CO_2 emissions from the agriculture sector make up a relatively minor component (< 5%) of total emissions although carbon sequestration by agricultural systems can make an important contribution to mitigation.

Aims

- To develop novel approaches to greenhouse gas mitigation in the crop and

livestock sectors though improved understanding of underlying processes;
- To assess the mitigation potential of new measures using field experiments and modelling;
- To provide policy and practical guidelines to greenhouse gas mitigation in Scottish farming.

This, and related, RDs have significant engagement with international partners in this field and the work funded through the Scottish Government programme will help facilitate those interactions delivering high impact research papers and potential funding opportunities. This includes work linked to modelling activities (e.g., Models4Pastures http://www.gl.ethz.ch/research/projects/Models4Pastures and Agmip http://www.agmip.org/) and will feed into work of the Global Research Alliance on Agricultural Greenhouse Gas Emissions (http://globalresearchalliance.org/) that will deliver international assessments of the ability of a suite of process based models (DNDC and Daycent) to simulate GHG emissions and mitigation options. This work will contribute to the delivery of RDs across WP2.3 and link to modelling being undertaken in WP 1.1.3

Summary of the proposal:
This RD will undertake research to identify new approaches to the mitigation of greenhouse gas emissions from agricultural systems in recognition of the need to reduce emissions in response to current policy targets. Using an interdisciplinary approach and taking full advantage of new and emerging technologies, opportunities to mitigate nitrous oxide, and methane emissions whilst enhancing carbon sequestration will be assessed. Outcomes will include improved scientific understanding of underlying processes controlling emissions and opportunities to improve the spatial variability in landscapes. Practical guidelines and policy briefs will be developed to help with the rapid implementation of research findings.

This RD is structured with five specific objectives:
Objective 1 The use of information technology to deliver greenhouse gas savings in the crop and livestock sector
O1 The aim of this objective will be to apply emerging technologies to improve efficiency of resource use and develop an improved understanding of underlying processes in order to help deliver reductions in greenhouse gas emissions. The objective will build upon previous research on greenhouse gas mitigation to develop a holistic approach to greenhouse gas mitigation. Deliverables will include a paper summarising the mitigation potential of precision farming techniques across the crop and livestock sector, regular KE events, and a final report (year 5) identifying the contribution to national emissions reductions that are potentially available from precision management.

Objective 2 Greenhouse gas mitigation through improved animal health
O2 This objective will develop our understanding of the link between animal health and greenhouse gas emissions, focussing on methane emissions from ruminant livestock, providing the opportunity to deliver mitigation through more efficient production systems. Using a modelling approach the work will target common disease threats and will combine an assessment of abatement potential with costs. Deliverables will include a paper quantifying the impacts of livestock diseases on

GHG mitigation, and a final report (year 5) identifying the importance of livestock disease on overall GHG mitigation.

Objective 3 Greenhouse gas mitigation from agricultural systems
O3 Focussing on nitrous oxide this objective will assess how altered management can contribute to mitigation in cropping systems. Innovative approaches to crops and soil management will be explored to establish their potential to contribute to mitigation in field experiments. This work will link closely to proposed work on improving existing mitigation measures in RD 2.3.5. Deliverables will include a paper quantifying the impacts of crop rotations on GHG mitigation, KE events, and a final report (year 5).

Objective 4 Greenhouse gas mitigation in the dairy sector
O4 This objective aims to understand how a range of management interventions in the diary sector can contribute to greenhouse gas mitigation. Taking a systems approach, changes grassland and livestock management will be used to assess net changes in greenhouse gas emissions and include an assessment of such changes on soil carbon sequestration. Deliverables will include a paper quantifying the overall GHG balance of grassland systems, regular KE events and a final report (year 5).

Objective 5 GHG mitigation with grazing beef cattle
O5 This objective will assess the affect of different feeding strategies on methane and nitrous oxide emissions from beef cattle. Work will investigate the use of novel dietary supplements and deliver an improved understanding of their affects on rumen microbiology and greenhouse gas emissions. Deliverables will include a paper quantifying the impacts of livestock diet on methane emissions, regular KE events, a paper quantifying the importance of diet in the overall balance of methane and nitrous oxide emissions from livestock, and a final report (year 5).

Technical approach
Objective 1: The use of information technology to deliver GHG savings in the crop and livestock sector
O1 The use of information technology, precision farming and modelling approaches provides an opportunity to deliver a step change in mitigation potential from farming systems and is likely to be an underlying driver in delivering innovation to the sector. Such an approach also provides real scientific challenges in terms of the analysis and interpretation of data that will contribute to an improvement in our fundamental understanding of underlying processes. Understanding the role of spatial heterogeneity in landscapes offers the potential to manage fertiliser and manure additions to soils more efficiently. New field experiments will be established in conjunction with industry practitioners in precision farming to quantify the GHG mitigation potential of developing precision management approaches. Precision management of grasslands will be compared with conventional management practices to estimate the potential GHG savings and costs. An intensively managed grassland will be mapped to characterise the spatial heterogeneity of pH and parallel measurements of the spatial variability of denitrification activity will be assessed compared to molecular techniques (measurements of nosZ and nirK genes). Precision liming will be compared with conventional liming approaches in order to assess affects on yield and nitrous oxide emissions. In the livestock sector, more targeted use of resources underpinned enabled by precision management would

also provide opportunities to reduce GHG emissions. A synthesis paper will be prepared that gives an overview of new and emerging technologies that can contribute to GHG mitigation with estimates of potential GHG savings. These areas represent opportunities to deliver valuable KE outputs, working in collaboration with industrial partners in the sector. It is envisaged that this work will develop alongside funding applications to AgriTech in this context. This area of work aligns closely with the current strategic priorities of the MRPs in this area.

Objective 2: Greenhouse gas mitigation through improved animal health

O2 Novel approaches to GHG mitigation in the livestock sector will develop new understandings of the relationship between greenhouse gas emissions and animal health, and the role of farming systems (linking to the programme of work on agricultural systems, elsewhere in WP2.3). Targeted animal health interventions could provide a means of achieving enhanced biological efficiency and sustainable intensification of livestock production by improving productivity, reducing environmental impact and reducing zoonoses simultaneously. There is a growing body of evidence linking animal health quantitatively to GHG emissions intensities in Europe showing, for example, that controlling diseases like mastitis and Bovine Viral Diarrhoea (BVD) can reduce GHGei by 5-10%. This work will seek to identify the potential production and GHG mitigation benefits that could arise through improved livestock health in Scotland. It will also quantify the cost-effectiveness of different animal health interventions and identify the likely total (economically efficient) abatement potential. It will identify potential constraints to achieving improvement in animal health, and ways of overcoming them. The work will collate data on livestock diseases and burdens (by species and production system) from: (i) literature review; (ii) communication with projects and networks (e.g. EPIC, GRA Animal Health and GHG Network); (iii) public databases; and (iv) administration of dedicated questionnaires to animal health and production specialists. Based on (1) and RD2.2.6 (Evaluation of livestock health), identify the contribution of (sub-clinical) diseases by species and production system to farm animal production systems as a whole, and using a decision framework that prioritises targets for potential impact on criteria such as GHG mitigation potential, impact on productivity and zoonotic risk. Significant challenges exist in obtaining the data required on disease prevalence and impact. We are proposing a fairly modest piece of work that will be based on existing data as far as possible, such as in the (as yet unpublished Defra/AVHLA study) “Life cycle analysis of endemic diseases on GHG emissions intensity - AC0120”. Data lected and modelled in RD 2.2.2 will inform the analysis. One of the outputs of this Objective will be a clearer view of the extent to which it is possible to use existing datasets (such as those gathered by the Scottish Animal Health Planning System) to assess the GHG impacts of disease treatment with current data. Empirical measurement of GHG costs of infection will be undertaken in RD 2.2.9 (GI parasitism in lambs and Fluke in cattle) using the SRUC GHG chambers (builds on research in Ewes in current Programme). Liver Fluke associated GHG emissions will be combined with the SRUC predictions of change in liver fluke risk to estimate GHG implications under projected climate change scenarios. The financial costs of control measures, would be quantified and their likely impact on EI (using GLEAM), and their cost-effectiveness. The quantification the total (economically efficient) abatement potential, under different assumptions and scenarios will be assessed and constraints identified. This work would deliver principally to RD 2.2.9, but link to RDs 2.3.1 and 2.2.6.

Objective* 3 *Greenhouse gas mitigation from cropping systems
O3 Manipulation of farming systems provides a significant opportunity for GHG mitigation. Using the Hutton farming systems experiment at Balruddery we will make measurements of greenhouse gas emissions from cereal crops grown under the conventional and sustainable management treatments. This work will be integrated and interpreted with the wider assessment of environmental impact of the management systems in WP 2.3 of which greenhouse gas emissions make a significant contribution.

In the cropping sector there are large uncertainties about the importance of crop residues in contributing to greenhouse gas emissions. These will be addressed by a programme of experimental work that will explore emissions from a range of crop residues and soil conditions. The data will be used to improve emission estimates and emission factors as well as developing process based modelling approaches being developed in RD 1.1.3. The use of vegetation and soil management (including soil amendment) to minimise GHG emissions and loss of carbon from soil, targeting areas of potential mitigation and adaptation will be supported by targeted experiments. This work will link to studies being undertaken in RD2.3.8 and will use shared experiments.

Objective 4: Greenhouse gas mitigation in the dairy sector
O4 The need to increase the efficiency of milk production has been seen as a national priority in recent years due to the high output of greenhouse gases (GHG) produced by ruminant livestock, coupled with the need to increase food production globally. The use of animals with high genetic merit for milk production has been seen as an important part of the solution, as fewer productive animals can be used to produce the same amount of milk. However, it is known that animals that have very high genetic merit for milk production are prone to poor fertility and to suffer from production diseases, which often necessitates higher culling rates. However, the trade-offs between GHG emissions from cows and their health and welfare status is not fully quantified. The aim of this project is to examine the relationships between emissions and health, welfare, fertility and longevity in the Langhill herd of dairy cattle.

Measurements of CO_2, N_2O and CH_4 currently being made on intensively managed grasslands at the Crichton dairy research centre will be synthesised to produce a full GHG budget, and using DNDC a modelling approach (developed in alignment with RD 1.1.3), opportunities for optimisation of the management system will be identified that are able to contribute to lower net emissions.

The Langhill database contains a wealth of data on dairy cattle in the genetics x environment systems study. Data is available on disease incidence, fertility, activity, feed intake and feeding patterns and all aspects of production. The aim of this part of the study is to use this data to use an empirical modelling approach of the full effects of conditions such as mastitis, lameness and dystocia on the whole system methane outputs.

Methane outputs can be measured directly from animals using techniques such as the Laser Methane Detector. Other methods of measuring methane are also available, such as methane hoods. These will used to assess the effects of states such as low social rank (which will affect feeding patterns), poor, but not clinical lameness, heat stress etc at the cow level. This will provide important information on the relationships between emission and health and welfare traits, but also provide further data to parameterise empirical models.

Previous work showing the effect of feed composition, feed supplements and additives, as well as new work on grazing management and grass composition for RD2.2.9 has identified/will identify effects on both GHG emissions (methane and nitrous oxide), as well as productivity and product composition. Additional work is required to optimise these strategies and identify beneficial ‘win-win’ combinations - both in terms of methane and nitrous oxide, as well as emissions and productivity. Modelling work in the first two years of the project will be used to identify treatment combinations for new experimental work with grazing cattle in subsequent years. These studies will build on the improved techniques for measurement of methane and N emissions from grazing ruminants developed within RD2.2.9.

Objective 5: GHG mitigation with grazing beef cattle

O5 Previous work showing the effect of feed composition, feed supplements and additives, as well as new work on grazing management and grass composition for RD2.2.9 has identified/will identify effects on methane emissions, as well as productivity and product composition. Additional work is required to optimise these strategies and identify beneficial ‘win-win’ combinations - both in terms of methane and nitrous oxide, as well as emissions and productivity. Measurements of methane emissions (through respiration chambers) will be made on a sub-set of the animals in the management stress/feed efficiency study within RD2.3.1. Modelling work (using a multiple regression approach) in the first three years of the project will be used to identify treatment combinations for new experimental work with grazing cattle in the final two years. Treatments may involve different herbage varieties, different grazing management strategies or the use of dietary supplements or additives that can be administered to grazing cattle that are not routinely offered concentrates. These studies will build on the improved techniques and proxies for measurement of methane and N emissions from grazing ruminants developed within RD2.2.9. It is anticipated that these techniques will have developed to the point where we can distinguish other aspects of rumen methanogenesis (e.g. the relative contributions of hydrogenotrophic and methylotrophic methanogenesis pathways). We will use metagenomics and transcriptomics tools to describe changes in rumen populations responsible for methanogenesis and nitrogen transformations. It is anticipated that continued rapid developments in sequencing technologies will substantially reduce the cost of these analyses.

Detailed work plan

In each of the RDs any experimental work will be focussed in years 1-4 with year 5 available for analysis, synthesis and reporting of the research.

Objective 1: The use of information technology to deliver GHG savings in the crop and livestock sector

A field experiment will be established in an intensively managed Scottish grassland in year 1 in order to make baseline measurements of spatial heterogeneity of soil properties and yield (M1.1). In yea r2 precision liming treatments will be compared with conventional liming approaches and treatment affects on yield and nitrous oxide emissions will be assessed.

Objective 2: Greenhouse gas mitigation through improved animal health

Data will be compiled (M2.1) in order to undertake a comprehensive analysis of data and livestock disease and its affect on GHG emissions will be undertaken in year one informing approaches to empirical observations and measurements (years 2-4).

Objective 3 Greenhouse gas mitigation from cropping systems

Measurements of GHG emissions from the Balruddery experiment will be initiated in year 1 (M3.1) and continue throughout the programme. Measurements of emissions from crop residues will take place between years 2 and 3 following an initial scoping exercise

Objective 4: Greenhouse gas mitigation in the dairy sector

Data analysis and empirical modelling approaches will be initiated in year one of the programme (M4.1) and continue over the 5 years. New measurements of feed composition and methane emissions (M4.2) will be undertaken between years 2-4.

Objective 5 GHG mitigation with grazing beef cattle

Modelling of the affect of diet on GHG emissions from beef cattle will be undertaken in years 1-3 (M5.1) followed by the use metagenomics and transcriptomics tools to describe changes in rumen populations responsible for methanogenesis and nitrogen transformations in years 4-5.

Deliverables from Objective 1

D1.1 A synthesis report quantifying the potential greenhouse gas savings of precision management (Month 24).

D1.2 A KE event to discuss the importance of spatial heterogeneity (Month 12).

D1.3 A KE event to discuss the importance of precision soil management (Month 15).

Deliverables from Objective 2

D2.1 A KE event to discuss the impacts of selected livestock diseases on GHG mitigation. (Month 12).

D2.2 Research paper quantifying the impacts of selected livestock diseases on greenhouse gas mitigation (Month 22).

Deliverables from Objective 3

D3.1 A research paper on greenhouse gas mitigation from opportunities for improved rotational management in farming systems (Month 24).

D3.2 An open day to demonstrate how optimised rotational management can improve resource use efficiency and GHG mitigation (Month 15).

Deliverables from Objective 4

D4.1 A research paper defining the net greenhouse gas emissions from an intensively grazed grassland (Month 23).

D4.2 Open day to demonstrate research on greenhouse gas emissions from dairy farming (Month 4).

Deliverables from Objective 5

D5.1 A research paper outlining the importance of feed on greenhouse gas emissions from livestock (Month 24).

D5.2 An open day for famers and advisors on best approaches to animal nutrition to optimise greenhouse gas mitigation and production (Month 6).

Expertise

The research team offers world-leading expertise in the field of greenhouse gas measurement, modelling and mitigation. This work brings together experts in the field of soil science, crop science, animal science and economics in order to provide a highly interdisciplinary approach to the topic of greenhouse gas mitigation. Such an approach is essential to address the understanding of complex farm systems and derive solutions that take account of synergies and trade-offs. The expertise of this team is demonstrated by their involvement in a range of external grant awards (e.g. NERC; Generating Regional Emissions Estimates with a Novel Hierarchy of Observations and Upscaled Simulation Experiments, DEFRA; Greenhouse gas Platform programme, Minimising nitrous oxide intensities of arable crop products, BBSRC; Refinement of techniques and evaluation of options to reduce greenhouse gas emissions from ruminant production systems in Brazil and the UK), interaction with stakeholder organisations (Scottish Government, ClimateXChange, the Committee on Climate Change and EU consultative bodies, farmers organisations) and related publications.

Key linkages, interdisciplinarity & collaboration

This work will undertake an interdisciplinary approach to the understanding of farming systems and opportunities to develop new approaches to greenhouse gas mitigation. Within the programme it links closely to RDs 1.1.3, 2.1.7, 2.2.9, 2.3.5, 2.3.7, 2.3.8 and 2.3.12 by sharing experimental facilities, data and expertise. It will build upon existing understanding and knowledge of greenhouse gas emissions from agricultural systems developed from previous RESAS research programme and related research activity such as the greenhouse gas platform programme. The science will provide strong links to related activity and expertise in partner research organisations such as the University of Edinburgh Centre for Ecology and Hydrology, and other national and international research collaborations. Work in O4 will use data from our long running experiment on production, feed intake, health and reproduction in the Langhill dairy herd. Collection and maintenance of these data are part funded via the SRUC Underpinning Capacity tender.

Added Scientific Value

Expertise developed within the group and supported by Scottish Government funding provides critical leverage in developing complementary research and innovation in the field. Funding for this RD is likely to increase opportunities to win new research funding from research councils, government bodies and the European Commission. The work is also highly relevant to international collaborations which are already allowing the group to develop strong linkages in Africa, Asia and South America. These regions of the world look to expertise within Scotland to develop local capability for greenhouse gas mitigation.

KE, Audiences and Impact

In conjunction with RDs 2.3.5 and 2.3.7 work in this RD provides critical support for Government policy in delivering a low carbon economy. Workshops briefing documents and policy papers will be prepared for Scottish Government policy advisers to help support delivery of climate change mitigation targets. A range of stakeholder events will be undertaken to interact with and inform key agencies and organisations including: Scottish Environmental Protection Agency, UK Committee on Climate Change, NFUS, the farming industry, fertiliser manufacturers, precision farming industry, farming consultants.

Impact

Outcomes of this research will be communicated to the Scottish and UK Governments to help inform future carbon budgets for agriculture and land use. Channels of communication with these organisations have been well established through previous research programmes. Scientific impact will be delivered through publication of research papers, and presentations at conferences and workshops. It is anticipated that the findings of the research from this programme will be of sufficient quality to generate publications in the highest impact journals (Science, Nature, PNAS). Industry engagement will be achieved through open days, the preparation of technical notes and guidelines, and presentations at events such as the Royal Highland Show, Scotgrass, science festivals, and other public engagement events. Interaction with farm consultants will form an important part of the impact from this programme. Development of the carbon calculator will allow improved footprinting in farming systems. New mitigation technologies will be developed within the farming for a better climate programme as a consequence of this research, and interaction with consultants will ensure farmers are provided with the most up-to-date information on mitigation. Policy makers are a target audience for this RD. Expected greenhouse gas savings expressed on an area basis and per unit of product from the technologies developed in this research will be communicated to policy makers through policy briefs and in conjunction with CxC. Greenhouse gas savings will be expressed as a proportion of government targets with projections to 2030. Interactions with other stakeholders including regulators and NGO organisations will be achieved through workshops, conferences and field visits.

RESEARCH DELIVERABLE NUMBER: 2.3.6
Work planning and timetable for Year 1:.
(KE output Yellow; Reporting to RESAS Red; Work in progress Blue).

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Objective 1 Precision agriculture Establishment of grassland experiment on precision management										M1.1		
Objective 1 Precision agriculture A KE event to discuss the importance of managing spatial heterogeneity												D1.2
Objective 1 Precision agriculture Grassland KE event to discuss precision soil management		M1.3										
Objective 2 Animal health Identification of relevant literature sources (M3.1) and KE event to discuss the impact of livestock disease on GHG emissions								M3.1				D2.1
Objective 3 Rotations Open day to demonstrate the value of optimised rotations for resource use efficiency												
Objective 3 Paper on GHG mitigation opportunities from improved rotational management									M4.1			
Objective 4 KE event on GHG Mitigation in dairy farming (soil)												M4.2
Objective 5 Paper outlining the importance of feed on GHG emissions from livestock												
Annual Report (Year 1)												R1

RESEARCH DELIVERABLE NUMBER: 2.3.6
Work planning and timetable for Year 2:.
(KE output Yellow; Reporting to RESAS Red; Work in progress Blue).

Year 2: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Objective 1 Precision agriculture. KE event on precision management And synthesis paper			D1.3									D1.1
Objective 2 Animal health. Research Paper quantifying impacts of animal Health on GHG emissions										D2.2		
Objective 3 Paper on optimised Rotations and GHG mitigation			D3.2									D3.1
Objective 4 GHG from grasslands Paper defining net GHG from grasslands systems											D4.1	
Objective 4 Open day to discuss GHG mitigation in dairy farming (livestock)		D4.2										
Objective 5 Paper on livestock Nutrition and GHG mitigation			M5.1									D5.1
Objective 5 Open day for farmers and advisors on GHG mitigation in livestock farming						D5.2						
Annual Report (Year 2)												R2

Name of RD: 2.3.7: Getting further value from the GHG Research Platform
Research aim and key drivers: Greenhouse gas (GHG) mitigation is of significant importance to Scottish Government. Defra and the Devolved Administration funded the Agricultural Greenhouse Gas Research Platform which had the prime objective of improving the national agricultural inventory. Discussions have taken place with key players to allow sharing of these datasets. Within the Platform project, as part of the analysis process, gaps in current knowledge have been identified on background emissions from soils, the linkage between the key drivers and emissions from soils, and actual intake of grazing animals. This work is to improve our understanding of these issues.
Summary of the proposal: (Numbering system for deliverables relates to Gantt charts listing Deliverables (D#) and KE/impact events (KE#) The Agricultural Greenhouse Gas Research Platform (www.ghgplatform.org.uk), which was funded by Defra and the Devolved Administration governments, was established to improve the accuracy and resolution of our reporting system for the national agricultural inventory by providing new experimental evidence on the factors affecting emissions and statistics which describe the activity data farms and farming systems in the UK. It is providing evidence for a UK-specific method of calculating methane and nitrous oxide emission factors that will reflect the adoption of mitigation practices by the industry, enabling the forecasting and monitoring of performance against target emissions reductions set by the UK and Scottish Government Climate Change Acts. Throughout the lifetime of this project, on-going discussions with key players from the Inventory Project will be held. Greenhouse gas (GHG) mitigation is a significant challenge to Scotland, and therefore the aim of this work is to ensure Scottish Government have a clear understanding of the role of Scottish agriculture and management practices on emissions. This will aid in the identification of management practices that will contribute to mitigation based on a more realistic estimate of emissions. As part of the GHG platform, new experimental data on N_2O emissions from mineral soils has been collected which has been supplemented with data from other experiments on mineral soils. In addition, new data on enteric CH_4 production has been added to the existing database that is managed by Reading University. As part of the improvements to the national inventory, data on farming systems has been collated. As part of the project, gaps in our knowledge have been identified, namely, i) the high background emissions from Scottish soils, ii) importance of driving variables (particularly soil wetness) on N_2O emissions and iii) actual intake of grazing animals. The scaling model, NitOx, is derived from data on N_2O emissions, and soil wetness, and therefore the enhancement of the datasets on N_2O emissions will be used to update the existing NitOx model. The knowledge gained from these assessments will be used to inform the further development of dynamic and deterministic models of N_2O emissions. The analysis will also aim to identify periods of high risk of N_2O emissions from the application of N sources to mineral soils used for agricultural purposes. In relation to nitrous oxide, it has been found that the background emissions from Scottish soils tend to be relatively high compared to those reported for

England. This discrepancy will be explored in more detail using historical datasets. There is also a need to understand the actual emission peaks in relation to the key soil and climate drivers in order to improve modelled representations of emission data. In relation to enteric methane, there is a lack of information on the specific diets that are fed to livestock in Scotland, which will have major implications for emissions and the opportunities to reduce these emissions.

Overall aims

1. To improve the understating of environmental and management controls of nitrous oxide emissions from the soils. This will be used to inform model development and identify periods of risk.
2. To update the NitOx scaling tool with data from the data collated as part of the GHG platform. This is linked to the further development of NitOx in RD1.1.4
3. To improve the estimation of methane emissions from grazing cattle and sheep.

Using a combination of statistics, modelling and experimentation, this RD will enhance the information currently derived from the Greenhouse gas platform projects, which is of particular relevance to Scotland in terms of emissions from livestock and soils. Relevant experimental data will be incorporated into this analysis. This will include experiments on novel crops (RD 2.1.8), crop residues and tillage management (RDs 2.3.6, 2.3.8, 2.3.9).

Objective 1 Assessment of key drivers of nitrous oxide emissions and incorporating new data into the NitOx scaling model

The objective of this work is to determine the role of the key soils and climate drivers, and previous management in determining background emissions and emissions from different N sources on an annual and sub-annual scale. It is known that water filled pore space and the soil mineral nitrogen are important factors as well as e.g. soil carbon, pH. Statistical and boundary line modelling approaches will be used to analyse the data and assess the effect of the key drivers on emissions. Initially, the rd will focus on background emissions (Yr 1) and emissions from grassland (Yr 2). Yrs 3 and 4 will focus on the further understanding of emission from grassland on an annual basis and arable on a sub-annual. This analysis will be used to inform the further development of the dynamic and deterministic models of soil processes. The final stage will be the development of a risk algorithm (Yr 5). In yrs 3 and 4, the data generated and analysed in yrs 1-3 will be used to improve the background data within NitOx (Linking to RD 1.1.4).

M1.1 Initial evaluation of the background emissions at a DA level (M6, Y1)

D1 Report on the key drivers for background emissions (M12 Y1)

M2.1 Initial evaluation of the effect of inorganic fertilisers on emissions from grasslands on a sub-annual basis (M16, Y2)

KE1 KE activity – with RDs 2.3.5 and 2.3.6 (M18, Y2)

D2 Report on the effect of N sources on emissions from grassland on a sub-annual basis (M24 Y2;)

M1.3 Initial evaluation of the effect of inorganic fertilisers on emissions from

arable on a sub-annual basis (M28, Y3)
KE2 KE activity – with RDs 2.3.5 and 2.3.6 (M30 Y3)
M1.4 Integration of the emissions data for grasslands to assess annual emissions (M32, Y3)
M1.5 Evaluation on how NitOx will be modified (M36 Y3)
D3 Report on describing the improvements to the water balance model in NitOx (M42 Y4)
M1.6 Integration of the emissions data for arable to assess annual emissions (M44, Y4)
D4 Report on the effect of N sources on emissions from arable (M48 Y4)
KE3 KE activity – with RDs 2.3.5 and 2.3.6 (M54 Y5)
D5 – Report detailing the risk model (M58 Y5)
D6 – Report detailing how the information can be used to improve the dynamic deterministic models of soil c and n cycling (M59, Y5).

Objective 2 Enhancement of the assessment of the predictions of enteric methane emissions from grazing beef cattle and sheep
As part of the research effort in the UK Agricultural Greenhouse Gas Research program, methane emissions data were gathered from both suckler beef cows and sheep grazing grass of both typical lowland and hill swards to fill identified gaps in knowledge. These data were only reported as daily emissions, as measuring forage intake was outwith the scope of the project. However, suitable samples (both herbage and faecal samples) were obtained to estimate intakes by the n-alkane method and analysis of these samples would allow for improved estimates of emission factors for both beef cattle and sheep grazing different pasture types. More accurate estimates of methane emissions would be available for modelling and hypothesis development for further work on GHG emissions from grazing systems. The objective will be completed within the first two years.
M2.1 – samples collated and submitted for analysis (M12)
KE1 KE activity – with 2.3.5 and 2.3.6 (M18, Y2, A1)
D7 Report on the methane emissions on a DM intake basis for different genotypes of cattle and sheep grazing hill and lowland pastures. Evaluation of results against similar results obtained from grazing studies in Wales and Northern Ireland (M24 Y2)

Technical approach

Objective 1 Assessment of key drivers of nitrous oxide emissions and incorporating new data into the NitOx scaling tool
From the database of annual emissions, the control treatments for all UK sites will be analysed in relation to the soil characteristics and the weather conditions experienced on a calendar year and an experimental year basis. Regression and other statistical approaches will be used to identify the key drivers of the emissions. This will build on work that has been carried out as part of the Defra-Link Min-No project and the Defra GHG platform project. The soil water status and the available nitrogen are important factors in determining emissions, and thus their effects on emissions will be explored. This will include an assessment of the effect of soil water on the emissions. The approaches adopted will include boundary line analysis, as well as statistical and simple modelling approaches.

The second stage of the analysis will assess the effects of the quantity of N applied and the N source on the emissions sub-annual emissions from grasslands. This will be followed in by an assessment of the data required to be able to estimate annual emissions for grasslands (Yr3), sub-annual assessment of the effect of the key drivers on sub-annual (Yr3) and annual basis (Yr4) for arable systems. The final stage will be the development of a risk tool (Yr5) for N_2O emissions. This analysis will link to the Global Research Alliance and our understanding of N_2O emissions from soils.

In yrs 3 and 4, the analysis carried out in yrs 1 and 2 will be used to further develop NitOx, a scaling tool that estimates N_2O emissions based on wet and dry periods. The first stage of this work would be to improve the temporal resolution of the water balance model. In recent years, there have been several experiments that have been conducted where N_2O emissions have been measured. This daily emissions data would be used with an assessment of the wet and dry periods derived from the experimental data to determine the scale of the emissions for arable, grazed and ungrazed grasslands. Based on the results of the earlier analysis and the Defra GHG platform projects, an assessment will be made as to the feasibility of including other key soil characteristics into the framework.

Objective 2 Enhancement of the assessment of the predictions of enteric methane emissions from grazing beef cattle and sheep

Two studies were conducted as part of the DEFRA GHG Platform research programme to capture methane emissions from grazing beef and sheep:

Study 1: Methane emissions were measured from 40 lactating grazing cattle with calves at foot using the sulphur hexafluoride (SF6) technique. These represent 2 divergent breeds (crossbred Limousin and purebred Luings) x 2 different pasture types (reseeded predominantly perennial ryegrass, *lolium perenne*, pasture and rough hill grazing) x 2 periods [approx. 5 replicates per treatment group]. These animals were dosed with n-alkanes and estimates of DM intakes can be obtained if feed and faecal samples are processed and analysed. Representative herbage samples were also collected for chemical analyses. We will combine faecal samples (8/animal) into one sample per animal (equivalent to mean methane emissions). We will also analyse the 4 bulked herbage samples (2 periods x 2 samples each) and the 11 batches of alkane-soaked bungs used over the course of the work.

Study 2: Methane produced by grazing ewes (n = 48), with a single lamb at foot, was measured using the SF_6 method. The experiment was a 3x2 factorial, continuous design experiment with 3 genotypes (Mules, Scottish Blackface with high estimated breeding values (EBVs) for maternal ability (SBF_H), Scottish Blackface ewes with low EBVs for maternal ability (SBF_L)) and two sward types (lowland reseeded pasture and a fenced area of rough hill grazing on semi-natural grassland sward). In the same way as the cattle study, vegetation and faecal samples were collected and will be analysed to allow individual feed intake to be estimated using the n-alkane method.

The objectives of this work are to (i) analyse stored vegetation and faecal samples and calculate individual animal feed intake values, (ii) estimate genotype effects on grazing feed intake of different pasture types and (iii) produce more accurate estimates of genotype differences on methane emissions, expressed in different units. The specific work will involve lab analysis (n-alkanes) of vegetation and faecal samples relating to the 40 beef cattle and 36 ewes that produced reliable methane output values, as measured using the SF6 method. Samples preparation and data interpretation will be conducted at SRUC, with n-alkane analysis contracted out (AFBI). Regression analysis using the existing data set to relate SF6 data to genotype, pasture type and other fixed effects, including correction for feed intake, as measured by the n-alkane method will be carried out.

Expertise

This RD will benefit from the expertise and skills that have been developed and enhanced through the Defra GHG platform projects. SRUC has been a key player in the Defra GHG platform projects. As part of the projects, SRUC has been involved in the collection on enteric methane data, nitrous oxide measurements from the field experiments. More specifically SRUC has led the work in the Defra GHG platform, and the Defra-Link Min-NO, on deriving the emission factors from the experimental work through statistical analysis.

Key linkages, interdisciplinarity & collaboration

Examples of key linkages are given here. Further information on links in relation to soils, GHGs and grassland systems are given in the WP2.3 document. The estimates of intake for sheep and cattle from the N-alkane work will provide data to other RDs within Theme 2, including RD2.2.1 (genetic improvement tools/technologies), RD2.2.9 (methane emissions from grassland), RD 2.3.6 (grassland systems and modelling), RD2.3.1 (developing strains and traits beneficial for sustainable production), RD2.3.6 (development of new technologies that reduce GHG emissions) and RD2.3.11 (objective 1 trade-offs in livestock systems and objective 2, RD2.3.7). The understanding of the factors controlling the background emissions, and the key drivers, particularly soil wetness, will inform the subsequent analysis of emissions in RD2.3.5, RD2.3.6. There will be a direct link to RD1.1.4 in terms of the development of the NitOx model.

We will evaluate results obtained for O2 with results obtained from similar grazing studies in Wales (IBERS) and Northern Ireland (AFBI) in order to obtain a clearer picture of issues that need to be explored further within new grazing studies (RD2.3.6).

KE, Audiences and Impact

Audience

The Scottish and UK Governments, along with organisations such as CCC, CxC, DG Agri and DG Clima will directly benefit from the research findings, and a regular engagement (two KE meetings organised jointly with RD2.3.5 and RD2.3.6 and presentations at policy workshops) will ensure that the relevance of the research questions and the presentation of the findings will be maximised to the policy stakeholders. The audience for this work also has an international element as countries seek to improve the calculations of the emissions from agriculture. In addition, information on baseline emissions and how emissions can be reduced will be of interests Scottish and UK Governments and the EU. For example, an improved understanding of background emissions and the key drivers for N_2O emissions from N sources will help identify management methods to lower N_2O emissions. In addition, any methods identified to breed sheep and cattle with lower methane emissions, especially from grass-based systems. In particular, this RD will provide evidence that would help meet government priorities to reduce GHG emissions from agriculture. This would be of increasing interest to farmers if direct incentives/penalties were associated with GHG emissions. These results would also be of interest to other research groups aiming to increase the understanding of GHG emissions from livestock.

In relation to mitigation, we will continue to engage with farmers, industry representatives and policy makers through publication of research results, open days, meetings and other KTE events. The KTE activities will be co-ordinated through RDs 2.3.5 and 2.3.6.

Impact

O1. Understanding the conditions which result in minimising N_2O emission will help to mitigate GHG emissions from soils. This will be enhanced by the development of a risk tool which will help in identifying options for reducing GHG emissions from soils. The improved understanding of emission from soils will also benefit any future developments of AgRECalc. The understanding gained from the analysis of the data will also be used to inform the further development of dynamic and deterministic models of the soil processes.

O2. The key to O2 is to help improve the relationship between the intake of sheep and cattle and emissions. Similarly to O1, this understanding will aid in the identification of mitigation in relation to intake, and diet composition (linked with RD 2.2.9). The improved understanding of emission from soils will also benefit any future developments of AgRECalc.

RESEARCH DELIVERABLE NUMBER:
Work planning and timetable for Year 1 & 2: Major milestones, (key research activities, A#; deliverables, D#; KE/impact events KE#), and the timing of delivery for each item.

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Background emissions						M1.1						D1
O2 Predictions of enteric methane												M2.1
Annual Report (Year 1)												R1

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.2 Sub-annual emissions from grassland				M1.2								D2
O2 Predictions of enteric methane												D7
KE Event (with 2.3.5 & 2.3.6)						KE01						
Annual Report (Year 2)												R2

Name of RD: Alternative approaches to sustainable land management
Research aim and key drivers Producing food while protecting biodiversity and ecosystem services is fundamental to the objectives of the Scottish Land Use Strategy. Associated resource use efficiency issues are also central to the Scottish Government 2015 Economic Strategy. Recent debate on sustainable intensification has led to the conclusion that increasing productivity requires a holistic, interdisciplinary and systems based approach including more appropriate soil and land management, greater resilience to biotic and abiotic stresses and improved resource use efficiency. In other words, there is an inherent recognition of the role of alternative as well as conventional approaches to sustainable land management. In WP preparation a 1 page summary of all RDs was circulated to a range of policy and industry stakeholders and general feedback incorporated.
Summary of the proposal: Delivering the desired outcomes of both profitability and a reduction in the adverse environmental impact of food production requires a combination of alternate management practices and approaches to “input substitution” (for example, use of alternative fertilisers or biological pest control) as well as options for redesigning agricultural systems. Agroecological approaches aim to apply our understanding of ecological processes to develop agricultural land management practices that enhance ecosystem services (ES) (e.g. productivity, pest and disease control, pollination) whilst minimising negative environmental and socio-economic impacts. Alternative and agroecological systems will include systems referred to as “low input” in terms of their use of non-renewable resources but recognising that they are often knowledge intensive. A sustainable flow and appropriate mix of services from agricultural land at local and regional scales requires a balance of trade-offs. Within limits, this mix can vary to suit particular circumstances (e.g. agricultural systems, underlying capacity of the land to deliver specific ES and socioeconomic conditions) provided that the capacity to adapt is not compromised. These challenges can be particularly acute in low-input agroecological systems for two main reasons. These systems often lack resilience to climatic and economic shocks and also the inputs normally used to increase resilience are restricted (often for public good or consumer/industry demand). On the other hand, with respect to the delivery of ES, agroecological systems may be perceived as being more resilient due the buffering effects of biodiversity. This situation demands research to better understand the systems involved to devise policy that maintains and develop systems that fulfil their potential. Both technological and knowledge based solutions, involving participatory approaches with farmers and land managers, are required to deliver profitability and step changes in environmental performance. A recent study “The Role of Agroecology in Sustainable Intensification” commissioned by the Land Use Policy Group (LUPG) highlights the need for robust datasets which compare agroecological and conventional approaches and recognises that there is not one formula for sustainable land management but many options for developing and combining sustainable solutions. Using a combination of on-farm experimentation, survey and participatory approaches this RD will explore how alternative crop, soil, livestock and uncropped area management and alternative farm system design influence productivity and the delivery of non-agronomic

benefits of different systems.

Aims:

1. Investigate the key drivers of alternative land management practices in Scotland including the role of EU, national and local policies.
2. Characterise alternative approaches to sustainable land management and barriers to uptake as perceived by stakeholders.
3. Investigate the potential productivity and environmental impacts of the introduction of alternative practices including measures introduced as part of CAP Greening.
4. Work with land managers to disseminate knowledge of alternative management practices.

(Note numbering system for Gantt charts listing Objectives (O#), Deliverables (D#), Milestones (M#) and KE/impact events (KE#) for Years (Yr) 1-2.)

Objective 1: Socio-economic and political drivers of farm-level uptake of alternative land management practices.

This sets the context for the RD and looks at lowland and upland systems (crop and livestock) as well as holdings of different sizes and different tenure. An empirical assessment of key changes in Scottish land management practices from the perspective of ES delivery and sustainable development will be conducted in Yr 1. This national overview will be explored in more detail at the farm level, in Yr 2-5, using farm level modelling to understand impact of external drivers on farm manager decisions and agroecological performance. D1: Report on assessment of changes in agricultural land management practices in Scotland post 1947 (UK Agriculture Act) (Yr 1).

D2: Research briefing showing the dynamics of, and the factors influencing, the intensity of farm input use and the extent to which this varies by farm type. (Yr 4)

Objective 2: Characterising innovative alternative land management practices.

The aim is to establish a typology of the main alternative approaches to sustainable land management in Scotland that will focus research and KE in the rest of the RD and beyond and help in the development of an associated analytical framework. This framework will characterise alternative land management systems from an economic, social and environmental perspective. It will establish the current and potential contribution of such systems, and help explain why such systems arise in practice and thus what the barriers to further uptake and development might be, from the perspective of both RD scientists and land managers. Methods will include a combination of meta-analysis of other research (Yr 1), in-depth interviews with farmers and other key stakeholders (Yr 1-2; feeding into stakeholder activities in O5), and associated mathematical modelling (Yr 2-5).

D3: Poster/handout summarising typology of alternative practices (Yr 1).

D4: Identification of key practices and systems contributing to alternative land management practices in Scotland (through participatory approach and mental models) and in N Europe (from literature) (Yr 2).

D5: Research paper exploring the results of farm-level modelling to assess the performance of alternative land management systems and practices, their costs and benefits, thus highlighting some of the drivers of and barriers to uptake of such systems and practices (Yr 5).

Objective 3: Developing alternative land management practices for improved efficiency - crop systems, soil and nutrient management.
Here we test the hypothesis that yield and productivity are unchanged between conventional and alternative farming systems. Early work (Yr 1-2) will include a literature review/meta-analysis to help ground the later experimental investigations. O3 will develop and test practices at different scales (platform, field, farm) rotation design, nutrient management and residue management (Yr 1-5). A range of approaches will be considered including precision agriculture, as well as targeted experiments and model components (Yr 1-5).
D6: Interim report (Yr 2) and full report (Yr 4) on the potential productivity and potential penalties with conversion to alternative land management systems in the UK and relevant parts of N Europe.
D7: Participatory engagement and KE with farmers enabling “hands on” information to be delivered by farmers practicing, or willing to practice alternative management techniques (Yr 1-5).

Objective 4: Impacts of alternative management on biodiversity and ecosystem services.
O4 will assess the impact on ES of management designed to promote diversity (plant, invertebrate) in field margins and within-field, and habitat diversity at the farm and landscape scale. Experiments (field/farm scale) in Yr 1-4 will be conducted to determine field and margin management that optimises abundance and diversity of beneficial organisms and delivery of key ES (i.e. pollination, biocontrol, nutrient cycling, food production). Landscape modelling will be used to upscale experimental findings and examine the potential effects of implementing agri-environment policies (e.g. Ecological Focus Areas) on biodiversity and ES delivery.
D8: Research briefing recommending optimum field and margin compositions with respect to enhancing beneficial organisms/ecosystem resilience (Yr 2).
D9: Research paper comparing BACI ESs on Experimental and Control farms (Yr 5) D10: Establish guidelines for spatial targeting of agri-environment measures to deliver multiple benefits (Yr 5).

Objective 5: Synthesis of alternative approaches to land management and “putting it into practice”
Drawing together attitudes and current practices within the farming systems studied here will be important to assess both cost effective and novel practices employed. Co-ordination will be achieved through a common framework drawing on the work in O2 and a systematic approach to assessing and monitoring the effectiveness of proposed changes. Straightforward tools need to be developed that include the key messages from each research component alongside an assessment of the success of ‘putting into practice’ and the socio-economic advantages.
D11: Establish and report on a common framework and models for feasibility-testing of alternative approaches with a range of staff and stakeholders, including farm managers on Hutton’s and SRUC’s experimental farms (Yr 1)

D12: Host annual workshops to understand how detailed information on crop, livestock, soil, land and biodiversity management can inform alternative land management (Yr 1-5)
D13: Final report and dissemination event for industry/stakeholders (Yr 5).

Technical approach

Objective 1: Socio-economic and political drivers of farm-level uptake of alternative land management practices

O1.1 Analysis of socioeconomic and political drivers of agricultural land management practices. An empirical analysis will be conducted, taking into account key historical changes in Scottish land management practices (EU and national agricultural policies) from the a sustainable development perspective. The focus is at a macro scale (Scottish level) thus providing the broad context within which both the micro scale (farm-level) analysis and work in the other objectives can be placed. Work will be based around a longitudinal analysis of farm management systems, by farm type, farm size and by tenure. This will draw on a range of secondary data sources including the agricultural census, land use cover data and information from the Farm Accounts Survey. The implications for the delivery of ES at a generic level will be considered and placed within the wider debate about food security and sustainable development. The assessment will also be informed by the result of an analysis in RD2.3.12 of drivers of farmer behaviour to adopt organic farming using the survey of livestock and crop farmers' intentions to change farming practices in response to the CAP reform (conducted in the current SRP, WPs 6.3 & 4.1).
The empirical analysis will be informed by theories and previous studies on the drivers of farm management decisions, highlighting the interplay between policy mechanisms and broader social and economic changes. The latter will include the influence of research funding on farm management innovation and the way in which changes in Knowledge Exchange have affected the uptake and diffusion of new practices. Both agriculture-specific (eg the EU's CAP, and proposed agricultural tenure legislation) and wider policies (the land reform agenda, income and inheritance tax regulations) impact land management decisions. The review will thus highlight both the internal and external drivers of land management decisions and will feed into subsequent analysis of land manager mental models, as well as informing approaches to encourage the adoption of alternative practices.

O1.2 Farm-level modelling of external drivers of land management decisions. Complementing findings from (O1.1), farm level analysis will focus on understanding better how external drivers such as non-agricultural diversification or the uptake of off-farm work influences land management decisions through, for example, the substitution of inputs and/or adoption of time saving practices and how this, in turn, leads to agroecological impacts. This work will be based on panel data analysis of the Farm Accounts Survey and work proposed in RD2.4.2 on farm business adaptation strategies by focussing on the agroecological implications of the findings. The proposed research will also complement work in RD3.4.1 on how changes in farming in remote rural areas affect the sustainability of local economies. More directly, it will build on findings from a Scottish Government funded project being conducted by MRP researchers looking at the implications of CAP greening measures from a farm business perspective.

Objective 2: Characterising innovative alternative land management systems.

O2.1 Establish typology of alternative/agroecological land management systems. This will build on the LUPG report addressing the links between agroecology and sustainable intensification. Initially, it will i) use a synthesis of the literature to work with different definitions of alternative/agroecological land management and compare them in terms of their relevance to different future scenarios for Scotland (climate, energy, society), their optimisation for different input/output combinations, their differing assumptions about 'natural' or 'wild' ecosystems, and the difference between ideals and results on the ground (M1). ii) This approach will be complemented by 'mental models' elicited from scientists, relevant agency staff, and land managers (farmers) through interviews (M2). Based on the review and interview material we will characterise different practices or combinations of practices ('systems') associated with agroecological agriculture existing in or relevant to Scotland. The deliverable will be a typology of alternative farming systems/practices including a qualitative assessment of their relative importance and impact.

O2.2 Assessing the performance of alternative land management systems. Based on the typology identified above, we will devise (M12) and test alternative approaches to manage low-input systems. This will include using mathematical models (developed for O1 and in RD2.3.12) to compare the economic performance of alternative land management practices and systems.

Objective 3: Developing alternative land management practices for improved efficiency - crop systems, soil and nutrient management.

O3.1 Current status of alternative land management in Scotland. Initially we will conduct a meta-analysis derived from a combination of farm data, a literature review, appropriate Scottish agricultural statistical data and long-term datasets (M3) from a selection of established Scottish system experiments (Yr 1-2). This approach will be used to assess the effects of management and rotation on the productivity of conventional and alternative systems, specifically the alternative land management strategies within the typologies that emerge from O2.2 and help identify key indicators (M13).

O3.2 Research station and on-farm experiments to quantify effects of alternative management on productivity. A range of research station and on-farm experiments covering different land capabilities will then be performed. Short-term field and glasshouse experiments will be used to supplement data produced annually from the long-term trials by focusing on specific sub-components of the rotational systems under test (M4-6; M14-16), with the option to use more controlled conditions than those available from the large plot / field based sites as required. i) Elements to be investigated will encompass the management of organic materials and residue composition (e.g. C:N ratio, C fractions, incorporation methodology and timing) to improve system productivity over more than one season (links to RD2.1.8 Novel Crops). These approaches will include both crop and soil management options, such as the use of intercrops and their residues, green manure replacement of fertiliser, seaweed as a fertiliser on Machair systems and use of a range of established and emerging waste products (e.g. urban green compost, distillery waste, sewage sludge) as fertiliser in arable systems. ii) Assessment of an integrated set of these interventions will be assessed specifically at the CSC at Balruddery. A participatory approach will also be explored enabling "hands on" information to

be delivered by farmers practicing, or willing to practice alternative management techniques (KE1; KE3). This will enable the co-innovation of more sustainable practices to be developed which capture and capitalise on the breadth of farmer experience relating to soil, crop and livestock management which can be used to inform future experimental work. At a systems level, the impacts of management changes investigated will be monitored as yield, quality and productivity, but also through the use of farmer-friendly soil quality indicators (RD2.3.4 Soil Tool Development) e.g. Visual Evaluation of Soil Structure (VESS) and soil quality indices).
O3.3 Modelling of alternative management strategies. Utilising the experimental data, dynamic deterministic modelling approaches to describe C and N flows within the cropping systems. Appropriate models and data compatibility will be assessed for hypothesis testing (M7, Yr 1), followed by testing with experimental data to assess the need for technical improvements to the model (M17, Yr 2). Long-term effects of the alternative management strategies will be assessed within the modelling framework.

Objective 4: Impacts of alternative management on biodiversity and ecosystem services. The impact of sustainable management practices on beneficial organisms (i.e. insect pollinators, natural enemies, soil microbes), ecosystem resilience and the delivery of key ESs (i.e. pollination, pest biocontrol, food production, nutrient cycling) will be assessed using a combination of experimental studies at the plot and farm scale and spatial modelling at the landscape scale. Findings from this research will be used to formulate sustainable management prescriptions aimed at enhancing beneficial organisms and the ESs they provide.
O4.1 Determine vegetation compositions that optimise beneficial organisms. In Yr 1-2, using plot scale experiments relevant to a range of agricultural systems (i.e. intensive livestock, extensive upland and arable/mixed) and informed by existing knowledge in this area, we will identify vegetation compositions for crop and field margins that enhance abundance of beneficial organisms. To increase the range of data captured, field trials being established at Hutton/SRUC farms under other RDs will be utilised (Legume-cereal intercrops and forage-legume mixtures in RD2.1.8, functional arable plant types in RD1.3.1, weed canopy manipulations in RD2.1.6). During periods of peak abundance, beneficial invertebrates and soil microbial assemblages will be monitored (M8, M18). The effect of treatment on the abundance/diversity of beneficial organisms and the complexity of ecological networks (i.e plant-pollinator, natural enemy-crop pest) will be explored as a measure of ecosystem resilience (M9, M19).
O4.2 Before-After-Control-Impact (BACI) experiments. To assess the impact of sustainable management on beneficial organisms and key ESs at field scale, BACI experiments will be conducted with Experimental farms being paired with ‘current practice’ Control sites. Assessments of beneficial organisms and ES delivery (i.e. pollination via phytometers, pest biocontrol via aphid baited plants, food production via agricultural yield, nutrient availability via soil microbial communities) will be conducted at predetermined locations (in fields and field margins) to establish baseline values in Yr 2 (M20). Assessments will be repeated at all sites in Yr 3-4, following the adoption of sustainable crop and field margin management practices (derived from plot-scale experiments) at Experimental farms. Synergies and trade-offs between sustainable

management practices and the delivery of target ES will be examined.

O4.3 Examine the effects of implementing agri-environment policies. The impact of alternative management strategies on biodiversity and ES delivery will be assessed with spatially explicit landscape models (e.g. AgBioscape). Datasets held by SRUC/Hutton (e.g. spatially explicit biodiversity data from arable and grassland dominated agricultural landscapes) will be compiled in Yr 1-2 (M10) and these data, alongside data obtained from plot and farm scale experiments, will be utilised to refine existing spatial models and to validate their predictions (M21, Yr 2 onwards). These models will help to determine the influence of landscape context on the performance of alternative management strategies, including EFAs, at the landscape scale. Spatial modelling will build on recent research (e.g. Hutton's modelling pest-suppressive landscapes, SNH's/SRUC's habitat network modelling and SNH's habitat connectivity indicator) to evaluate agri-environment measures, and their placement, on the delivery of multiple benefits (e.g. ecological connectivity, food production, biological pest control, pollination and species conservation) and will help to identify synergies and trade-offs between these benefits.

Objective 5: Synthesis of alternative approaches to land management and "putting into practice". Objective 5 will bring together the common outputs of Objectives 1-4 in a range of methods and tools to inform and promote best practice at the farm scale.

The different adaptations for the rural businesses identified in O1 will form the basis of the alternative approaches to land management that have been employed, with the most successful of these being drawn together as tools for agroecological best practice. A common approach will be implemented iteratively across the types of farming systems using frameworks and models for synthesis, application and outreach. MRP farms will be used to assess feasibility. An initial stakeholder meeting in Yr 1 will draw out the form of tools that will be most useful and this will be used as a template across all outputs. The outcomes of the modelling work will be used to inform the options for agroecology assessed in terms of yield, profit, biodiversity, supporting and regulating ES and their benefits to the cultural values of the rural scene.

O5.1 Design and test 'best practice' alternative systems. Since the systems under study are highly diverse, covering livestock and crop based farming, the first aim is to develop a common understanding of 'agroecology' and a common methodology (O2 will contribute to this). Various overarching models and decision frameworks will be examined. Examples include the NDicea model which is used as an advisory tool in the Netherlands and DEXi-based decision aids now used for IPM. Practices that are currently successfully used by land managers (identified in O2) will be contrasted with the suite of "best practice" approaches suggested by scientists across a range of system typologies, soil type and climate to optimise a range of ES, including net productivity, supporting functions of soil and food webs, regulation of pollution and disease, reduction in pesticide use and cultural impacts on employment and landscape (M11).

Interaction with work in other Objectives, particularly 1 and 2, and application of the modelling frameworks indicated above, will generate by the end of Yr 1 a set of indicative 'alternative' systems. By an iterative process, (linking with RDs 2.3.9 and 2.3.12), these systems will be fully designed, tested and put into practice. The first stage of this process will be to examine, by extensive and

detailed desk studies, the feasibility of implementing the alternative systems at experimental farms (late Yr 1, then Yr 2; M22). These farms cover a wide range of soils, climates and systems including Balruddery/Mylnefield near Dundee (arable and horticulture), Glensaugh (upland sheep, cattle, deer) and Hartwood Home Farm (livestock, mixed) and Crichton (dairy), Bush (arable/mixed) and Aberdeen (mixed/arable). The process will explicitly include farm managers and staff to draw from their expertise. The aim of this phase is to determine which aspects of the alternative systems are feasible and most applicable to current and future legislation and, if not, what modifications are necessary.
O5.2 Extension to commercial practice. The next phase in the iterative sequence, beginning Yr 2, is to extend the ideas to commercial farming. Novel agroecological practices developed (O3-4) and assessed for feasibility will be promoted to farmers at a series of events linked to different agricultural systems. Farmers will be encouraged to 'put these approaches into practice' and follow up assessments will be made of the benefits to their business. This will involve workshops for both researchers and farmers to encourage the use of the tools and on-farm demonstrations (KE2, KE4), linked to on-farm research activities in Objectives 3 and 4 and RDs 2.3.9 and 2.3.12. Promotion will operate through the existing major networks developed with bodies such as LEAF, NFUS, etc.

Key linkages, interdisciplinarity & collaboration
Examples of key linkages are given here. Further information on links in relation to soils, GHGs and grassland systems are given in the WP 2.3 document.
O1.1 analysis of sociological and political drivers of alternative land management will be informed by the results of an analysis in RD2.3.12 (O2.4) of drivers of farmer behaviour to adopt organic farming using the survey of livestock and crop farmers' intentions to changed practices in response to CAP reform. RD2.3.12 will be informed by work in this RD to define agroecological practice (O2) and identify drivers of, and barriers to, changing practice (O1).
O3.2 and O3.3 will utilise the same long-term rotation experiments at JHI and SRUC as 2.3.4 (O1, O2) involving shared data and management decisions.
O3.2 and O4.1 will co-design shared experiments, and share data from cereal/legume cropping systems with 2.1.8 (O3.2) and findings with RD1.1.1 on soil C and N cycling (O3) and responses of soil AM fungi to nutrient inputs (O4).
O4 will share research findings on biodiversity and resilience with RD1.3.3 (O1.1) to compare measures across systems at annual meetings (yr1 & 3; see below). O4 also links with O1.4.3b on a grass/arable case study
O4.2 Before-After-Control-Impact experiments will partly utilise pollinator friendly margins established in lowland fields at Kirkton within RD2.3.11 (O1)
O5.2 will establish annual meetings for stakeholder consultation and extension of research to commercial farming, with participation by RD1.3.4 (O2) to consult on development of new agri-environment options.
There will be an annual field meeting of key RDs across Theme 1 and 2. Representatives of RDs 1.1.1, 1.2.1, 1.3.1, 1.3.3, 2.3.4, 2.3.6, 2.3.8 and 2.3.9 will meet at a different field site or platform (annually, early summer) to discuss progress, collaboration and opportunities with regard to research on soil management and ES. (RD2.3.8 O3 on organising group).
Wider RESAS Programme This RD will link to ClimateXChange on 1) carbon sequestration, 2) optimising the application of fertiliser and manures, and 3) increasing the resilience of agricultural ecosystems and the services they

provide. RD2.3.8 will provide advice on the pros and cons of existing and novel land management for food security and reducing GHG emissions. Work in the RD will utilise plant genetic populations, insect collections, field platforms, and NSIS archive and database from RESAS underpinning funding.

Added Scientific Value

The proposed research will impact on priority areas for levy boards, RCUK and EU funding streams and could impact on the research priorities of Global funders supporting participation in multilateral international funding bids e.g. Newton Funds. Researchers in this RD collaborate across the UK through networks such as AgriTech Innovation platforms and AIMS and the Defra Sustainable Intensification Research Platform. Beyond the UK, the RD integrates well with research partners e.g. INRA, FIBL, ZALF, CSIRO, ICRAF.

KE, Audiences and Impact

Impacts are expected in six areas: (i) Uptake of new, more sustainable, land management practices by farmers through increased awareness of the understanding and challenges of agro-ecological farming and through the provision of management guidelines (O1-5), (ii) improved micro-economic impacts for farmers (O1-5), (iii) enhanced environment in rural regions including biodiversity (O3, O4), (iv) influencing policy in order to remove barriers to increased uptake of extensive/ agro-ecological farming practices (O1, O2) (v) contribution to the scientific state-of-the-art (O1-4); (vi) through strengthening all areas, the innovation capacity of the Scottish farming sector will be enhanced (O1-5). Our outputs will vary from those that are technology ready to others which will need further transformation or research before adoption. The project will directly contribute to two out of the 7 Grand Societal Challenges, namely Challenge 2 Food Security and Sustainable Agriculture, and Challenge 5 Climate Action and Resource Efficiency.

Linking to KE throughout the programme. Co-ordinated at Theme and WP level and with the Crops/Soils and Environment sectors of the CKEI through emerging themes (e.g. biodiversity, soil health, production) by contributing to CKEI activities, including annual campaigns relevant to specific stakeholder/policy groups and practitioner/training workshops.

Land managers, practitioners and industry.

- **An agreed programme of Land Management Technical Notes (O3, O4, O5)**. 2016 - field margin management and cover crops delivered through SAC Consulting Solutions. In 2016 and 2017 research notes on biodiversity and soil management will be disseminated through the GWCT Agricology website.
- **Contribution to KE centres for demonstration events (O3, O4, O5).** LEAF Open farm Sunday annually at various locations demonstrating the benefits of alternative management (O3 to provide an annual display). Cereals in Practice - annually demonstrating the benefits of alternative crops/ crop management (O3 on organising committee). Institute farm open days (annual).
- **Participatory engagement with farmers** enabling “hands on” information to be delivered by farmers practicing, or willing to practice alternative management techniques (September 2016 to 2020).
- **Industry and levy boards.** Scientists will engage with relevant industry and levy boards building on existing contacts and the AHDB annual conferences.
- **Policy.** Policy brief on current status and future potential of alternative management systems in Scotland (Jan 2017 (O3). Interim (Dec 2018) and full report (Dec 2020) on potential productivity and penalties of conversion to alternative land management in the UK and relevant parts of N Europe (O3). Reports on changes in agricultural land management practices (O1, March 2017) and identifying key practices and systems contributing to alternative land management in Scotland (O2, Nov 2017). A seminar held Victoria Quay to present and discuss results, with handouts to summarise key findings (O2). Impact will be monitored through interaction and discussion with policy groups.

International science community to promote our research on the global stage.

- **Peer-reviewed papers** for example i) reviews of current land management practices, typologies and their productivity, ii) research articles on soil process responses to alternative nutrient inputs and links between biodiversity and key ESs, and iii) theoretical analysis of biodiversity and ES at landscape scale.
- **Scientific presentations at conferences.** Examples: Alternative land management session at European Society for Agronomy Congress (2016, 2018) (O3/O4/O5). Posters/presentations at SRUC/SEPA congress 2018, 2020 (combined contribution across Objectives).
- **Education.** Findings used in SRUC MSc Organic Farming, Food Security and Hutton MRes Crops for the Future and as MSc project opportunities.

RESEARCH DELIVERABLE NUMBER:
Work planning and timetable for Year 1:

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Analysis of socio-socioeconomic and political drivers Empirical analysis of key drivers of and changes in Scottish land management practices												**D1**
O1.2 Farm level modelling Farm level modelling of effects of external drivers on farm management decisions and agroecological performance												
O2.1i Characterising alternative land management systems Identify different definitions of alternative/agroecological land management through synthesis of the literature						**M1**						**D3**
O2.1ii Characterising alternative land management systems Interviews to construct ‘mental models’ elicited from scientists, relevant agency staff, and land managers (farmers)									**M2**			
O3.1 Current status of alternative land management in Scotland Meta-analysis to assess the current performance of alternative land management strategies within the typologies that emerge from O2.2 and extension of information to assess future potential												**M3**
O3.2i Research station and on-farm experiments: nutrients Field experiments and platform studies to assess the impact of replacing conventional fertilisers with alternative sources of nutrients												**M4**
O3.2ii Research station and on-farm experiments: rotations Undertake field experiments and platform studies to assess the impact that rotations including novel genotypes and crops have on productivity and sustainability of the cropping system												**M5**
O3.2iii Research station and on-farm experiments: crop mixtures Undertake field experiments and platform studies to assess the impact of including mixtures of crops (intraspecific mixtures, intercrops and relay crops) on productivity and sustainability of the cropping system												**M6**

O3.2iv Research station and on-farm experiments: KE Industry KE – on farm event				KE1								
O3.3 Modelling of alternative management strategies Dynamic deterministic modelling to assess long-term effects of alternative management strategies												M7
O4.1 Determine vegetation compositions that optimises beneficial organisms. Plot-scale experiments using legume-cereal intercrops, forage-legume mixtures and weed manipulations						M8			M9			
O4.3 Examine the effects of implementing agri-environment policies. Spatially explicit landscape models to examine impact of alternative management strategies on biodiversity and ES delivery												M10
O5.1 Design and test 'best practice' alternative systems. Identify indicative 'alternative' systems and model frameworks.							M11			D11		
5.2 Extension to commercial practice: KE Stakeholder consultation meeting to identify tools for best agroecological practice.							KE2	D12				

RESEARCH DELIVERABLE NUMBER:
Work planning and timetable for Year 2:

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.2 Farm level modelling Farm level modelling of effects of external drivers on farm management decisions and agroecological performance												
O2.1ii Characterising alternative land management systems Interviews to construct 'mental models' elicited from scientists, relevant agency staff, and land managers (farmers)								D4				
O2.2 Performance of alternative land management systems Devise and test alternative approaches to manage low-input systems based on the typology of alternative systems/practices												M12
O3.1 Current status of alternative land management in Scotland (Apr 2016 – Apr 2018). Meta-analysis to assess the current performance of alternative land management strategies within the typologies that emerge from O2.2 and extension of information to assess future potential										M13		
O3.2i Research station and on-farm experiments: nutrients Field experiments and platform studies to assess the impact of replacing conventional fertilisers with alternative sources of nutrients												M14
O3.2ii Research station and on-farm experiments: rotations Undertake field experiments and platform studies to assess the impact that rotations including novel genotypes and crops have on productivity and sustainability of the cropping system												M15
O3.2iii Research station and on-farm experiments: crop mixtures Undertake field experiments and platform studies to assess the impact of including mixtures of crops (intraspecific mixtures, intercrops and relay crops) on productivity and sustainability of the cropping system												M16
O3.2iv Research station and on-farm experiments: KE Industry KE – on farm event				KE3								
O3.3 Modelling of alternative management strategies Dynamic deterministic modelling to assess long-term effects of									M17			

alternative management strategies												
O4.1 Determine vegetation compositions that optimises beneficial organisms. Plot-scale experiments using legume-cereal intercrops, forage-legume mixtures and weed manipulations.						**M18**			**M19**			**D8**
O4.2 Before-After-Control-Impact experiments. Field-scale assessment of sustainable management conducted at Experimental farms paired with 'current practice' Control sites.							**M20**					
O4.3 Examine the effects of implementing agri-environment policies. Spatially explicit landscape models to examine impact of alternative management strategies on biodiversity and ES delivery												**M21**
O5.1 Design and test 'best practice' alternative systems. Examine feasibility of implementing 'alternative' systems at experimental farms.							**M22**					
5.2 Extension to commercial practice. Stakeholder workshop to understand how detailed information on land management can inform alternative land management**.**						**KE4**	**D12**					

Name of RD: 2.3.9 Integrated Management Systems
Research aim and key drivers With increasing pressure on farmers to produce more food from the same land area at lower inputs and with less pollution, there is an urgent need to test, refine and demonstrate management options that can reconcile these conflicting requirements. This research deliverable (RD) will develop integrated management systems to enhance economic and environmental sustainability, focusing on two contrasting production systems: arable and ruminant livestock. Opportunities to improve production efficiency, and therefore sustainability, through adoption of integrated management approaches are being developed in current workpackage (CWP)1.1, CWP3.3, CWP3.4, EU IUK “Beefmonitor”, IUK “Precisionbeef” and IUK Cowhealthmonitor”, Eblex Nutribeef, AMIGA, EU PURE and underpinning capacity (UC). Outputs from these projects in the form of best practice options will be implemented and tested here using case studies in both arable and livestock sectors. New and novel sensor systems and indicator monitoring protocols will be explored to establish their performance and function in assessing soil condition, plant stress, animal physiology, greenhouse gas emissions and system processes in commercially-equivalent settings, including a long-term research platform maintained through UC funding. These case studies will be used to generate an evidence base for the economic and environmental impact of more sustainable integrated management options to assist land managers in overcoming the challenges of managing the land for both environmental protection and high quality food production. Data generated from this research will feed into RD2.3.12 in uptake of best practice and will inform Scottish, UK and EU policy directed towards obtaining multiple environmental benefits from both arable and livestock production systems.
Summary of the proposal: The objectives of this RD are to create tools and strategies for arable and livestock Integrated Management Systems (IMS) and to develop methods for the collection, storage, integration, analysis and use of data from different sources, in order to improve decision-making by farmers and policy makers. In the livestock sector, the focus will be on ruminant production (both grazing and in-door systems) and the management benefits made possible by new sensor systems and associated data processing. In the arable sector, the focus will be on integrating management strategies to increase the efficiency of crop production and maintain crop yields at lower levels of agrochemical input. This will be based on developments at the Centre for Sustainable Cropping (CSC) supported by underpinning capacity funding, and the ENDURE rotation supported by the ENDURE network (www.endure-network.eu). Research in livestock will be carried out at the SRUC Dairy Research and Innovation Centre, SRUC Beef and Sheep Research Centre, and using national data. In both the livestock and arable sectors, research will be carried out in parallel and data generated from both will feed into assessments of systems trade-offs in RD2.3.11 and a demonstration (via specific case studies feeding into RD2.3.12) of the costs and benefits to the agricultural industry. **O1 Livestock: data collection, storage and analysis for improved livestock production.** Significant improvements to the efficiency of livestock production can be made through technologies that allow direct links to be made between data on animal health, nutrition and genetics and individual animal. This

objective will focus on methods for automated monitoring of animals and use of stored data to inform management and diagnostics.

D1.1 EID affords the opportunity to reliably map animal details to the individual. The specific advantage of EID as both an identifier, and potential holder, of specific information will be assessed. The data storage option on the animal will be explored for both on-farm and transactional/supply chain benefits.

D1.2 Understanding how to store, accommodate and process animal-based data, and transform them into useful management or diagnostic information presents a novel challenge. Data streams from D1.1 and O2 will be mined for relationships with the available metadata such as physiological or metabolic state. This will link to the statistical methodology for automated monitoring of organisms and the environment being developed under RD2.3.10.

D1.3 Building on current work, existing data will be mined to examine genomics of the responses to different nutritional and health treatments. This work will identify the potential for "designer" management decisions to optimise the efficiency of nutritional and animal health management.

O2 Livestock: implementation and testing

Demonstration and testing of the use of individual data or improved/integrated management in the livestock sector will be carried out in the form of three specific case studies.

D2.1 Collaboration with the Centre of Excellence for Sensor and Imaging Systems (CENSIS) will lead to refinements of sensor systems for measuring respiratory gas concentrations, piloted in a current Innovate UK project and previous Defra funded work. These measures will provide proxies for emissions under real grazing conditions and will be validated in conjunction with RD2.2.9. This will inform models to predict field scale emissions in Scotland's variable pasture environments.

D2.2. Pilot studies undertaken in a current Innovate project have shown that an animal-mounted sensor can detect parturition. It is anticipated that these measures will better relate to animal health status when combined with behavioural data. Studies are proposed which will capture data at the milking point and assimilate both fixed and animal-mounted data streams to allow a relational analysis of the link to health conditions.

D2.3 Gastrointestinal nematode parasites are a major constraint on efficient livestock production globally. Control is achieved through chemical intervention, however anthelmintic resistance seriously threatens the sustainability of livestock production. Through previous and current SG funding we have developed a decision support system, using EID, for optimised anthelmintic use (targeted selective treatment, TST) in sheep. Here, this work will be validated and farm specific thresholds developed, linking with studies in RD2.3.11, and used to inform best practice advice in RD2.3.12.

O3 Arable: technologies and integrated management strategies for improved arable production.

Intensive crop production practices have increased reliance on non-renewable agro-chemicals to maintain crop yields and evidence from recent reviews indicate a negative impact on environmental quality, farmland biodiversity and ecosystem services. New technologies and strategies are required if these negative effects are to be reversed whilst still maintaining high yields and quality food production. Here, we review the state of the art in integrated farm management options, develop monitoring protocols, tools and applications for assessing the impact of new management strategies, and develop a whole systems framework for iterative testing.

D3.1 Best practice options for all components of arable production need to be identified in order to generate an effective system scale IMS. Here, we will review IMS options and new innovations from previous and current WPs, focusing on: IPM to reduce reliance on agro-chemicals; weed management to enhance ecosystem services; precision fertiliser placement to minimise inputs; soil management to reduce losses, and multifunctional field margins. Output will be a published review and a prioritised list of best practices for implementation in two case studies.

D3.2 Monitoring tools and apps will be developed including multi-sensor imaging for early detection of plant stress by linking above ground plant responses to below ground stress (linking with RDs 2.1.1 and 2.1.2), and methods for proximal sensing and direct measurement will be developed for field-based monitoring of soil and crop condition (linking with RDs 1.1.1, 2.1.5, 2.3.4 and InnovateUK SoilBio projects).

D3.3 A whole systems framework for designing, implementing and testing a sustainable cropping system has already been developed through previous WP1.7, CWP1.1, UC (Balruddery CSC) and EU PURE (now ENDURE). Here, this framework will be used to adapt an existing DEXiPM model developed as part of EUF7 project (AMIGA) and ENDURE. The resulting model will be used to test the efficacy of the new arable IMS implemented in O4.

O4 Arable: implementation and testing

Demonstration and testing of the new integrated management system in the arable sector will be carried out in the form of case studies based on two existing long-term research platforms.

D4.1 Case study 1: the CSC. A long-term platform for sustainable cropping, funded through UC, was established at Balruddery Farm in 2009 (http://hutton.ac.uk/csc). A ‘sustainable cropping system’ was designed with input from scientists funded on current SRP together with agronomists, growers and industry bodies. The goal was to maintain yields at lower chemical inputs, improve soil health, enhance arable biodiversity and reduce environmental impact. The sustainable cropping system is compared to conventional practice over a six year crop rotation. In this deliverable, the sustainable treatment will be modified on the basis of the results from D3.1 and linked RDs 2.1.6 (IPM), 2.1.7 (novel crops), 2.3.4 (soil systems) and 2.3.8 (sustainability) to incorporate the new IMS at a field scale. The impact on key system indicators (economic, environmental and ecological) will be monitored throughout the second six year crop rotation 2017-2021 using protocols, tools and apps developed in D3.2. The extensive field and agronomic data collected through UC on the CSC is held in an existing relational SQL database from which relevant data may be extracted for a cost-benefit analysis and assessment of sustainability using DEXiPM and an economic model. Outputs will include an evaluation of the success of the IMS and recommendations for refinement to further improve on the levels of sustainability achieved. This deliverable will feed in to RD2.3.10, RD2.3.11, RD2.3.12 and AIMS.

D4.2. Case study 2: the ENDURE rotation. A wheat-based three-year rotation experiment was established as part of a six-site collaboration within the EU PURE project to test intermediate and advanced IPM systems in practice. Now linked through the ENDURE network, the legacy effects of the first rotation cycle will be assessed in terms of yield, pests and diseases (including weeds) and agronomy inputs including pesticides in a second rotation using the DEXiPM sustainability tool together with cost-benefit analysis and Synops environmental risk tools.

Technical approach

O1 Livestock: data collection, storage and analysis for improved livestock production

This objective will provide practical scientific developments that are necessary to deliver the livestock industry priorities. This information will contribute to developing decision support tools for IMS in ruminant livestock. The following groups of stakeholders will benefit from this work: beef and dairy farmers, livestock industrial partners, policy makers and scientists.

D1.1 Exploration of anticipated benefits and future options and advice for Bovine EID Candidate options of the available commercial offerings will be selected based on performance and reliability (and in consultation with Scottish Agricultural Organisation Society Ltd (SOAS)/ Scottish EID Livestock Traceability Research (ScotEID)). These will be tested on animals at a pilot level in years 1 and 2 using commercially available readers, and the tag/reader combination embedded within fixed data gathering systems - proposed as breath monitoring and/or optical sizing systems (M1). Results will be used to inform practical implementations in both the beef and dairy sectors, both as stand-alone systems for precision livestock management, and in combination with other systems to provide database identifiers, and assess viability of animal-mounted performance/health data storage (M2). This work will contribute to the delivery and implementation of EID in cattle, based on regulations published Sept 2014 and Technical Specs being developed in the EU. Further, the work will help identify barriers to uptake and ensure that the legislation can work to the best effect.

D1.2 Data analysis techniques and fusion to provide optimal output. The purpose of this objective is to examine data handling and processing techniques that may be best aligned to these outputs (M3). In conjunction with Biomathematics and Statistics Scotland (BioSS), algorithms and decision support techniques will be developed, based on intensive analysis of large datasets. This will maximise the functional utility of consolidating large, time-series data streams into useful management support information. This work will be aligned with elements of RD2.3.10, where data will be aggregated across the supply chain.

D1.3 Integrating genomic information into novel management systems. Building on work in RD2.3.1, we will examine the genomics of response to different disease and/or treatments (routine and targeted) in a research herd of dairy cattle (M4). Using a system that has been applied to national systems of animal recording we will further explore the genetics of the extent and recover of negative energy balance (with diet interactions in national data) (M5). The nutritional interaction with energy balance (and diseases) will focus on herds that have been participating in national programmes of work undertaking repeated condition scoring, disease monitoring (with detailed data and treatment recordings) and milk mid infrared. Finally with these results of how different genetics respond to different management options we will examine how this information could be implemented in animal management programmes with industrial partners (M6).

O2 Livestock: implementation and testing

This objective will develop and demonstrate proxies that will deliver real-time feedback on animal health condition, physiological status and performance, and allow appropriate management interventions to take place. Key stakeholder groups (farmers, policy advisors, and industry partners) will be involved in discussion at the early stages of designing the IMS and in knowledge exchange.

D2.1 Development of rapid methods/proxies for GHG emissions applicable to outdoor livestock In partnership with CENSIS (where a parallel funded project is anticipated), testable prototypes will be assessed in calibration facilities and performance verified. These will then be incorporated into the previously verified, wearable harness and telemetry package. An experiment will be planned using the Greencow facility to verify both accuracy and temporal performance of the measurement systems and correlate with the Greencow chamber outputs (M7). The experimental animals will be chosen to represent a range of outputs. Pending successful conclusion of this year 1 study, an outdoor grazing trial will be conducted, in combination with RD2.3.7 studies (M8). In indoor and grazing environments, there is still a deficiency in obtaining accurate and convenient recording of methane production in livestock. Initial pilot work from a Technology Strategy Board (TSB) ALERTS programme and previously SG funded work suggested that proxyrecording mechanisms are feasible for outdoor emission estimation. This will be explored in controlled trials. Once accuracy and robustness in methane output determination is confirmed, the system may then be deployed in further studies to examine the effect of herbage/species and animal interactions, and contribute to the data inventory for systems modellers to predict emissions at larger scale.

D2.2 Sensor based systems for prediction and reporting of physiological and health conditions in livestock. An experiment to capture individual animal variability in both dairy and beef cows will be conducted in conjunction with elements of RD2.2.7 using a combination of tri-plane accelerometry sensors mounted at different positions on the animal (M9). This will expand on the successful simple detection with single sensor option in line with the Scottish Government's Animal Welfare and Health Framework principles, 'Prevention is better than cure'. This work will link with explorations in "the development of sensors and systems to remotely and automatically monitor and record animal health, welfare and physiological condition in real time" in RD2.2.7 and the relationships with animal welfare. In consultation with QMS and NFU, fusion of separate data streams and their analyses will be explored to establish prediction robustness, and how this could feed back to livestock keepers in alerting or assisting in management decisions. CENSIS will be tasked with examining the feasibility of additional options in measurement, known to be possible model co-variate inputs (such as Heart Rate Variability and peripheral vascular responses reflected by changes in local surface temperature), and this will form the basis of a more intensive study in year 2/3 to validate the approach in data synthesis/analysis from different sensor modalities in more accurately reporting physiologically important events e.g. parturition progress and dystocia risk to the livestock keeper (M10).

In the dairy environment, a pilot-study will be conducted to capture individual animal milk parameters in combination with other fixed and animal mounted sensor systems. Again dialog with CENSIS and other parties is expected, to examine the feasibility of trace biomarker detection in-line in milk and real-time in breath (M11). This combination of outputs will contribute to the data fusion techniques to be carried out in D1.2.

D2.3 Further development of decision support system to target anthelmintic use in lambs. In order to validate the previously developed decision support system, data (weight, production efficiency, response to anthelmintic) will be collated from previous studies where the approach had been implemented on a range of farms (lowland, upland and hill) and with different sheep breeds (Texel, Suffolk, Blackface etc) and collected from the field trial conducted in RD2.3.11 where the approach is tested on an upland/hill flock (M12). The analysis undertaken will be to define optimal treatment thresholds under each farming condition (M13). The outcomes are expected to be an optimised decision support system for pen-side anthelmintic treatment decisions in lambs, with a long-term aim being the implementation of the system into routine farm management. The outputs will be KE to farmers/veterinarians and the scientific community by a publication in peer-reviewed journal.

O3 Arable: technologies and integrated management strategies for improved arable production. This objective will provide the evidence base for designing integrated management strategies that can enhance the efficiency of crop production, thereby allowing a reduction in the reliance on agrochemicals and a resulting improvement in environmental health and sustainability. Key stakeholder groups (policy advisors, agronomic consultants, industry bodies and growers) will be involved in discussion at the early stages of designing the IMS and in review of impact.

D3.1 Review of IMS options. Information will be gathered from a range of sources (including industry groups: the Association of Independent Crop Consultants (AICC), Agrii, Soil Essentials and SRUC agronomy consultants; and scientific research: data from previous workpackage 1.7 on agricultural systems, CWP3.4 on biodiversity and functioning in agroecosystems, CWP1.1 on systems frameworks for impact assessment and CWP3.3 on soil health and resilience) to review sustainable land management options (M14). Target areas for review will be: soil management and organic matter amendments for improved physical structure (linking with RDs 1.1.1, 2.1.7, 2.3.4 and 2.3.8); precision agriculture for optimal spatial and temporal agro-chemical placement; weed and margin management for supporting ecosystem services (linking with RDs 1.3.1, 2.1.6 and 2.3.8); crop varieties for environmental traits including resistance and resource use efficiency (linking with RDs 2.1.6, 2.1.7 and 2.1.8); novel cropping systems including legumes and inter/mixed crops (linking with RDs 2.1.7 and 2.1.8); IPM practices to reduce reliance on prophylactic use of crop protectants (linking with RD2.1.6). From this review, a set of management options will be prioritised for incorporation into the CSC and ENDURE (M15).

D3.2 Monitoring tools and apps. A suite of key indicators will be identified for monitoring the impact of the new IMS (D3.1) on system properties. These indicators will be based on the systems framework already developed for the CSC and will cover soil physical properties and chemistry, plant nutrient inputs and losses, GHG emissions, plant and invertebrate biodiversity, crop development, yield and end product quality, input costs and gross margins (M16). Protocols for biodiversity and environmental monitoring and for capturing financial information are already well established and will be applied in the case studies in O4. Soil monitoring apps and models will be developed here to process data in real-time for land management decision support (M17). This will link with CENSIS to develop and apply cheap in-field hyperspectral soil monitoring. A model for estimating soil nutrient and physical characteristics from mobile phone imagery will be developed in year 2 and a library of visible-range hyperspectral signatures for soil samples will be generated (M18). This deliverable will also link closely with RD1.1.4 (Fourier transform infrared spectroscopy (FTIR) for field based analysis of soil properties, RDs 2.1.1, 2.1.2 and 2.1.5 (imaging sensor technology using hyperspectral and infra-red cameras for high throughput phenotyping and crop monitoring), RD2.1.5 (hyperspectral imaging system for soil testing), RD1.1.1 and InnovateUK (SoilBio) (soil health and quality testing using resilience measures, carbon turnover and nematodes as indicators). Much of the tool development for this monitoring work will be conducted within these RDs, but will be applied here from year 3 for calibration and testing.

D3.3 Whole-systems framework and DEXiPM. The framework will be adapted from an existing DEXiPM, constructed as part of an EU F7 project (AMIGA), where overall sustainability is divided into smaller, more quantifiable components, each of which is characterised by one or more indicators (M19). The indicators are organised hierarchically allowing evaluation of the cropping system according to many potentially conflicting goals. Modifications to the cropping system based on this assessment can then be implemented iteratively to improve on the desired goals during the second and subsequent rotations. This framework will also be used in RD2.3.11 to identify trade-offs within arable ecosystems.

O4 Arable: implementation and testing. This objective will apply the IMS options from O3 to two case studies in order to provide quantitative evidence to the agricultural industry, growers, agronomists, policy makers and the scientific community for their efficacy in achieving the desired goals of reducing environmental impact whilst maintaining yield and product quality.

D4.1 Case study 1: The Centre for Sustainable Cropping platform, supported through UC funding, will be used as a case study for implementation, testing and demonstration of the IFM package. Data on the key biodiversity (weeds, natural enemies, pollinators) and agronomic (input rates and costs, crop development and yield) indicators under sustainable versus conventional management will be provided through Underpinning Capacity. Data from soil monitoring apps and tools in D3.2, crop pests and diseases, and system processes (natural enemy predation of crop pests, pollination and decomposition) will be generated here (M20) and data from all sources will be used to populate a web based SQL database, developed in year 1, of spatially referenced Geographic Information Systems (GIS) data on environmental, economic and ecological indicators of arable ecosystems (M20). Data on the measured indicators (soil, plant, invertebrate, crop and finances) collected here and through UC, will be fed into the DEXiPM model developed in D3.3. This will be used to test and demonstrate the efficacy of the IMS options in improving sustainability relative to standard practice. Model output will indicate which system components respond positively and negatively to the IMS and this data and information will be delivered to RD2.3.8 for economic analysis, to RD2.3.11 to assess trade-offs between system components, RD2.3.12 to provide

evidence for uptake of best practice by the farming community, and RD1.4.3 to inform the potential for delivery of multiple benefits at the catchment scale (Objective b). **D4.2** Case study 2: After the second ENDURE wheat-based three-year rotation implementation of standard current, intermediate and advanced IPM systems, all inputs and outputs together with yield, pests, diseases and weed data will be analysed using standard statistical approaches together with cost-benefit analysis and Synops environmental risk analysis and subsequently subject to DEXiPM analysis to determine impact on social, environmental and ecomonic sustainability impact (M22). These will be compared with up to five other European trials under the ENDURE network to define robust and effective IPM systems principles applicable over a range of environments. This RD will require significant statistical and potentially modelling input in which BioSS will be involved, their inputs being supported by BioSS funding for Underpinning Capacity Function 7.
Expertise This RD builds on a significant body of research by an established multi-disciplinary group of research leaders at the Hutton, SRUC and MRI with a strong track record in sustainability research evidenced by successful grant funding from EU (PARASOL (2006-2009), GLOWORM (2012-2015), AMIGA (2011-2015), PURE (2012-2015), Legume Futures (2011-2014)) and other funding bodies (Innovate UK, Home Grown Cereals Authority (HGCA), Potato Council, Danish Innovation Fund, Genomia, Strategic Partnership for Food and Drink, Defra). The expertise represented across these MRPs has resulted in successful establishment of a range of long-term, state of the art platforms and applications including the Langhill herd and world-class livestock greenhouse gas emission research facilities (SRUC), the development of vaccines, diagnostics and control options including the Targeted Selective Treatment (TST) decision support system (MRI), the long-term organic rotation at Craibstone (SRUC), the Centre for Sustainable Cropping long-term research platform (Hutton) and ENDURE wheat based rotation at Balruddery Farm (Hutton). Significant expertise is also available in modelling, including economics models for risk assessment, DEXiPM for evaluation for sustainability and off the shelf frameworks and protocols for environmental impact assessment. This RD will build on this expertise to develop, test and demonstrate new approaches and applications in Integrated Management for sustainable production.
Key linkages, interdisciplinarity & collaboration The unique value of this RD is its integrative approach, bringing together research across the MRPs, themes and EU networks to develop a whole-systems solution to achieving sustainable production. Active working links: WP1.1 soil function, WP1.2. water management, WP1.3. biodiversity impacts, and Hutton theme SNC, WP2.1 Sensors, IPM and novel crops/systems, and Hutton theme WPD, WP2.2 livestock genetic improvement, livestock health, disease mechanisms, welfare assessment, GHG reductions from livestock, WP2.3 soil management, GHG emissions, animal productivity, agroecological approaches, trade-offs, big data, uptake of best practice and Hutton theme Sustainable Production Systems, WP3.1 impacts on crop quality and Hutton theme Enhancing Crop Productivity and Utilisation. Work in this RD will use data from our long running experiment on production, feed intake, health and

reproduction in the Langhill dairy herd. Collection and maintenance of these data are part funded via the SRUC Underpinning Capacity tender. The work outlined here will build on a wide range of existing research funded through RCUK (primarily BBSRC), HGCA and Potato Council (platforms for sustainable management), TSB (legumes and IPM research), H2020 (impact assessment and sustainable production practices), AgriTech and InnovateUK (soil health, end product use and quality) to achieve multiple benefits from agricultural land. The CSC platform is linked with the Defra Sustainable Intensification Platforms (16 sites including IBERS, Powellyn) and is a node in the EU ENDURE network with 14 partner organisations across the EU. It has already attracted £1,5M from EU and AHDB and this is set to continue and expand. Defra Platform project ACO115 will provide data for more novel approaches to sensor modalities and livestock monitoring. Along with RD2.3.11, links will also be made with The Centre for Agricultural Informatics and Sustainability Metrics (AIMS), including Rothamsted Research, University of Reading, Scotland's Rural College (SRUC) and the National Institute of Agricultural Botany (NIAB) to make use of shared data and expertise amongst stakeholders and apply 'smart analytics' (statistics, visualisation and modelling) to identify potential solutions for improving sustainability.

Added Scientific Value

The integration of research in this RD using a whole systems approach based on long-term platforms with direct links to the farming community is unique in Europe. We are linked with EU and UK networks including the ENDURE network, INRA Long term experiments (LTEs), Bioforsk, Rothamsted and Defra-funded long term platforms (SIP). Complementary approaches adopted across such networks provide added scientific value in terms of the ability to generalise and extrapolate findings to the UK and Europe. In addition, this RD will generate specific, practical applications for the farming industry, providing opportunities for industrial collaborations and funding. For example, a rapid and cost-effective soil assessment for land managers, soil surveyors and citizen science proponents. Additional methodologies underpinning animal and crop monitoring will be transferrable to commercial development and subsequent exploitation. Open access, web based databases will also provide opportunity for national and international collaborations (e.g. through AIMS), particularly where this work links with long-term platforms and datasets provided by Underpinning Capacity.

KE, Audiences and Impact

A stakeholder group will be established at the outset of this RD in collaboration with RD2.3.11, with representatives from the farming community (farmers from Hutton's existing East of Scotland Farm Network, and advisors from SRUC and the AICC), NFUS livestock group, QMS, policy groups (SNH), environmental conservation (LEAF, BCT) and research (MRP scientists from linked RDs and key contacts at networked sites including Rothamsted, INRA, IBERS). An initial workshop will be organised jointly with RD2.3.11 to set out the objectives and approach and gather feedback from across all stakeholder groups on desired outcomes. This will be followed with annual newsletters and biennual workshops to provide feedback and gain judgement on progress. A mid-term MRP workshop will be run with RD1.3.3 (Resilience and Biodiversity) to explore commonalities in resilience and sustainability between managed and natural/vulnerable systems. KE demonstration sites will also be established based at existing long-term platforms. These sites will be the focus for visits by stakeholders including the general public, scientists, industry representatives and policy makers and will link with activities organised through the KE centre.

- **International science community**: Conferences and peer-reviewed publications/review articles: SUM, Agric Ecosys Environ, Int J Sust, Weed Res, Animal, J. Dairy Sci., Biosystems Engineering, Intecol, WAAVP, British Society of Animal Science, European Federation of Animal Production (EAAP); Site visits and scientific workshops (e.g. NASSTEC, AAB); Web based data centre for accessing long-term datasets and information.
- **Industry:** Prototype animal monitoring systems; Mobile phone apps and software for free download (Android and Apple); Site visits and workshops for farmers and agronomist consultants (through the AICC and East of Scotland Network) to introduce the IFM for feedback and to present results/review progress; Stakeholder engagement events (Potatoes in Practice, Cereals in Practice and LEAF Technical days, Hutton and SRUC open days, exchange of visits with Monitor Farms).
- **Policy groups:** Technical leaflets and advisory notes to be published via the website; Workshop and site demonstration for policy advisors.

RESEARCH DELIVERABLE NUMBER:
Work planning and timetable for Year 1: (M= Milestone; KE= KE output; R= reporting to RESAS)

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Candidate bovine EID options selected and tested on animals at a pilot level using commercially available readers.										M1		
O1.3i Integrate milk MIR based predictors of immune/health function with genomic data to examine the genomics of response to different disease and treatments in a research herd of dairy cattle.												M4
O1.3ii Examine the genetics of the extent and recovery of negative energy balance.												M5
O2.1 Experiment using the Greencow facility to verify the accuracy and temporal performance of the measurement systems developed in collaboration with CENSIS.												M7
O2.2 Experiment to capture individual animal variability using tri-plane accelerometry sensors mounted at different positions on the animal.												M9
O2.3 Validate a decision support system to target anthelmintic use in lambs using data collated from previous studies on a range of farms and with different breeds.									M12			
O3.1i. Review of sustainable management options for arable crop production that have the potential to benefit the environment whilst								M14				

maintaining crop yields.												
O3.1ii. Prioritise management options for incorporation into a new IMS and publish review											**M15**	
O3.2i Identify a suite of key indicators of arable ecosystem function and sustainability, following from CWP1.1 and EU (AMIGA) and UC				**M16**								
O3.2ii Develop soil monitoring models linking smartphone imagery/location and soil nutrient and physical characteristics (carbon, nitrogen, bulk density, texture, structure etc.). A library of visible-range hyperspectral signatures for soil samples will be generated and used to produce a calibration model for soil chemical parameters.												**M17**
O3.3 Parameterize the multi-criteria, hierarchical decision tree based on DEXi that combines qualitative and quantitative data into a single modelling framework to assess the impact of changes in cropping systems or management practices.								**M19**				
O4.1 Design an open access web based SQL database to be populated with data and information on key indicators at the CSC												**M21**
KE Events: Stakeholder workshop						**KE1**						
KE Events: Potatoes in Practice					**KE2**							
KE Events: Cereals in practice			**KE3**									
KE Events: LEAF Technical day			**KE4**									
KE Events: Moredun Foundation								**KE5**				

Roadshow												
Annual Report (Year 1)												**R1**

RESEARCH DELIVERABLE NUMBER:

Work planning and timetable for Year 2: Please include major milestones, (key research activities, deliverables, KE/impact events) and their timing.

Year 2: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Convenience and efficiency of read (or write as appropriate) performance will be monitored, and results used to develop practical implementations.												**M2**
O1.2 The outputs from D1.1 and case studies in O2 will provide a multiple data stream linked to individual animals. Data handling and processing techniques will be identified that are best aligned to these outputs. Data handling, decision support and processing techniques will be examined.												**M3**
O1.3 Integration of MIR and genetic information in animal management programmes with industrial partners.												**M6**
O2.1 Outdoor grazing trial in conjunction with RD2.3.7 to test feasibility of proxyrecording mechanisms for estimating methane emissions.										**M8**		
O2.2i Validate the approach in data synthesis/analysis from different sensor modalities in more accurately reporting physiologically important events (e.g. dystocia risk												**M10**

and parturition)												
O2.2ii Pilot study to capture individual animal milk parameters and examine the feasibility of trace biomarker detection and data fusion												**M11**
O2.3 Define optimal treatment thresholds under a range of farming conditions									**M13**			
O3.2 Development of soil monitoring apps and tools. Based on work in Year 1, these apps will incorporate datasets and calibration models, and will allow rapid soil characterisation in the field. The technology used for this monitoring will cover smartphones and low-cost visible-range spectroscopy devices.												**M18**
O4.1i Incorporate the new management options identified in O3 into the sustainable treatment, and apply across all 6 fields/crops at the CSC. Apply monitoring apps from O3 and collate data on key indicators from UC to populate database and parameterise DEXiPM model in year 3.												**M20**
D4.1ii Continue development of web based database and populate with year 1 data												**M21**
D4.2i Apply IMS options at the ENDURE rotation and monitor key									**M22**			

indicators for data to parameterise the DEXiPM model in year 3												
KE Events: Potatoes in Practice					**KE6**							
KE Events: Cereals in Practice			**KE7**									
KE Events: Stakeholder feedback											**KE8**	
KE Events: Develop web material and leaflets										**KE9**		
KE Events: stakeholder meetings to present and review smartphone-based soil monitoring systems						**KE10**					**KE11**	
Annual report (year 2)												**R2**

Name of RD: 2.3.10 - Using and sharing data across supply chains

Research aim and key drivers

This RD will involve the development of tools and strategies to promote the increased use of data from across agricultural supply chains and industry networks, for management and feedback in order to improve efficiency across the industry. We will focus on developing methodologies to help quantify and communicate the uncertainties resulting from pooling data across the supply chain which will be then extended into particular case studies building on links with RDs 2.3.9 & 2.4.1 (barley) and WP2.2 & 2.4 (beef supply chains) later in the Strategic Research Programme (SRP). Through industry dialogue we have identified that work related to the beef supply chain will be an initial focus. This will link to other work in the SRP and external projects on the improvement (genetic and management) of efficiencies of production along the entirety of the beef supply chain. We will work with the beef industry to identify data that could be shared across the supply chain (public and private sources) and the potential benefits in doing so. We will also work with the barley industry (which is also relevant to the beef industry), by linking with the Home Grown Cereals Association (HGCA) on focusing improvement of business opportunities by providing tools to measure and interpret the impacts of climate change on barley production and quality for both animal and industrial purposes.

Summary of the proposal: (Numbering system for deliverables relates to Gantt charts listing (sub-)Objectives (O#.#), Deliverables (D#) and KE/impact events (KE#), M# Milestone, Y# Year).

O1: Exploring cattle supply chain efficiencies using a big data approach to supply chain data

Via holistic integrated data mining, this project will generate information and tools to improve efficiencies of supply of beef to abattoirs, and identify novel approaches to monitor the supply and wastage profiles. By studying the pattern and consistency of supply of beef and wastage (e.g., carcass condemnation causes, individual killing out %) the project will identify critical control points in supply chains (e.g., weather influences, weak points in integrated chains) across time. Novel data integration and mining will compare and contrast efficiencies that can be achieved through different management and integration actions in the beef supply chain (i.e., dairy beef vs dedicated sucker beef production). The results will enable supply chain participants, from farmer to processor, to improve profitability, breeding, animal health and beef production efficiency overall. This will build on external linkages with major abattoirs and cattle product supply chains on analysing condemnations.

O2: Methodologies for analysis of automated sensor data on organisms and the environment and animal movement data

Sensor data can be used to automatically measure a wide range of metrics (including location, speed, acceleration, temperature and altitude) and are rapidly becoming an essential tool in answering key questions relating to biology, agriculture and the environmental sciences. Automated sensors tend to produce large quantities of high frequency data. These data typically have a complex spatio-temporal structure, and novel statistical approaches to the design and analysis of sensor data will therefore be developed. This work is linked to BioSS strategic development area “DAMOE” (Data for the automated monitoring of organisms and the environment), and the methodology developed here will also be relevant to the analysis of data coming from

2.3.9. This research is primarily methodological, and will therefore also be relevant to range of other research deliverables, including those that relate to quite different areas of application (such as water quality, 1.2.2, and animal behaviour, 2.3.7). In addition a valuable source of data relevant to the supply chain is that describing the movement (trading) of livestock e.g. from the cattle tracing system (CTS). Current methods of analysis for such data are relatively crude e.g. based on using particular sequences of trades or on summary statistics based on trades with a given period. Here we will explore the potential to utilise more statistically rigorous approaches developed in RD2.2.3 (**HEI bid 4)**. Fitting dynamic models to the CTS data will provide valuable information to inform the development of disease control strategies and models in RD2.3.3 and RD2.2.6 which seek to take into account such aspects of the supply chain. We also intend to explore its potential to inform analysis of the value chain or more correctly value network, being conducted in RD2.4.1. If successful the approach could be applied/adapted to other data and systems currently analysed as static or dynamic networks.

O3: Modelling the resilience to extreme events of barley

The major activity of this objective will be to use a soil-crop-atmosphere model to study the impacts of weather and climate on barley production and quality. The model will run using a data-intensive input from gridded soil and weather information of the agricultural land in Scotland. A crop simulation model can quantify the interaction between multiple stresses and crop growth under different environmental and management conditions. We will simulate barley production using historical and projected weather data to understand the response of barley under extreme events and under change in climate. The results of this SD will be shared with stakeholders such as the HGCA, and policy-makers to provide useful information regarding the improvement of business opportunities by developing tools from the simulated results that will help to measure and interpret the impacts of climate change on barley production and quality.

Technical approach

O1: Exploring cattle supply chain efficiencies using a big data approach to supply chain data

This project will generate knowledge that will help beef supply chains monitor and manage the supply profile and reduce wastage - actual carcass losses and efficiency losses across the chain. By mining a range of supply chain data, from within the farm gate to the abattoir, we will be able to identify signals that can be used to improve the resource efficiency and resilience of the beef supply chain. We will use multivariate data acquisition to link information on carcasses (weights, condemnation causes) back to environmental data and primary production information, where available. The Main research Providers (MRPs) have projects that utilise both public and private data including linking national animal records to individual farm and carcass information, with all appropriate data agreements, protection and storage in place. We are therefore confident that we can obtain access to sufficient data to develop the proof of concept presented here in. The extrapolation to wider industries and other supply chains will be discussed with industry stakeholders and the Beef Efficiency Scheme Stakeholder group (RD2.2.1). We will collate data, where available, and analyse data from defined beef supply chains (e.g., dairy crosses, veal production systems, suckler beef-finisher systems). Whilst part of this data has been previously analysed to produce statistics etc. no other project has encompassed such an extensive subject scope or used the same methods to gather the data effectively. Using statistical modelling of the supply chain, from farm to factory, will help identify key critical control points in the supply chain and therefore help to manage supply chain fluctuations. We will do this initially by focussing on the case study on sharing data across the supply chain to improve animal health and reduce waste at abattoirs. Of cattle sent for slaughter at abattoirs across Britain in 2013, 24% had their livers condemned as a result of liver fluke (Food Standards Agency, 2014), a rise of 5% compared with 19% in 2012. Most cattle with fluke achieve target weights and show no ill health, but the infestation is considered important because of financial losses to the industry as animals take a longer time to finish (i.e., reduced daily live weight gain). If successful this work will help provide information to the supply chain to breed for lower incidence of disease and less waste.

Detailed work plan

This work, over the five years of the programme will be co-designed with the beef supply chain stakeholder group that will be established to help inform work and engage in the value of sharing data (this group will advise a portfolio of beef supply chain work sitting across WPs). We will initially focus on a case study around the benefit of sharing data along the beef supply chain to reduce condemnations and improve efficiency. There will be three parts to the study.

O1.1. Identify causes of variability in carcasses (including condemnations) based on abattoir and linked production chain data including (i) previous environmental conditions experienced by the animal (e.g., weather and/or remotely monitored environmental conditions, extreme weather events, drug treatments/health management where available); (ii) farm/finishing system type variation; (iii) genetic variability in sires for carcass finishing time and/or quality metrics and causes of condemnations in offspring and (ii) relationship with production efficiency and carcass attributes (weight, conformation, fat and killing out % if available). (Y1, **D1**)

O1.2. Identify critical control points for different causes of condemnation to help understand the risk and therefore forecast level of condemnations in beef chains and the effect on beef supply. (Y2, **D2**)

O1.3. Economic and environmental analysis of beef supply from animals of differing carcass types and condemnation fates to quantify the costs (economic and environmental) of condemnation in the beef supply chain. (Y2, **D3**)

O1.4 Further aspects of beef supply chain modelling driven by data science methodologies developed elsewhere and identified with beef improvement stakeholder group (linked to 2.2.1, **KE1**) will take place Y3+

O2: Methodologies for the design and analysis of automated sensor data on organisms and the environment

Automated sensor data are becoming increasingly widely used in disciplines such as agricultural science, hydrology and ecology. Sensor data tend to be relatively quick and cheap to collect (compared to more traditional data collection), but, because of their size and the complexity of their structure, relatively time-consuming and challenging to analyse. The fundamental types of statistical model that can be used to analyse sensor data are similar to those that can be used to analyse other time series data and spatio-temporal data; autoregressive models, hidden Markov models (or their continuous-time analogues), and state space models can all provide natural frameworks for the analysis of sensor data. There are substantial computational and statistical challenges in actually applying these models to substantive real datasets. The computational challenges are directly related to the size of the datasets, whilst the statistical challenges relate to the complexity of the structure (e.g. high-resolution multivariate data, complex patterns of missing data and correlated observation errors). There are also statistical challenges relating to aspects other than modelling: how to pre-process the data in a way that properly accounts for uncertainty, and how to design sensor-based studies in an optimal way (e.g. how to choose the optimal sampling frequency to use when collecting GPS data). This work will aim to identify and address some of the key methodological gaps that exist in relation to the types of sensor data that will be collected within the RDs: i.e. to identify those areas where the existing methodology is inadequate to deal with these types of data, or areas where the choice of method is unclear and requires further study. This will allow the value of sensor-based data to be fully exploited.

Data on the movement of animals between farms is an important example of network type data. However, in this case it is particularly clear that these data are generated by a dynamic process and therefore it is appropriate to model them as such but this is not done typically at present. Here we propose to fit dynamic models of animal movement, in the context of national scale modelling of livestock disease, using CTS data (linked RD2.3.3 and potentially O1). Initially we will fit simple homogeneous models assuming the data are complete and then consider progressive levels of heterogeneity e.g. covariates describing different farm types, hierarchical models describing individual-level variations and methods to account for incomplete and noisy data.

Detailed work plan

O2.1 identification of relevant datasets, from both this RD and from other RDs that can be used as case studies when comparing and developing methodologies (**D4,** Y1). This will be accompanied by a literature review of existing methods for design and analysing studies that involve sensor data, and the implementation of key existing methods within the statistical programming environment (**D6**, Y1).

O2.2 The methods will be compared and evaluated, using both simulated data and real data relating to the selected case studies, and these comparisons will be used to produce guidelines which outline good practice for the design and analysis of studies that use sensor data. We will develop inference procedures for simple dynamic network models based on complete and incomplete data and test these using simulated data. CTS data will be used to fit such models assuming these data are complete (**D6,** Y2).

O2.3 These guidelines are likely to highlight at least some areas in which existing statistical methods are inadequate to deal with the characteristics of the sensor data being collected within the RDs, and the next stage of work will therefore move on to the development of new methodologies – these may either be new models, or they may be new methods for designing or pre-processing sensor-based studies, depending on the key gaps in existing methodology and on the requirements of the RDs that will make use of the methods. (Y3-5).

O3: Modelling the resilience to extreme events in barley

The amount of data needed to run the model will be significant; detailed information on soil such as chemical and physical properties (e.g. clay, silt and sand content, soil organic carbon, soil nitrogen, bulk density and so on at different soil depths), daily weather data (minimum and maximum temperature, solar radiation, and

precipitation), crop management information (e.g. sowing date, fertilisation date and timing, and so on), and crop genetic coefficients (parameters that describe different cultivars in terms of sensitivities to photoperiod and vernalization, leaf appearance rate, and potential grain growth rates are needed as model inputs.
The model will be calibrated using variety trials information. The variety trials are experiments were cultivars are grown without water and nitrogen stress, and by minimizing pest and disease. In this case, yield will be close to its potential optimum. The crop model will be run against these data to parameterize the crop coefficients using two variety trials, one from north and the other from south Scotland, the data are available on the HGCA online database. Then, the crop model will be evaluated using the data from the Balruderry experimental farm (linkage with RD2.3.9). The model will be evaluated on the ability to predict flowering time, maturity time, grain yield, grain protein, and crop biomass. Several indices will be used to compare the crop model performance against similar studies in the literature; the indices are the Root Mean Square Error (RMSE), the Relative Error (RE), and the D-Index. Then, the model will be run on the entire barley-production area of Scotland using the SKIB soil-database. This database has all the information needed to parameterize the soil component of the crop model, but the data need to be formatted into the standards used by the crop model. Programming software like R will be used to facilitate this task. The gridded daily weather data will be provided by the MetOffice, and crop management data inputs and feedback from the work in RD2.3.9 in addition to existing agronomic databases. Projected weather patterns (in the next 20 and 50 years) will be used along with historical weather data to understand the past, current and future weather anomalies and extreme events that can affect barley production and quality. Projected climate data will be obtained from many Global Circulation Models (GCMs) and the ensemble of these models will be used following the methodology currently in the wide scientific community. The GCM outputs will be downscaled at the level of resolution needed by using available computer programs (e.g. Clymsystem).

Detailed work plan
The first year of the project the data will be collected, analysed for outliers, quality-checked and re-formatted for use as inputs in the crop model.
Between the end of year one and beginning of the second year the model will be calibrated and evaluated **(D7)**. During the second year the data for the large-scale runs will be put into the model which will be run again for the whole of Scotland **(D8)**. Since this is going to be a large data input for the model, it will take a few months to run for the baseline (historical simulations). It is expected that by mid/end of the second year the model runs will be completed. They will be checked for their quality and the data will be analysed for understanding the effects of climate extremes on barley production under baseline conditions. This part will take part in year three mainly. The work in year four will be concentrated mainly in running future projections, and at the end of these simulations, the data will be checked and analysed. The last year will be used to write scientific articles aiming for high-quality publications. Stakeholder interactions will take place throughout the 5 years. For example, the results at the end of the first year will be presented to key stakeholders (e.g. the HGCA, policy-makers) and this interaction will be inform the work for the following years. There are opportunities to extend the work here through external grants (e.g. HGCA strategic plan has a clear indication about studies on the impacts of future climate on crop production). The results at the end of the five years will be

also shared with the stakeholders and policy-makers for further discussion and implication for Scottish agriculture.

Expertise

The analysis of sensor data is an emerging data of methodological research within BioSS, but the organisation already has a track record of working in projects involving the analysis of GPS data, accelerometry data and IceTag data, and has contributed to a major project to assess the use of electronic tagging in monitoring livestock movement. BioSS has also been extensively involved in the development of methodologies for spatio-temporal data, including hidden Markov models, which are crucially important for the analysis of sensor data and continuous time Markov process which are used in modelling the spread of disease and have great potential to describe network phenomena.

SRUC has extensive expertise in Livestock Informatics to improve health, welfare and fitness-related traits in domestic species, improving the economic value and quality of livestock products and exploiting developing technologies (e.g., bio-markers, big data, sensors, genomics) in farm animal breeding and day-to-day farm management decision making. Through the delivery of national genetic evaluations for dairy cattle, beef cattle and sheep (Edinburgh Genetic Evaluations Services, EGENES) we have expertise in the development of databases, recording protocols and wide experience in the development and maintenance of databases to manage the huge array of data required for national evaluations from multiple sources (including BCMS).

Hutton will contribute expertise in agronomy, crop and soil sciences; application and development of crop models, precision agriculture, remote sensing and GIS application to natural resources management, environmental science, climate change and climate forecasts in agriculture.

Key linkages, interdisciplinarity & collaboration

The statistical methods that are being developed for the analysis of sensor data will also be applicable to work being undertaken within other areas of the programme, including RDs 2.3.7 and 2.3.9, and are likely to exploit related methodological work being undertaken in RD 1.2.2. Methods for the analysis of cattle movement data have direct relevance to work designed to develop improved control strategies for disease in RD2.3.3 and RD2.2.6. In addition, these methods have the potential to inform analysis of the value chain/network in RD2.4.1 and contribute to the analysis of other network data.

Work here will link to beef genetic improvement work (RDs 2.2.1 & 2.3.1), the proposed SRDP Beef Efficiency Scheme and the recently-announced AgriTech Agricultural Informatics Innovation Centre (AgriMetrics Ltd. - SRUC are one of the core academic partners and JHI and BioSS are part of the Network of Excellence). The linkages with AgriMetrics will also be used to advise on data integration and archiving as well as providing linkages to a wider network of scientists and industry stakeholders.

O1 (Beef supply chains) will build on collaborations with industry stakeholders to allow us access to private data such as condemnation data and slaughter information. We have already implemented data models for the transfer of data from private sources to help drive such research activity that links with to wider industry public and private data. We will use these previous models to define the data flow

and privacy requirements, archiving and output management. This will be delivered through regular meetings/updates with the stakeholders involved (**KE1**). **O3** (Barley simulation) will focus on developing crop simulation models (which simulates daily interactions between soil-plant-atmosphere) that are dynamic process-based models and making them generic enough to be applied in a wide range of situations given the site-specific inputs of soil, weather, management, and cultivar and build on the knowledge/outputs from well-established and accurate models that exist. The international efforts in this field go towards model improvements and multi-model assessments and we aim to achieve higher scientific impact using multi-model simulation of barley rather than developing a new model *per se*.
Added Scientific Value The development of statistical methodologies for analysing and designing sensor data will allow such datasets to be fully exploited, and will help to maximise cost-effectiveness of studies which use these data. They will also ensure that the uncertainties associated with the sensor data are properly quantified, and that the limitations and caveats associated with these forms of data are properly understood and accounted for. Methods for the analysis of cattle movement data have direct relevance to work designed to develop improved control strategies for disease in RD2.3.3 and RD2.2.6. In addition these methods have the potential to inform analysis of the value chain/network in RD2.4.1 and contribute to the analysis of other network data.
KE, Audiences and Impact In preparing the work package a 1 page summary of each RD was circulated to a wide range of policy and industry stakeholders and general feedback incorporated. We received favourable feedback on this RD from industry stakeholders from the beef and barley supply chains and willingness to participate in the proposed activities. Policy stakeholders identified wider national benefits that could be derived from sharing and analysis of supply chain data. For example, we will liaise with bodies/agencies such as Zero Waste Scotland for added value and input to our proposed work. The proposed work on livestock product chains will interact with an industry stakeholder group to both help secure data and guide how the data are mined. This will link across WPs to help strengthen the social and economic science input to the work with an initial focus on the beef supply chain in Scotland (discussions have taken place with SG (agriculture and animal health) policy stakeholders, QMS, beef breed societies) linking across WP 2.2 (Animal Production and Health), 2.3 (Agricultural Systems) and WP2.4 (Rural Economy). We plan to engage with AgriMetrics highlight planned work and results as they arise to engage a wider industry and scientific stakeholder community.

RESEARCH DELIVERABLE NUMBER: 2.3.10
Work planning and timetable for Year 1: Major milestones (M#) for key research (sub-)objectives, (O#.#) identifying deliverables (D#), KE/impact events (KE#), and their timing.

Year 1: 2016/17	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
O1.1 Beef supply chains Integrate and model beef supply chain data for carcass variability and losses in abattoir							**M1**					**D1**
O2.1 Sensor data Identification of relevant datasets in this/other WP												**D4**
O3.1 Barley Simulation Data collection, formatting, input in the model												**M2**
O1 Beef supply chains Beef supply chain stakeholder group to discuss data sharing and proposed data mining		**KE1**	**KE1**									**KE1**
Annual Progress Report												**R1**

RESEARCH DELIVERABLE NUMBER: 2.3.10
Work planning and timetable for Year 2: Major milestones (M#) for key research (sub-)objectives, (O#.#) identifying deliverables (D#), KE/impact events (KE#), and their timing.

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.2 Beef Supply Chains Critical Control Points for forecasting in the beef supply chains								M6				D2
O2.2 Sensor Data Review of methods for analysis of automated sensor data							M3					D5
O2.3 Sensor Data Develop and fit prototype models to animal movement data							M4					D6
O3.1 Barley Simulation Data collection, model calibration and evaluation.		D7						M7				D8
O1 Beef Supply Chains Analyse costs associated with different efficiencies and losses in supply chains and discuss with industry partners							M5				D3	KE1
Annual Progress Report												R2

Name of RD: 2.3.11: Trade-offs between productivity and sustainability

Research aim and key drivers

This research will examine the balance between potentially competing outcomes associated with agriculture in Scotland. Higher yields to meet increasing global demand for food must be balanced by considerations of the wider impacts of farming. Ways must be found to balance farm performance to achieve profits while promoting animal health/welfare, protection of the environment, the nature/amenity value of the countryside and the interests of future generations. By detailed research on major crop and livestock systems guided by our stakeholders, we will examine the relationships involved and draw conclusions that help farmers. adapt/improve.

Summary of the proposal:

Hill farming and arable farming represent dramatic production contrasts within radically different environmental conditions. Both seek to be productive and support livelihoods, now and into the future, through the development of socially, economically and environmentally sustainable practices. In this RD, research on these two significant systems will be developed in parallel; first identifying system specific trade-offs in productivity and environmental sustainability, while also establishing general features in trade-off behaviour that are common to both agricultural systems. In tackling these systems, the research will help address a substantial component of the Scottish agricultural sector while, with links to other RDs, supporting the development of a comprehensive interdisciplinary research base capable of extending the systems approach to other aspects of Scotland's agriculture and land use.

Objective 1: Trade-offs in livestock systems

There is a need to understand how best to improve the production, economic and wider environmental resilience and sustainability of upland sheep systems (especially as these cover over 60% of farmed land in Scotland). This project will establish two alternative Precision Livestock Farming (PLF)-based upland sheep systems at SRUC's Hill & Mountain Research Centre and subsequently compare and contrast the overall sustainability of the systems. Sustainability metrics to be assessed will include a focus on environmental implications (e.g. above and below ground carbon sequestration; GHG emissions; vegetation, invertebrate and bird biodiversity; use and importation of nutrients and feed from on- and off-farm sources) and animal health and welfare implications (e.g. longevity of livestock; incidence of diseases; body condition scores; lamb survivability; abnormal behaviour) as much as on more traditional productivity and economic metrics. This will provide the evidence base required for understanding the trade-offs involved in making upland livestock systems more resilient to economic and climatic shocks. This will then provide the platform for systems models and analytical frameworks to underpin the decision support/KE needed to encourage uptake and impact in later years of the programme (see linkages). Aspects of this proposed research have been discussed with colleagues in NFUS, Quality Meat Scotland, National Sheep Association, SEPA, SNH, Loch Lomond & Trossachs National Park and members of SRUC's Kirkton & Auchtertyre Farming & Industry Advisory Group.

Deliverables:

D1.1 Report on trade-offs associated with parasite control in alternative extensive sheep grazing systems.

D1.2 Report on trade-offs between production, economics, animal health and welfare, environment and biodiversity in extensive livestock systems.

Objective 2: Trade-offs in arable systems

Intensification of arable production since the early 1970s has tended to maximise commercial off-take but to the detriment (it is now known) of supporting and regulating services. Continuing to maximise inputs and off-take is not sustainable, since supporting services will begin to limit yield, however high the inputs. A more balanced strategy is now needed. In O2 we will use extensive existing data on the performance of crops and their management to explore trade-offs in short-term productivity with longer-term economic and environmental sustainability and to identify the optimal combination of crops and the management of those crops for future arable production.

Productivity, environmental impact and management data from the survey of 100+ fields of the East of Scotland Farm Network (2007, 2008, 2014) will provide detailed information on key indicators of the arable crop performance across a range of intensity scenarios, i.e. conventional, integrated and organic (O2a). A multi-criteria decision analysis of the data will evaluate the performance of each crop in response to the management strategies deployed and so establish trade-offs between productivity and sustainability for the major crop types by considering the balance in financial costs, environmental impact, biodiversity and ecosystem services. We will also explore crop choice (O2b) and seek to identify optimally-performing crop sequences that account for the trade-offs across productivity and sustainability criteria.

Deliverables:

D2.1: Crop Performance Database. M12

D2.2: Comparison of productivity/sustainability performance of existing crop management strategies. M24

D2.3: Optimal cropping strategies designed to maximise the productivity and sustainability performance of crop sequences based on East of Scotland Farm Network data. M24

Objective 3: Sub-system trade-offs

This desk study will address two sub-systems. The first complements O1 and other studies across the programme by exploring in-depth the economic and environmental trade-offs associated with protein supplementation in animal diets. It makes use of a large number of studies carried out over the last 17 years at SRUC to establish sustainable levels of protein supplementation. In particular, it will help us explore the trade-offs associated with parasitism in sheep grazing systems (D1.1) as protein nutrition provides a link between animal health/ welfare, grazing/feed management and environmental impact of production systems. The second makes use of RD 2.2.8 output on laying hens, where performance and economic data on housing and feather pecking management will be gathered. Data will be used to assess whether novel approaches results in trade-offs or win-win situations.

Deliverables:

D3.1: Data gathering (M12)

D3.2: Methodology establishment (M24)

The Gantt chart below covers years 1 and 2. All deliverables above start in years 1 or 2. However, collection and collation of empirical data will form the primary focus for years 1-3 and the focus will shift in years 3-5 onto more detailed analyses and modelling of the trade-offs under investigation.

Technical approach

Detailed work plan

O 1: Trade-offs in livestock systems

This work is focused on SRUC's Kirkton & Auchtertyre upland research farms where it is feasible to split our Kirkton farm combined flock of Scottish Blackface and Lleyn ewes between two alternative systems, each system making more or less use of in-bye, semi-improved and hill grazings as well as more or less use of home-grown or bought in feed and different finishing systems.

Both systems will incorporate best practice Precision Livestock Farming approaches that have been investigated and evaluated in the current programme of RESAS funded research (such as the Targeted Selective Treatment (TST) of lambs, and ewe breeding selection). This implementation at flock level will also be a direct extension of the current RESAS programme work on the barriers to technology (EID) uptake, as well as the work concerning trade-off issues linked to farm labour and implementation of EID technology for upland sheep management. The planned work will extend the evaluation of different genotypes (genetically improved Scottish Blackface, unimproved Scottish Blackface, Lleyn) under different management systems, by responding to stakeholders suggestions to compare between-breed or within-breed selection under management systems typical of different hill-farming areas of Scotland. The proposal also builds on on-going collaboration between Moredun and SRUC trialling the TST approach in upland flocks. This new study provides the foundation to extend the testing of the TST approach to different farming conditions. It is the vital next step to determine the applicability of the TST approach and associated decision support systems to other farms, allowing us to give best practice advice for optimised liveweight gain and sustainable parasite control with the lowest environmental impact.

The SRUC input focuses particularly on assessing trade-offs within each system and their implications for management. This will highlight differences between systems needed to balance these trade-offs in pursuit of more productive yet sustainable land use. Key sustainability metrics will be: environmental implications (e.g. above and below ground carbon sequestration; GHG emissions; vegetation, invertebrate and bird biodiversity; use and importation of nutrients and feed from on- and off-farm sources; etc.); pedigree and production data (numbers of lambs, weights of ewes and lambs, carcass quality via ultrasound and/or slaughter data, maternal traits etc.); grassland and hill pasture management requirements (e.g. quantity, cost and timing of input requirements); livestock spatial utilisation of the grazing resource and impacts on grazing resource biomass availability and productivity; animal health and welfare (e.g. longevity of livestock; incidence of diseases; body condition scores; lamb survivability; abnormal behaviour; etc.); economic and labour implications. Precision Livestock Farming (PLF) approaches will be further developed and utilised in both systems both to facilitate the research and to explore pathways to impact through the demonstration and use of PLF in commercial practice. The systems work also provides a platform for data collection by Moredun and sharing across other elements of the RESAS programme (see linkages section).

This research platform will provide a detailed database of sheep production, health, welfare and environmental impacts for two important UK sheep breeds in two contrasting upland management systems. This will allow us to assess the economic resilience of both systems and construct trade-off matrices to allow an assessment of the associated impacts and outcomes across the range of metrics under investigation. These are essential to allow us to assess which system (or variants) may be most relevant for farmers and land managers with different motivations and circumstances.

O 2: Trade-offs in arable systems

O2a: Optimising crop management

Initial analysis will be based on existing information on the productivity and environmental impact of crop types cultivated in the East of Scotland using data collated from earlier surveys of the East of Scotland Farm Network (2007, 2008, 2014). This provides a stratified sample of 114 field sites from 59 farms providing data that are representative of the range of conditions and practices of the Scottish arable production system. The productivity and environmental criteria, and associated indicators developed in current RESAS WPs 3.4 and 1.1 will be used and the data organised into a newly developed Crop Performance Database. We will seek additional compatible data to add to the database and to develop a strategy for the ongoing management of the database as an open-data resource facilitated through AgriMetrics (Agri-Tech funded Centre for Agricultural Informatics and Metrics of Sustainability).

Data on the productivity and environmental impact of key arable crops will be obtained from the Crop Performance Database and combined with data on crop management from the East of Scotland Farm survey. Using these data, standard statistical approaches will be used to characterise the crop performance and provide crop specific productivity/sustainability performance measures, conditional on management intensity (conventional, integrated/LEAF, organic) and geographical region, and establish the response of these to the crop management practices.

Both the productivity/sustainability performance and its response to alternative management will be compared across intensity classes and used to quantify and rank Scottish crops on intensity and sustainability gradients which will inform subsequent tasks within this objective. These results will be cross-referenced with the comparable analysis between sustainable and conventional management treatments carried out on the CSC data (RD2.3.9). A DEXi multi-attribute decision model will be developed in parallel with RD2.3.9, though focused here on the detailed performance of individual crops, and tested by using it to compare the performance of existing management scenarios (e.g. conventional versus organic).

In subsequent years (years 3-5) analysis of the DEXi model will be extended to identify the management inputs that are required to produce *a priori* defined ‘ideal’ performance outcomes, and to identify optimal management inputs that maximise the crop performance across multiple productivity and sustainability objectives.

O2b: Optimising cropping strategies

A Monte-Carlo approach will be used to construct a large set of random crop sequences and estimate sequence level performance (productivity/sustainability), including uncertainty, by applying appropriate methods of aggregation to the individual, crop-level, performance estimates determined in O2a. Multi-objective optimisation methods will be applied to these data to identify the set of crop sequences that maximise performance across the productivity/sustainability spectrum conditional on farm type (conventional, integrated/LEAF, organic) and geographical region.

An additional approach to the construction of optimal crop sequences will also be pursued. A static-balance model for crop sequences will be built to calculate performance (productivity/sustainability) profiles for simulated crop sequences based on functional relationships between crop inputs and outputs, and the performance criteria that follow from these e.g. crop yield, net economic value, N_2O emissions, soil carbon, nutrient and pesticide leaching, and functional biodiversity measures. This approach allows novel crops and crop management not included within the Crop Performance Database to be considered; it will also facilitate the development of a farm or regional scale model in subsequent years (years 3-5). In years 3-5 the crop sequence model will be coupled with a multi-criteria optimisation procedure to generate sets of optimal cropping sequences. In addition, the model will be used to calculate performance profiles for selected crops sequences reflecting specific future scenarios, e.g. high short-term productivity versus long-term sustainability. These will be valuable for use with stakeholders to communicate the range of possible outcomes against which optimal sequences can be compared.

Both database- (year 1-2) and model- (year 3-5) derived optimal crop sequences will be analysed to identify the trade-offs and synergies that exist between the productivity/sustainability criteria. At this stage, a valuation/weighting exercise of the criteria will be carried out in partnership with stakeholders and “ideal” target values for relevant provisioning, supporting, regulating and cultural services defined. This information will be used to identify a subset of the optimal crop sequences that are preferred under alternative future scenarios.

GIS methods will be used throughout to assign the preferred optimal crop sequences to existing fields across Scotland, taking into account bio-physical and climatic constraints. This will allow cropping patterns and the associated performance criteria to be predicted and mapped for the preferred optimal scenarios. These will be compared with sub-optimal and existing scenarios to derive and map the opportunity costs that would result from failing to achieve the optimal scenarios.

O 3: Sub-system trade-offs

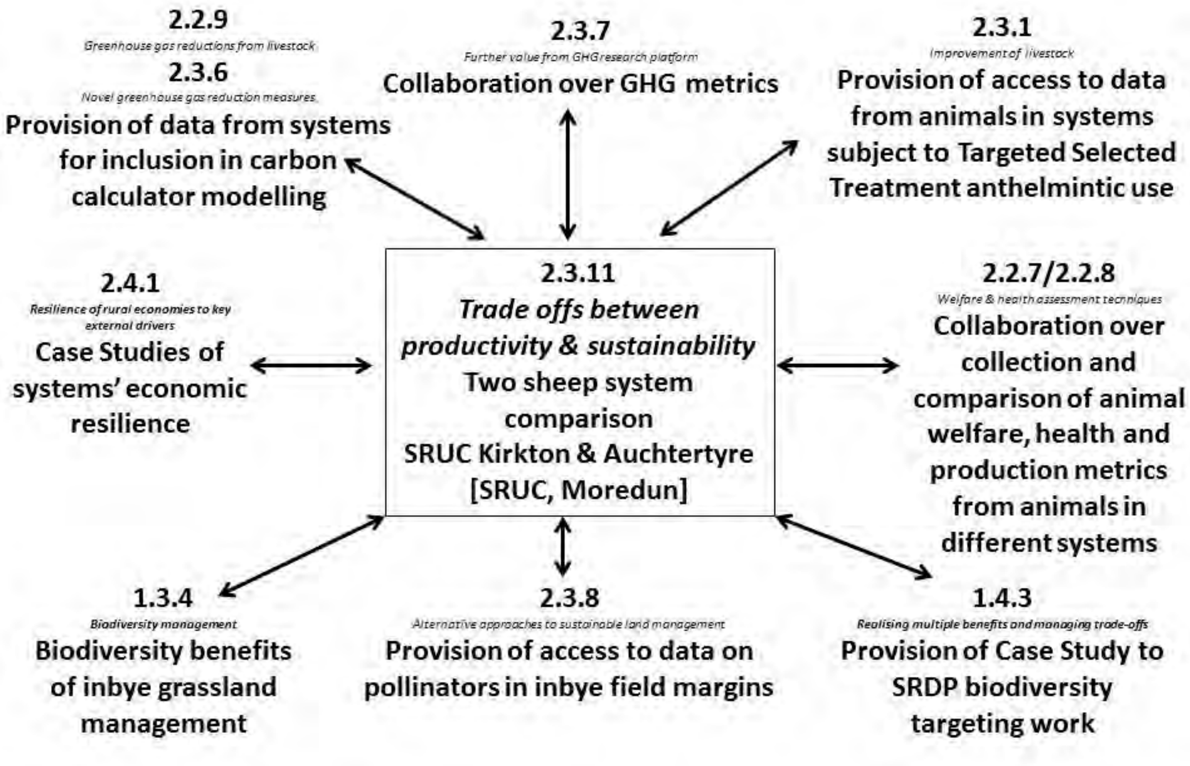
This work will make use of cross-species data on host responses to protein supplementation, both in terms of productivity and health. The first phase will be to determine the methodology, to compare outcomes between studies within species and across species. This will be achieved through literature review and interdisciplinary collaboration, and builds on from O 1 methodology in the absence of supplementation. The method will then be applied to data from more than 2000 animals, in order to estimate resource efficiency and environmental consequences, including impact on GHG intensity for lamb production through making use of existing literature, assumptions and empirical measurements derived from other RDs (e.g. RDs 2.2.9 and 2.3.6) to protein supplementation. Results will be interpreted with reference to the livestock systems study including productivity and parasitism. In collaboration with RD2.2.8, data on furnished cages, stocking density (single-vs multi-tier), egg and bird quality will be collected for detailed economic and resource efficiency evaluation. As above, the latter will include impact on GHG intensity for egg production, using existing literature on laying hen’s carbon footprints.

Key linkages, interdisciplinarity & collaboration

1. **RESAS Research**

Researching trade-offs requires many strong links on soils (RD1.1.1 (soil function), RD1.1.3 (soil and GHG emissions), RD1.1.4 (soil health)), biodiversity (RD1.3.1 (biodiversity and ecosystem function), RD1.3.5 (resilience and biodiversity), plant and animal health (RD2.1.4 (epidemiology), RD2.1.6 (IPM), RD2.1.7 (plant-soil-water interactions)), environmental impacts/GHG mitigation etc. (RD2.3.7 getting further value from the GHG research platform project and other related RD's see diagram below) and agricultural management practices (RD2.1.8 (novel crops), RD2.3.5 (integrated management systems) and RD2.2.8 (improved husbandry). RD2.3.11 will also share approaches and outcomes with other RDs (RD2.3.9 Integrated Management Systems, RD2.3.12 Uptake of best practice, RD3.2.3 Sustainable healthy diets, RD1.4.2 Identifying and understanding multiple benefits and trade-offs, RD1.4.3 Realising multiple benefits and managing trade-offs).

An example of some of the major trade-off linkages is provided below for the livestock systems work:



O1: Additional work in collaboration with Moredun will feed into other RDs across the programme. This collaboration will focus on two main areas: (a) a continuation of the current collaboration with Moredun over the application of the TST (Targeted Selected Treatment) approach to wormer use, and which will involve the animals under the RD2.3.11 systems forming a platform for further detailed investigation of the genetic and immunological basis of the response by individual animals to TST in the control of sheep gut parasites (to be conducted by Moredun colleagues within RD2.3.1) and the validation of the TST approach and development of farm specific thresholds (RD2.3.9). (b) data from both systems being used as a platform for detailed carbon calculations and greenhouse gas emission modelling (to be conducted by Moredun colleagues within both RD2.2.9 and RD2.3.6. Production data from on-going TST studies at Kirkton will be used to investigate the impact of gastrointestinal parasitism on the biological efficiency of grazing lambs and to inform the GHG modelling work within RDs 2.2.9 and 2.3.6, respectively).

The increased focus on assessing animal welfare trade-offs will be conducted in collaboration with SRUC animal welfare colleagues, and will build on work they are conducting within the current RESAS programme (and associated EU project) as well as the development and application of welfare assessment techniques being conducted in RD2.2.7.

Links to RD2.4.1 use this RD as a case study to assess the economic resilience of the two systems and adaptation to policy, economic and climatic driven shocks. Additional work in collaboration with Hutton will also utilise the two systems as platform for collaboration in two other areas of research (a) assessing the biodiversity (plant, insect pollinator and bird) benefits and productivity and economic trade-offs associated with incorporating more potentially biodiversity beneficial management of the margins of the in-bye fields under both systems (with a direct link to RDs 2.3.8 and 1.3.4), and (b) the wider farm and catchment within which the two systems sit will be incorporated as a case study into a largely desk-based assessment being undertaken within RD1.4.3 of (i) the ecosystem service implications at a landscape scale of different types and scale of habitat creation and management via agri-environment measures and (ii) potential barriers to farmers of implementing such measures at landscape scales (with a direct link to RD1.4.3). SRUC researchers also have extensive expertise in arable cropping and will utilise the long term SRUC crop data bases (included in AgriMetrics and RD2.1.6).

O2: The analysis of crop and crop system trade-offs will be carried out in parallel to work in RD1.4.3 (Objective b Potential for delivery of multiple benefits at a landscape scale) and RD2.3.8 (Alternative approaches to sustainable land management), which will consider the impact of other approaches (SRDP measures and agro-ecological management) on the performance of the lowland arable-grass system. Insight will be drawn from these where appropriate and incorporated into the farm or regional static balance models considered for years 3-5. Results from this RD (RD2.3.11) will also contribute directly to the analysis and implementation of an arable integrated management systems, specifically in terms of performance of existing crop management and by identifying optimal cropping sequences against which test systems may be calibrated.

2. National and International research networks:

RD2.3.11 will build on existing networks and collaborations to create synergies between this research and that of other groups working on trade-offs and other aspects of performance in farming systems. These include the Wageningen Centre for Agro-ecology and Systems Analysis (WaCASA), INRA, Aarhus University, and the Julius Kuhn Institute. These, and other international collaborations, are supported by involvement in a number of EU initiatives, e.g. C-IPM, Euphytica, ENDURE, EIP-Agri Focus Groups, EFSA working groups, and EU experimental farm platform group.

In addition, UK-based collaborations, with for example Rothamsted Research, Universities of Reading and Newcastle, and ADAS, will be facilitated by strong links with AgriMetrics, a BIS/Defra funded Centre for Agricultural Innovation, for which SRUC is a consortium partner and Hutton a member of the Network of Excellence. AgriMetrics will be a world-class agricultural ‘big data’ Centre with which RD2.3.11 will seek to work closely, both as a user and supplier of data, and to work with

stakeholders in the development of tools that support effective decision making leading to sustainable and productive agricultural practice.
Added Scientific Value **O1:** We will compare and contrast two alternative upland sheep grazing and finishing systems at SRUC's Kirkton & Auchtertyre research farms. Both systems will incorporate best practice Precision Livestock Farming approaches that have been investigated and evaluated in the current programme of RESAS funded research. SRUC are part of an INRA-led wider European consortium developing a Horizon 2020 *Sustainable Livestock Production* proposal within which the Scottish component would complement the proposed sheep-focussed RESAS research. **O2:** The research on crop productions systems will support efforts among EU collaborators in the application of the multi-attribute decision modelling tool, DEXi, to the analysis of crop production systems. The DEXi system has been used to assess IPM in multiple cropping systems (EU FP7 PURE, ENDURE) and is being extended to incorporate biodiversity impacts by Hutton and INRA (EU FP7 AMIGA); RD2.3.11 will make further contributions to the development of this tool by extending its application to all aspects of crop production systems. O2 will also add value to the East of Scotland Farm Network dataset and will be the first to assess its performance across multiple criteria. Opportunities will also be explored to apply the approaches applied within objective O2 to other farming systems and in particular to the extensive grass systems of Glensaugh and Hartwood Farms. **O3:** This desk study makes use of already published work, supported by a range of funding bodies, including Scottish Government, since 1998. It therefore adds great value to earlier outputs by extracting new conclusions out of existing data and linking this in particular to the wider trade-offs associated with production, health and welfare management of sheep grazing and egg production systems. Both SRUC and JHI are members of the Agricultural UK GHG Platform delivery consortium. This work draws on the methods and expertise developed in this platform and provides feedback on the impacts and implications of improved understanding of GHG emissions in agriculture.

KE, Audiences and Impact

Audience specific KE will be delivered by this RD. A stakeholder group will be established in collaboration with RD2.3.9, with representation from farming (farmers from Hutton's existing East of Scotland Farm Network, and advisors from SRUC and the AICC), policy (SNH), environmental conservation (LEAF, BCT) and research sectors (MRP scientists from linked RDs, key contacts at networked sites including Rothamsted, INRA, IBERS).To ensure the impact of the research reaches the intended targets, this group will be invited to assess and advise on the relevance of the research to stakeholders, while also providing a mechanism for delivering research findings to these sectors. For example, we have already had positive feedback on this proposal from SNH highlighting the hill farming labour/skill issues we will explore, links to Defra's SIP (Sustainable Intensification Research Platform) project which we are engaged with and the extent of trade-offs in protein supplementation. An initial workshop will be organised jointly with RD2.3.9 to set out the objectives and approach and gather feedback from across all stakeholder groups on desired outcomes. This will be followed by an annual newsletter and organisation of a biennial workshop and complemented by the delivery of scientific papers and conference presentations, plus informal and one to one discussion with stakeholders from all sectors. Formally, stakeholders will be provided with predicted outcomes arising from a range of optimal scenarios that balance production with sustainability, varying from fully production focussed to fully sustainable. Such advice will reduce the uncertainty around the impact of alternative strategies and improve policy choice.

The performance of the RD research and KE activities will be assessed as part of the annual reporting cycle but ultimately, impact will be judged on the frequency with which recommended practices are deployed by the Scottish farming industry.

Each objective will therefore take advantage of specific KE opportunities as follows:

O1: The development of this systems-oriented research will provide a firm platform on which to build further non-RESAS funded research into each of the above areas in more detail. SRUC's Kirkton & Auchtertyre Farms are well practised at hosting farmer and industry focused events at which the findings from the systems work and relevance to the farming industry forms a focus for stakeholder discussion and debate, particularly with regard to the future of upland sheep management systems and how best to increase their resilience to economic and climatic shocks. The siting of the study area within the Loch Lomond & Trossachs National Park, in an area frequented by hill walkers and West Highland Way walkers (~40,000 p.a.) also provides additional opportunities for interaction and knowledge gathering and exchange with the general public.

O2: This objective will utilise inputs from the Centre for Sustainable Cropping and the East of Scotland Farm Network and will report findings back into general KE activities undertaken by these. We will also take advantage of KE activities undertaken by Hutton, including attendance at Potatoes in Practice and Cereals in Practice to deliver findings to the farming industry and of existing links with environmental sector stakeholders such as the Tayside Estuary Group and to a general audience via the Living Field websites and Open Farm events, e.g. Hutton Dundee Open Day, LEAF Open Farm Sunday.

O3: KE activities will include presenting outcomes at stakeholder meetings such as farmer discussion groups and workshops, and site-open days. As and when appropriate, small articles will be published in trade journals.

Impacts will depend on co-construction of outcomes with stakeholders. However, it is likely that this RD will through this process identify specific and measurable targets, with associated actions that farmers can adopt. For example, investment in precision livestock farming systems is likely to trade-off against economic, welfare and environmental benefits (win-win-win) of better parasite control in extensive livestock systems.

RESEARCH DELIVERABLE NUMBER:

Work planning and timetable for Year 1: Please include major milestones, (key research activities, deliverables, KE/impact events) and their timing.

Year 1: 2016/17	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
D1.1:	Data from historic field trials conducted on SRUC's upland farms collated and sent for GHG emissions analysis											
D1.1:			TST target weight predictions for all lambs throughout the grazing season				Analyses of immune response to parasites (within 2.3.1)					
D1.2	Develop management protocols for the two systems			Implement systems specific grassland management, grazing and feeding protocols including KPI measurements for sustainability.								
D 1.2			Biodiversity assessments of in-bye grassland management									
D1.1:	Develop a framework for economic and performance data analysis						Analyse performance data for the TST trials					
D 1.2:1	Record pedigree, production, economic, welfare and labour data at key times during the sheep year. Collate with environmental and biodiversity measures. Interim Report											
D2.1	Quality assessment of crop performance data			Design and build crop performance database								
D2.2							Develop DEXi model of individual crop					

							performance.	
D2.3	Develop and apply Monte-Carlo approach to the construction of random crop sequences.							
D3.1	Data gathering and cleaning							
Annual Report								**R1**

RESEARCH DELIVERABLE NUMBER:

Work planning and timetable for Year 2: Please include major milestones, (key research activities, deliverables, KE/impact events) and their timing.

Year 2: 2017/18	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**
D 1.2:	Record pedigree, production, economic, welfare and labour data at key times during the sheep year											
D 1.1:			TST target weight predictions for all lambs throughout the grazing season			Analyses of immune response to parasites (within 2.3.1)						
D1.2:	Implement systems specific grassland management, grazing and feeding protocols											
D 1.2:			Biodiversity assessments of inbye grassland management									
D 1.2					Report on 1st year economic and performance data across the systems							
D 2.2:	Develop DEXi model of individual crop performance.					DEXi based analysis of existing crop management strategies.						
D2.3:	Identification of optimal crop sequences											
D3.2	Methodology establishment											
Annual Report											**R1**	

Name of RD: 2.3.12 Increasing uptake of best practice
Research aim and key drivers Ensuring long-term behavioural change is essential to meeting Government objectives for sustainable economic growth, food production, land use and environmental enhancement. The aim of this RD is to explore and advance the uptake of practices which improve the efficiency, productivity and sustainability of land, crop and livestock management throughout Scotland. Research in the current SRP has shown a number of factors determine the uptake of practices and that adoption requires decision-makers to go through several stages of problem recognition. A range of interventions at Scottish, UK and EU levels are now being used to overcome some of the hurdles towards improved uptake of technologies and techniques. These include establishing monitor farm-type approaches (e.g. Farming for a Better Climate) for promoting best practice in resource use and carbon mitigation, increasing regulation to improve water and soil quality, as well as financial incentives and targeted information to promote protection of natural capital. Examples of areas where regulation is a prominent driver of change are the management of on-farm nutrients, control for pest and diseases and improved animal welfare. Other approaches have tended to promote uptake through financial or non-financial 'nudges'. Key regulatory and non-regulatory (i.e. information, financial, social) interventions will be explored within this RD to understand their influence on uptake of management and technologies which improve competitiveness and ensure the long-term sustainability of farming systems and natural resources. In addition, this RD seeks to understand the factors behind adoption of best practice for animal welfare, as well as crop and animal health. To address the policy driver of promoting positive behaviour change we propose the following research areas (Objectives): **(O1) Developing evaluation tools and techniques** to identify a range of success factors which indicate uptake of best practice; **(O2) Investigating the uptake of efficiency measures and tools for land management** for environmental protection; **(O3) Improving best practice in pest and disease management** such as integrated pest management and animal health; **(O4) Uptake of animal welfare improvement practices** to explore the perceptions of best practice measures within welfare and to understand decision choices; **(O5) Improving uptake of existing and new technologies**, to understand the drivers behind technologies which offer both financial and environmental improvements. The priorities for research within this RD are based on ongoing discussions with Scottish Government (SG), key stakeholder groups within SG (Animal Health and Welfare, Crops and CAP reform) as well as, Livestock Health Scotland, National Farmers Union (Scotland), AHDB, UK Food Surveillance System, Quality Meat Scotland (QMS), Scottish Natural Heritage & individual livestock and crop producers through discussion at meetings and events. This RD will operate with close and regular interaction with the Centre for Knowledge Exchange and Impact, to ensure that findings on increasing uptake of best practice are shared widely with KE practitioners, including the KE Sectorial Leads, and other relevant stakeholders.
Summary of the proposal: *O*1 Developing evaluation tools and techniques. Key deliverable: Collate and identify indicators over the 2016-2021 period to understand how uptake has changed and, more critically, the impact this will have in terms of Scotland post-2020. The outcomes will be: 1) an *ex-ante* calculator for deriving rates of return to technological interventions; 2) identification of innovation and best practice indicators for crop, livestock and forestry sectors; 3) advancing tools and techniques to evaluate behavioural change within sets of land users; 4) an annual assessment of monitoring and development of best-practice indicators throughout the five year programme.

<u>*O*2: Investigating the uptake of efficiency measures and tools for land management:</u> Key deliverable: Establish the effect of various interventions (e.g. regulatory for water quality; voluntary via knowledge-sharing on monitor farms), to allow suggestions for improving interventions so that they offer appropriate monitoring and guidance for decision making within food production and natural resources management. It will also allow understanding of the characteristics and technologies adopted by farmers most likely to engage in low input systems, as well as the drivers behind the decision to intensify farming systems. The outcomes will be: 1) improved understanding of drivers and technology profiles of low input systems; 2) detailed understanding of present levels of uptake and influence of interventions on nutrient efficiency and soil improvement measures; 3) highlighting drivers behind sustainably intensifying systems in Scotland; 4) a decision-making model to understand reseeding of grasslands (Month 36); 5) detailed intentions towards uptake of the Beef Efficiency Scheme (Month 48); 6) comparative assessment of different interventions to increase uptake of best practices (Month 56).

<u>*O*3: Improving best practice in pest and disease management:</u> Key deliverable: Assessment of the effect of various interventions and exploration of the underlying drivers on the cropping and livestock sectors which improve management of pest and diseases. This will also ensure delivery of guidance of effective and consistent communication of messages of best practice within the industry. The outcomes will be: 1) understanding of characteristics and barriers to adoption of innovation towards integrated pest management; 2) identification of definitional differences of best practice within animal health disease management and the potential effect of risk aversion; 3) results to inform guidelines for communication of best practice to different farming communities (Month 58).

<u>*O*4: Uptake of animal welfare improvement practices</u>: Key deliverable: Examination of farmer and supply chain choices critical to identifying more effective ways of supporting the uptake of 'best' practice. The outcomes will be: 1) Use qualitative behaviour assessment (QBA) to engage a community of practice to promote training in higher welfare standards and use of tools for decision making; 2) Better understand the links between producers and other steps in the food chain to help increase uptake of best practice in animal welfare; 3) Delivery of a decision-making model for farm management decisions affecting animal welfare.

<u>O5: Improving uptake of existing and new technologies</u>: Key deliverable: Determine the importance of drivers and barriers to uptake of technologies which offer opportunities for increasing productivity and meeting societal goals. This will aid design of an effective strategy for maximising use of further new technologies which offer potential to achieve dual ecological and resource efficient goals required to meet Scottish, wider national and EU level targets for land use. The outcomes will be: 1) a typology of precision agricultural techniques and technologies applicable to Scottish cropping and livestock farming, 2) identification of key framing devices needed to increase uptake; 3) mapping of new technologies which offer promising dual benefits for Scottish agriculture (Month 48); 4) characterisation of barriers and opportunities for uptake to deliver to Scottish sustainable rural and agricultural economic growth post-2020 (Month 54).

<u>Technical approach and detailed work plan</u>

<u>*O*1 Developing evaluation tools and techniques:</u> Identification and monitoring of indicators which infer increasing uptake of animal health, welfare, cropping, nutrient and soil management and related improvements in best practices. Behaviours over the 2016-2021 period will be expected to change and this objective will provide a framework for developing both a baseline of current uptake and for monitoring progress. Moreover, as data collection by Government agencies becomes increasingly detailed and as different data begin to be matched, it would be expected that this framework develops in the post-2021 period to

ensure ongoing evaluation of behavioural change within industry. This objective covers (O1.1) Development of novel statistical methodology for analysis of ordinal farm survey data: Novel statistical methods for the analysis of the types of ordinal survey data being collected here in objective 3 and elsewhere in the Strategic Programme (RD3.1.2) will be developed. This work is expected to involve the development of novel mixture models and mixed models for ordinal data, and to investigate the ways in which these methods can be used to develop typologies of farmers based on their behavioural characteristics. (O1.2) An *ex-ante* evaluation and rates of return calculator: There is a specific requirement to evaluate uptake and returns to research investment within this RD. A project calculator developed for Defra (RPM 5134) will be extended to cover livestock and cropping technologies specific to Scotland. This will quantify the expected financial, social and environmental impacts for a range of technologies proposed within the Strategic Research Programme 2016-2021 (SRP) and assess their returns within an economic framework. A series of direct and indirect impacts will be identified and a web-based questionnaire will be developed to assess likely rates of adoption. This will be completed by scientists to explore the potential for uptake of a technology within the industry. (O1.3) Establish an ongoing observatory of uptake and best practice success indicators. A baseline of practices will be established from a range of one-off or annual surveys conducted by the MRPs, Scottish Government and related institutions such as the QMS enterprise survey, the farmer adaptation survey conducted in the current SRP, and Scottish Government (SASA) pesticide surveys. A database of metrics will be established to monitor change over time, inform innovation capacity for the Scottish agri-tech sector and provide a resource useful for assessing the impact of interventions. This would allow closer interaction with the Centre for Knowledge Exchange and Impact.

O2: Investigating the uptake of efficiency measures and tools for land management: Establishing most effective interventions to offer appropriate guidance for decision making on food production and natural resources management. Qualitative approaches, such as agricultural innovation systems methodologies, will be applied to understand the knowledge flows between actors in the agricultural and forestry sectors to understand the extent to which they support innovation processes. In conjunction, quantitative techniques based on survey analysis and time series econometrics of June Agricultural Census and Farm Account Survey databases will be used to examine characteristics and historic changes within farming systems in Scotland. This objective will also draw on data from the first five years of the Centre for Sustainable Cropping (CSC) platform to compare the profitability of conventional and sustainable cropping systems. These approaches will be used to examine a number of areas which will inform development of agricultural and forestry policy for Scotland during and post the SRP. The main focus in the first two years will be to examine (O2.1) the influences on increasing nutrient management and soil improvement technologies, linking with research on existing greenhouse gas mitigation technologies in RD2.3.5 and RD2.3.6. (O2.2) Assessment of the monitor farms programme as an intervention device to encourage uptake of soil and nutrient management techniques. (O2.3) Drivers of intensive systems which will inform and be informed by case study approaches in RD 1.4.2. In addition, O2.3 will examine the farming characteristics and technology adoption in low input systems, to frame socio-economic understanding for RD 2.3.8. Moreover, initiatives which will begin during the programme, such as the Beef Efficiency Scheme and agro-forestry adoption encouraged through Common Agricultural Policy (CAP) reform, which also offer opportunities for further integrative storylines with WP1.4, WP2.4 and WP3.4, will be explored within this objective.

*O*3: Improving best practice in pest and disease management. O3 will involve assessing various interventions and underlying drivers on the management of pest and diseases within the Scottish crop and livestock sector. To implement effective use of integrated pest management (IPM) and better animal health management requires identification of the effect of current interventions and possible improvements needed to engage target populations. This research will apply qualitative and quantitative social-science and business methodologies, along with investigations applying behavioural economic approaches, to elicit perceptions and definitions towards best practice and inform communication strategies for target industries. These will be: (O3.1) gap analysis to explore the differences between 'best' practice in farm management for up to two selected diseases; (O3.2) explore the potential effect of risk aversion on uptake of disease control measures using prospect theory; (O3.3) co-construct definitions of IPM, using planned workshops in RD2.1.6, to examine the understanding and definitions of IPM amongst stakeholders, as well as to explore knowledge exchange networks; (O3.4) develop a Delphi methodology to provide a systematic approach to elicit the barriers to the uptake of helminth control best practice advice, which builds on existing and new diagnostic tests developed in the current programme and links to workshops in both RD2.2.3 and EPIC ST2.4; (O3.5) identify the opportunity costs on related farm enterprises as a barrier to uptake of animal health management for a set of sheep health challenges; (O3.6) a comparative survey-based analysis to explore social and cultural capital as drivers and barriers to uptake of regulatory best practice within intensive poultry production and extensive cattle and sheep production (this links to work to improve biosecurity across livestock production systems in RD2.2.6 and T4.3 in EPIC III to explore the effect of disease threats on uptake of biosecurity measures); (O3.7) on-farm discussions and active participatory meetings to inform targeted animal health campaigns, working with key industry stakeholders to produce clear and consistent advice to producers in key areas. Translation and exchange of best practice advice on health/disease management will through industry charters/standard bodies such Cattle Health Certification Scheme (CHeCS) and Sustainable Control of Parasites in Sheep (SCOPS).

*O*4: Uptake of animal welfare improvement practices: Examine farmer and supply chain choices critical to identifying more effective ways of supporting the uptake of best practice. Better predictive models are required within the industry to ensure trust and effectiveness for animal welfare improvement. This objective builds on work in the current SRP on the development of QBA as well as exploring differences found with respect to views on lamb castration and pain management. This objective will use methods such as: (O4.1) machine learning approaches to develop new understanding of animal welfare in decision choice. This will use both specific data sets held by, for example SRUC's Dairy Research and Innovation Centre, on welfare and practices, as well as a survey of farmers; and (O4.2) a mix of natural and social science, perceptions and uptake of best practice to promote positive animal welfare and QBA. QBA builds on understanding a farmer’s relationship with his/her animals and the objective would to examine how farmers can apply QBA as a mechanism to improve uptake of welfare best practice. In addition, we will investigate key stakeholders and procurement specialists’ perceptions of how to improve best practice with respect to positive welfare in Scottish livestock. This objective links to RD2.2.7. In (O4.3) a panel of stakeholders will be recruited to explore differences in perceptions of best practice within the sheep sector using gap analysis techniques.

O5: Improving uptake of existing and new technologies: Identifying technologies which offer opportunities for increasing productivity and meeting societal goals, as well as factors behind their adoption. A framework based on innovation indicators, synthesis of technological impacts will be applied to a range of new technologies which show promise for meeting societal targets for Scottish land use. This framework will be used to initially produce a typology of precision agricultural techniques and tools applicable to the Scottish cropping sectors which will be used in conjunction with biophysical and climatic farm level investigations proposed in RD2.3.5 and RD2.3.6. This will provide a novel extension to behavioural theory known as the ‘theory of trying’ applied to historic and intended adoptions of new agricultural innovations. This will be used to derive a questionnaire for primary research within the potato and wheat sectors to explain and compare understanding and willingness to adopt. Furthermore, this will provide the basis for establishing the current uptake of precision agricultural tools, the perceived benefits of these tools, with respect to climate change and productivity. Quantitative assessment will be used to explore the potential for adoption of these tools under climate change scenarios. Expert opinion will be gathered via stakeholders in the Agritech Innovation Centre for Precision Agriculture (Agri-EPI Centre) in which SRUC is a partner. The framework will be extended in later years to technologies within the livestock and grassland areas.

Detailed workplan

O1. Novel methods of elicitation for behavioural intentions will be developed using statistical knowledge of mixed methods approaches to elicit hierarchies of intention from ordinal survey data. Primary data collected both within this RD (O4.3, O3.2) and RD 3.1.2 will provide a series of diverse topics which allow examination of the underlying antecedents to maintaining a particular behavioural posture, namely resistance to change or openness to innovative methods. An economic framework developed as a prototype for Defra Project (RMP 5134) will be extended to cover a range of proposed cropping and livestock technologies. Engagement with scientists and policy makers will create awareness of impact within these communities and a web-based application is planned for yr 3. A framework of monitoring success factors pertinent to behavioural change and innovation will be established in the first year. This will be continually updated over the 5 years of the programme to understand both the baseline behaviours pertinent to each sector and how behaviours are changing over the course of the programme.

Key deliverables

1. Database of indicators of best practice and innovation capacity (Month 8, D1.1)
2. Prototype modelling framework for eliciting farmer typologies (Month 18, D1.2)
3. Economic framework for evaluating ex-ante uptake and economic rates of return to selected projects from with the SRP 2016-2012 (Month 20, D1.3)

KE1.1 Engagement with scientists and policy makers to collect uptake rates of technologies and transfer first results of economic assessment (Month 11).

KE1.2. Disseminate results and methodology of economic evaluation to policy makers. (Month 23).

O2. Agricultural innovation system approaches to engage policy makers, scientists, advisors and researchers will identify how information and knowledge flows between actors within nutrient use efficiency and soil improvement technologies. The Farm Account Survey will be analysed using panel data techniques for the period 1995-2015. This will establish the nutrient use efficiency of farmers using coefficients of nitrogen value and augmented with discussion with experts and the British Survey of Fertiliser practice. Two farms within the network of monitor farms will be chosen after liaison with Scottish Government, SRUC and industry. Qualitative data will be collected over a two-year period and analysed using Nvivo textual software to identify characteristics of farm uptake. A large survey conducted in current SRP 4.1 on farmer adaptation will be analysed using logistical and probit modelling approaches to identify the main technology profiles of low input farmers and the characteristics behind the intention to intensify farming activity. This will be augmented with matched June agricultural census data from the period 2005-2015 at the holding level and specialist data from the Centre for Sustainable Cropping.

Key deliverables
1 Published report on motivates and historic nitrogen usage (Month 19, D2.1)
2 Published report on motivates, barriers and framing for nitrogen use efficiency advice (Month 24, D2.2)
3 Journal paper on the effectiveness of different approaches to encourage uptake of best practices (Month 24, D2.3)
KE2.1 Update meeting(s) on characteristics of drivers for low input systems (Month 9)
KE2.2 Policy workshop to SG Behavioural Change and Water Quality Management (Month 22)

O3: Gap analysis will be used to identify where differences in 'best' practice in animal health exist and causal factors. Participants will be key stakeholders, including farmers, animal health, welfare and livestock experts. Topics will be agreed with SG but may include biosecurity and the control of para-tuberculosis. The subjective risk-value relationships of farmers for a set of animal disease control practices will be investigated using prospect theory and the strength of their aversion to either disease losses or control costs estimated. The diseases and disease complexes studied will be determined in discussion with SG and be informed by the stakeholder meetings held in O3.1. Co-construction of IPM definitions and barriers will be through an agricultural innovation system workshop on IPM constructed and planned with RD2.1.6. The Delphi method will be employed to provide a systematic approach to elicit the barriers to the uptake of helminth control best practice advice. Expert bodies from industry and academia related to parasitology and veterinary science, along with other stakeholders, will be conducted. This will build on work in the current SRP as existing/new diagnostic tests have been validated generating data that informs the industry on best practice in the use of diagnostics and management practices. This links to RD 2.2.3 and to EPIC ST2.4 which will also contribute to development of the workshops. Opportunity costs concepts will be used to examine the effect of inter-enterprise linkages on farmer adoption of better health practices for a set of sheep health challenges. A qualitative comparative case study approach will be used to investigate barriers to uptake of regulatory best practice to include cultural as well as social antecedents which may be monopolised to raise the value of intervention and compliance. This has explicit links to work in RD 2.2.2 on smallholder biosecurity practices and RD2.2.6 on socioeconomic incentives for disease control to provide recommendations to improve biosecurity across livestock production systems, and Topic 4.3 within EPIC (Analyses of Potential Disease Control Options, Economic and Behavioural Analysis) to explore the effect of disease threats on uptake of biosecurity measures across different livestock industries. In consultation with stakeholders we will co-construct KE events to ensure relevance and usefulness to end-users, by generating industry relevant publications and meetings. Undertake industry relevant publications (Moredun Foundation and SRUC Newsletters, roadshows and farmer and vet meetings).

Key deliverables
1 Research brief on differences in 'best' practice for animal health (Month12, D3.1)
2. (Ongoing) publications relevant to livestock audiences on management of disease control (Months 6 ,9,12,15,21,24, D3.2).
3.Research brief linking O3.1, O3.4 and O4.3 (Month 20, D3.3)
4 Research brief on risk-value relationships (Month 24, D3.4)
5 Published report on IPM definitions and farm characteristics (Month 21, D3.5).
6 Report on barriers to uptake of helminth control 'best' practice advice (Month 24, D3.6)
7 Submitted paper on the opportunity cost barriers to uptake of sheep health (Month 15, D3.7)
8 Published report on regulatory interventions of regulatory interventions comparing the

poultry and beef sectors (Month 17, D3.8)
KE 3.1 Inform industry group for solutions to definitional differences to uptake of IPM (Month 12)
KE 3.2./3.5 Co-construction of KE events with stakeholders (Month 8, 20)
KE 3.3 Presentation to SG staff on best practice definitions within animal health and welfare (joint with KE 4.2)
KE3.4 Engagement with policy makers to identify sheep health management solutions losses (Month 19)

O4. A prototype model applying machine learning methods will be developed. Existing data sets such as those held at SRUC's Dairy Research and Innovation Centre will be used to establish the method's predictive potential and refine the approach before examining primary data collected from a representative farmer survey. In RD2.2.7 and EPIC, small groups of farmers will be recruited to form longitudinal study groups, to explore QBA to enhance positive welfare in dairy cattle on farms (SRUC), and to explore the use of mobile visual technologies to compare assessments and responses to Bovine Viral Diarrhoea amongst dairy and beef farmers (Hutton). Generally, this will be a participatory activity. However, in addition, at regular intervals farmers will be invited to express their views of the project's progress in feedback forms, one-to-one interviews, and group discussions, using both pre-structured and open ended questions. In socio-economic contexts such groups can be regarded as 'communities of practice' whose practical on-the-ground collaboration aims to articulate how the uptake of animal welfare values may be facilitated. In other work linked to RD2.2.7 we will use understanding of different perceptions of positive welfare to explore how the procurement supply chain could move towards accommodating best practice relating to positive welfare. Key stakeholders and procurement specialists will be recruited into an interview population. These people will be interviewed face-to-face to investigate decisions on an organisational basis on buying Scottish livestock products. We will hold workshops to discuss the perceptions of positive welfare (linked to RD2.2.7) and the implications of positive welfare products and how such organisations can make decisions to include such products in their buying choices –thus providing coherence across the supply chain with regards to positive welfare. A stakeholder group will be established to systematically identify and explore inconsistencies in practices defined as 'best' using gap analysis. It will build on the findings from the current SRP where differences in views on best practice for lamb castration and pain management were found.

Key deliverables
1 Research brief on perceptions in best practice in welfare (Month 12, D4.1)
2 Create farmer-generated QBA terminologies and implementation mechanisms (Month 24, D4.2)
3 Submitted paper on perceptions of best practice in welfare (Month 18, D4.3)
KE4.1 QBA training with stakeholders within the community of practice (Month 9)
KE4.2. Presentation to SG staff on best practice definitions within animal health and welfare (joint with KE3.2)

O5. A framework based on precision agriculture techniques based on impact on natural and economic sustainability but also secondary data and input from RD2.3.5 and RD2.3.6 will be used to construct a typology of barriers to uptake. This framework will be extended to include livestock and grassland based approaches through discussion with experts. Further work will extend the framework to other promising technologies in years 3 to 5. Latent variable modelling will be applied to data collected at trade fairs to establish the probability of adoption of precision agricultural approaches within the potato and wheat sectors. The questionnaire will be the first application of the theory of trying to understand barriers to adoption within an agricultural context.

Key deliverables 1. Framework synthesising effects and typology of PA approaches and barriers (Month 6, *D5.1)* 2.Submitted paper using theory of trying to understand uptake (Month 13, *D5.2)* KE5.1 Disseminate findings to SG (Month 15)
Expertise This RD represents a significantly cross-disciplinary effort to address the complex problem of ensuring best practice uptake within the agricultural and land use sectors. It is led by a social science researcher and economist with experience in exploring innovation and behavioural drivers of uptake of best practice. It consists of expertise from social and behavioural science (SRUC, JHI), agricultural economics (SRUC, JHI), veterinary science and surveillance (MRI, SRUC) and crop science and surveillance (SRUC, JHI). This RD offers the real opportunity to develop and test behavioural and economic theories towards decision-making and information processing within a very applied setting of livestock keepers, crop producers and land managers. This therefore offers a platform to enhance and inform the present state of science towards uptake of innovations and message framing to ensure uptake.
Key linkages, interdisciplinarity & collaboration This RD has significant cross linkages with a number of other areas of the SRP. This work will provide a framing analysis for RD2.3.8 in terms of understanding the motivates for adoption of low-input and organic systems and also provide input into the part of RD1.4.3 which is seeking to understand the characteristics of sustainable intensification of arable systems at a case study level. Work proposed in Objective 2 also links to WP 2.2. The uptake of advice can be influenced by a number of factors, but an understanding of the scale and cost of a problem may help persuade producers and land owners of the benefit/loss that might be incurred by a particular course of action or failure to follow. The work on analysing uptake and managing welfare techniques is directly related to work in RD2.2.8 on awareness of welfare impacts of castration in sheep. RD2.1.6 will focus on integrated pest management which is directly related to work proposed in Objective 3 on the drivers and definitions behind IPM uptake. WP2.3: The disease systems approach adopted in this RD focuses on the management practices that drive disease dynamics, persistence and spread which in turn are underpinned by the science in WPs 2.1 (Crop and Grassland) and 2.2 (Animal Heath). The analyses of uptake of animal health control strategies are directly relevant to work within this RD on management of endemic disease and uptake of best management practices. The information is imperative to better understand what barriers may impinge on best practice uptake. The outputs from this research will give a better understanding of how to promote best practice for risk and farm management. WP2.4, in particular RD2.4.2 adaptation of rural economies, where a behavioural model will be constructed of Beef Supply chains, and the responses identified within this RD through survey and workshop analysis will provide a basis for parameterising the decision-making model. The novel statistical models developed here will be created in conjunction with work proposed in RD3.1.2. Moreover, the topics covered over the five years of this RD, such as characteristics of farming intensification, support for uptake of the beef efficiency scheme, and proposed work on agro-forestry, offer opportunities for integrative storylines between WPs 1.4, 2.3, 2.4 and 3.4. A range of intervention mechanisms will be explored within the RD, from regulatory to voluntary uptake approaches and whilst some RDs explore the consequences of full scale adoption, the work proposed in Objective 1, on identifying farmer typologies and uptake potential, will help to provide a realistic scaling of land use and GHG

technologies proposed within the natural science investigations of Themes 1 and 2.

Wider linkages

Through interaction with Programme Advisors and relevant KESLs, wider Programme and Portfolio linked opportunities will arise e.g. contribution to CKEI-Think Tank core group horizon-scanning and agenda setting projects.

Work on QBA will be informed by EPIC (Topic 2.4) research into visual appraisal of dairy and beef cattle, specifically for signs of bovine viral diarrhoea (BVD). In addition, work on regulatory interventions in extensive beef systems will be informed by EPIC (Topic 4.3) to explore the effect of disease threats on uptake of biosecurity measures across different livestock industries.

The findings from Objective 3 will feed into activities and will be informed by a number of other research studies: the research proposed under the HEI link on controlling parasitic nematodes (**HEI bid 5**) will be informed by O3.1, O3.2, O3.4 and O3.5. In addition O3.2 and O3.5 will also inform the BBSRC sLoLa (BB/M003949/1) investigating mechanisms and markers of anthelmintic resistance. The HEI project on disease management options: insights from comparing forestry and agriculture (**HEI bid 9**) will be informed by work on O3.3 here.

Stakeholders: the objectives proposed within this RD are well aligned to priorities from various funding bodies, be they Levy boards such as AHDB and QMS, National funding bodies such as BBSRC or RCUK or the EU. The multidisciplinary research outlined within this RD will provide a platform to promote collaborations and foster opportunities to leverage further grants.

Added Scientific Value

The research and researchers within this RD will be informed and compliment the research being conducted in a large number of funded projects both from within the UK and Europe. Value will be added to crop IPM research through links with AHDB- cereals and oilseeds funded KE events at which stakeholder opinions can be gathered and through links with the proposed Agritech Innovation Centre for Precision Agriculture (Agri-EPI Centre). There will be collaboration with the North East Farmers network to explore to which extent the data of these farms can be used as a basis for analysing the costs of existing farms. Interdisciplinary working is required to determine the effects of measures.

Implementation of control measures for one disease can impact on the diagnosis and control of another, which is important information for determining best practice. This RD will benefit from the outputs of the EMIDA ERA-Net Mycobacteria diagnosis project (Defra project number SE3270), which addresses the problems of concurrent disease and interference of diagnostic testing for Johnes disease and bovine tuberculosis through integrating specific diagnostics and platform technologies that can be applied across both diseases. Through the links to BBSRC sLoLa (BB/M003949/1) and **HEI bid 5** there will be a substantive development of understanding of behavioural change with regard to management of sheep nematodes and the development of drug resistance.

There will also be exchange with other researchers on RD2.3.12 to complement findings since the uptake of practices is not only determined by economic but also social, personal, cultural and institutional factors. We will also draw on EU projects (e.g. PROAKIS) and the European Innovation Partnership 'Agricultural Productivity and Sustainability' to identify ways to enhance Scotland's Agricultural Knowledge and Innovation System.

KE, Audiences and Impact

Throughout the programme we will ensure close and regular interaction with the Centre for Knowledge Exchange and Impact, to ensure that findings on increasing uptake of best practice are shared widely with KE practitioners, including the KE Sectorial Leads, and other relevant stakeholders. Staff involved in this RD will participate in KE training events organised via CKEI. KE from the RD will feed up to the WP and theme levels, through the CoEs for animal and plant health.

There are opportunities for knowledge exchange in the process of working with farmers and advisors when identifying the relevant measures for farmers in target areas. Specifically, O1.2 requires input from stakeholders to derive indications of uptake of new technologies; O2.2 is taking an action research approach e.g. through involving stakeholders in the evaluation of both practices and effectiveness of monitor farms and feeding back results of the analysis. O2.1, O3.1, O3.3, O3.5 and O4.3 will all also specifically directly involve knowledge exchange with stakeholders, considering different understandings of concepts and language as well as system complexities.

MRI, JHI and SRUC have close relationships with SG policymakers and related stakeholders, such as SNH, to ensure that outputs relevant to policy decisions are rapidly and effectively communicated. Opportunities for knowledge exchange will be utilised wherever possible and appropriate. This will include working with farmers during the research when identifying relevant measures for farmers in target areas. Results of the analysis will be fed-back to farmers and, where the opportunity exists, linked into an ongoing monitor farm project. We will also participate in key agricultural events such as the Royal Highland Show, Beef Expo, Scottish Beef Events, National Sheep events, Cereals in Practice, Potatoes in Practice, Fruit in Practice, AHDB winter cereals and oilseed rape workshops, SRUC crop trial site open events. These will be used as an opportunity to both transfer the research produced here but collect information for the ongoing monitoring of best practice and success factors.

Lastly the welfare aspects will be enhanced through our online animal welfare education courses such as the Massive Open Online Course (MOOC) on animal welfare https://www.coursera.org/course/animal (over 5,000 completed the MOOC on its inaugural run; over 20,000 are enrolled for the 2nd course) and postgraduate taught programmes.

RESEARCH DELIVERABLE NUMBER: 2.3.12

Work planning and timetable for Year 1: Major milestones, (key research activities, A#; deliverables, D#; KE/impact events KE#), their timing of delivery for each item.

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1: Mixed methods approaches. Testing of approach across case studies									M1.1			
O1: Ex-ante RoR Calculator. Develop prototype model for rates of return. KE1.1 collect uptake rates with scientists and policy makers.						M1.2					KE 1.1	
O1: Observatory of best practice. Database of best practice indicators available from surveys								D1.1				
O2. Uptake of soil improvement and nutrient use efficiency. Econometric analysis of FAS.							M2.1					
O2: Monitor Farms. Selection of case studies. Identification of practices.			M2.2								M2.3	
O2: Characterise drivers of low input and intensive systems. Cross sectional analysis of drivers and characteristics of farmers operation low input and intensive systems. KE2 update meetings on characteristics to stakeholders for RD1.4.2 and RD 2.3.8						M2.4			KE 2.1			
O3: Differences in best practice in animal health. Convene stakeholder workshop. Produce research brief. KE3.1 feedback meeting with SG										M3.1		D3.1 KE3.1
O3: Risk-value relationships. Design and test prototype experiment.												M3.2
O3: Co-construction of IPM definitions and barriers. Probit regression analysis of factor determining uptake of IPM. KE3.1 Inform industry group for solutions to definitional differences.										M3.3		KE 3.1
O3: Barriers to uptake of helminth control "best practice" advice. Establish participant list and develop Delphi workshop.						M3.4				M3.4		
O3. Comparative analysis of regulatory uptake. Identification of comparative interventions within								M3.5				

extensive and intensive beef and poultry systems.												
O3. Co-construct KE events with audiences. Initiate consultation. Produce a series of publications relevant to audiences. KE 3.2 Road show.						D3.2		KE 3.2	D3.2			M3.6/ D3.2
O4: Animal welfare in decision choice. Identify factors required for model development.											M4.1	
O4: Perceptions of animal welfare and QBA. Complete stakeholder workshops and QBA training (KE4.1). Recruitment of procurement specialists for interviews									KE4.1/ M4.2			M4.3
O4: Perceptions of best practice in welfare. Stakeholder workshop. Produce research brief. Feedback meeting with SG.											M4.4	D4.1/ KE4.2
O5: Uptake of new technologies. Framework synthesising effects and typology of PA approaches. Construction and finalising of questionnaire based on 'theory of trying' conceptual model.					D5.1		M5.1					
R1 Year 1 Report to RESAS												R1

RESEARCH DELIVERABLE NUMBER: 2.3.12

Work planning and timetable for Year 2: Major milestones, (key research activities, A#; deliverables, D#; KE/impact events KE#), their timing of delivery for each item.

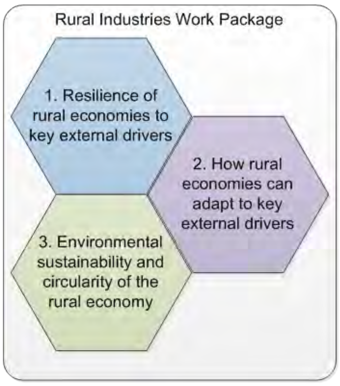
Year 2: 2017/18	Apr	Ma y	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1: Mixed methods approaches. Submission of a peer-reviewed paper on the mixed methods approach.						D1. 2						
O1: Ex-ante RoR Calculator. Rates of return for candidate technologies within SRP 2016-2012. KE1.2 Disseminate results to scientists and policy makers			M1. 3					D1.3			KE 1.2	
O1: Observatory of best practice. Update database with ongoing surveys. Short report on progress of indicators					M1. 4				D1. 3			
O2. Uptake of soil improvement and nutrient use efficiency. IS workshop. Report on motivates of nitrogen usage. KE2.2 Policy workshop in SG Behavioural Change and Water Quality Management. Brief using ISM behavioural framework				M 2.5			D2. 1			KE 2.2		D2. 2
O2: Monitor Farms. Interim data collection on monitor farms.KE 2.2 Feedback results in same policy forum as above. Journal paper on the effectiveness of different approaches to encourage uptake of best practices								M2.6				D2. 3
O2: Characterise drivers of low input and intensive systems. Framework for economic assessment Policy report identifying drivers for how systems have intensified	M2. 7						D2. 4					
O3: Differences in best practice in animal health. Research brief linking O3.1, O3.4 and O4.3. KE 3.3. Presentation to SG staff to identify solutions								D3.3			KE 3.3	
O3: Risk-value relationships. Convene stakeholder group and develop analytical framework. Report in research brief.										M3.7		D3. 4
O3: Co-construction of IPM definitions and barriers. Agricultural innovation system workshop on IPM. Published report on IPM definitions and farm characteristics.					M3. 8				D3. 5			
O3: Barriers to uptake of helminth control "best practice" advice. Conduct workshop and report and disseminate findings within HEI project D.5 and BBSRC sLoLa.			M3. 9					D3.3				D3. 6

O3. Identify opportunity costs for sheep health. Submitted paper to livestock journal. KE3.4 Engagement with policy makers to identify solutions			D3.7				KE 3.4					
O3. Comparative analysis of regulatory uptake. Analysis of poultry systems data. Report on regulatory interventions. Submitted paper.		M 3.10			D3.8				D3.9			
O3. Co-construct KE events with audiences. Complete Consultation. Produce a series of publications relevant to audiences (D3.2). KE 3.5 Road show.			D3.2			D3.2		KE 3.5	D3.2			D3.2
O4: Animal welfare in decision choice. Develop and test prototype model of animal welfare decision making. Paramaterising model using secondary data.							M4.5					
O4: Perceptions of animal welfare and QBA. Interviews/workshop with food procurement specialists towards accommodating best practice relating to positive welfare across the food supply chain; Create farmer-generated QBA terminologies and implementation mechanisms.									M4.6			D4.2
O4: Perceptions of best practice in welfare. Submit paper for animal welfare/farm management journal. Joint research brief with O3.1 and O3.4.						D4.3		D3.3			D4.4	
O5: Uptake of new technologies. Paper on ToT approach. KE5.1 Disseminate findings to SG Crop Branch Extend PA analysis to livestock and grassland. Selection of other candidate new technologies for framework development.	D5.2		KE 5.1			M5.2					M5.3	
R1 Year 2 Report to RESAS												R2

Work package 2.4 Rural Industries

1 Overview

Scotland's land-based and other rural industries are entering a period of uncertainty and change driven by: policy and legislative developments (e.g. major Common Agricultural Policy (CAP) reforms, Land Reform, Agricultural Holdings, Bovine Electronic Identification (EID), Safeguarding Scotland's Resources); volatility in market returns and input costs; climate change events, and potentially bilateral and multilateral trade agreements (e.g. Transatlantic Trade and Investment Partnership, TTIP). The Rural Industries Work Package assesses the causes and consequences of change in key rural industries, and the rural economy more widely. The research is conducted as three Research Deliverables (see figure). These parts consider the following topics: 1) change in the ability of rural industries to withstand external shocks (their resilience); 2) the ability to change their mix of activities in the face of external shocks (adaptive capacity) and 3) characterising the trade-offs between economic and environmental priorities, particularly whether waste materials can be reused (increasing the circularity of the rural economy). For all three RDs there is particular interest in the role for policy in promoting positive outcomes through behavioural, structural and governance mechanisms.



This research builds on substantive strategic and policy-supporting research conducted under previous and current research programmes. This work package will remain the leading source of support for CAP analysis, particularly for direct payments but also aspects of the Scotland Rural Development Programme. The implementation of the 2014-2020 CAP reforms is in effect an experiment in subsidy redistribution with potentially profound implications for economy of the land-based sector. Through monitoring and evaluation of adaptation in response to the reforms, the WP will generate an evidence base of policy outcomes to inform deliberations on the next CAP reforms (c. 2019). The WP team will also address scheduled reviews of specific CAP components (e.g. Areas of Natural Constraint, Greening), and have a foresight role for consequences of other changes such as TTIP or the end of EU membership. The proposed analyses have also been highlighted as having potential to inform development of land reform policy but support of this new area will have to be balanced against CAP commitments.

The WP exploits well developed inter-institutional and international cooperation, strong working relationships with SG analysts, policy staff and industry stakeholders, and experience of ensuring that research contributes effectively to policy-making processes in both design and delivery phases. While the WP is primarily policy focused it will also have active dialogue with key research collaborators in industry and with stakeholder groups. The WP will be interdisciplinary, with predominantly socio-economic and geographical sciences but utilising integrative informatics expertise in both the socio-economic and bio-physical science domains. The WP will draw together the existing strengths in spatial data analysis, statistical, simulation, agent-based modelling, econometrics and qualitative analysis. There are major opportunities to enhance the scientific impact of existing lines of research by undertaking these larger and better integrated projects. Such projects will allow new questions to be addressed and existing questions to be better answered demonstrating the added value for both science and policy that is achieved by cooperation between SG's Main Research Providers (MRPs).

1 Coordination and Management

1.1 Within-Work Package Working

Within-WP Collaboration – Collaborative approaches will be ubiquitous in the work package (WP) and Research Deliverables (RDs) given the aspiration from SG for increased integrative and interdisciplinary working. All activities planned in the WP are team-based, and a substantial number are cross-MRP. The collaborations will build on successful past co-production of deliverables and will create new networks of cross-WP collaboration. Collaboration is pragmatic and task-orientated. Management processes will encourage and facilitate collaboration but while looking for new opportunities will also prioritise, coordinate and evaluate their outcomes.

WP Coordination – Research leaders with coordination roles at WP and RD levels all have extensive experience in the planning and implementation of integrative and interdisciplinary research (together they have 100+ years research experience). Building on two previous Strategic Research Programmes (SRPs), a robust, flexible, network-type management structure is planned, with clear roles and responsibilities at WP and RD levels (see Figure 1 below). In this network there are WP Coordinators (WPCs) designated for each MRP. In addition to their WP-level responsibilities, each WPC will lead, for their respective organisation, one of the RDs. The Work Package Management Team (WPMT) is comprised of WPCs plus RD Coordinators (RDCs) from each MRP who will have responsibility in their organisation for RD delivery. The WPCs will act, in the first instance, as single points of contact for SG and other stakeholders for WP and RDs.

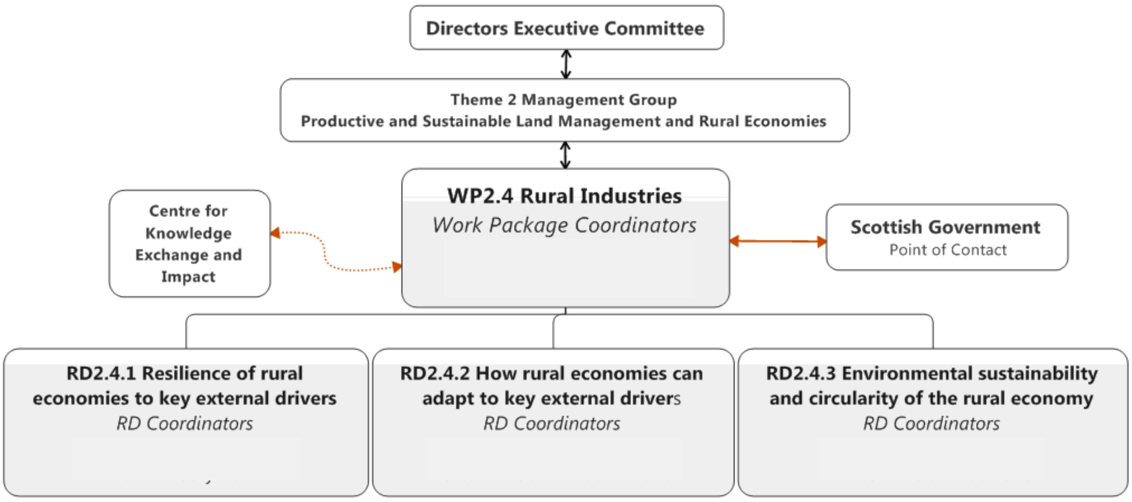


Figure 1 WP Management Structure

This network structure, and the sharing of WP and RD management roles, recognise the need to provide SG and others with clearly identified points of contact and to share the overhead of project management and directing research teams across two organisations with separate funding and line-management chains. The network structure ensures that for both RDs and the WP there are managers with both authority and responsibility to ensure delivery of outputs and that new opportunities are sought and the research is reshaped to reinforce successes. The WPMT will meet on a four-monthly basis, using online collaboration facilities where feasible. Decisions of the WPMT will be communicated to all WP staff to ensure transparency.

The WPCs will be responsible for the annual monitoring of progress by their organisation against the RD objectives, the quality of deliverables and WP Knowledge Exchange (KE). The WPCs will have a dedicated support resource to facilitate WP administration. Proactive change management will ensure that new opportunities are identified and fully exploited, remedial action is taken where necessary, and activities are discontinued where progress is not adequate or no longer prioritised.

Working with other WPs, Themes and Centres of Expertise

The SRP provides unique opportunities to tackle large-scale policy and scientific questions through partnership working beyond the scope defined by the individual WPs. It also provides opportunities to add further value to research undertaken by reuse, re-analysis and exchange of datasets and the enhancement of all phases of research conducted through knowledge sharing. Within Theme 2 (Productive and Sustainable Land Management and Rural Economies) coordination is provided by the Theme Management Group with representatives from the WPs, Centre for Knowledge Exchange and Impact (CKEI), Programme Advisors, Knowledge Exchange Sectorial Leads (KESLs), Rural and Environment Science and Analytical Services (RESAS) Science Advisers and stakeholders (see Figure 1).

Partnership working is, however, demanding of the skills and experience of research managers and establishing new partnerships is resource-intensive, generating substantial transactional costs. The strategy in this WP for working with other parts of the SRP is based on past experience of integrative and interdisciplinary research, particularly within the previous SG programmes but also in other multi-centre research programmes such as Rural Environment and Land Use (RELU), the EU Framework Programmes and the SG Contract Research Fund. The strategy is to define two levels of integration – *collaborations* and *links* and also to propose an adaptive management process to identify and assess new opportunities on an ongoing basis (termed here *liaison*). These definitions and their implications are further developed below and illustrated in Figure 2.

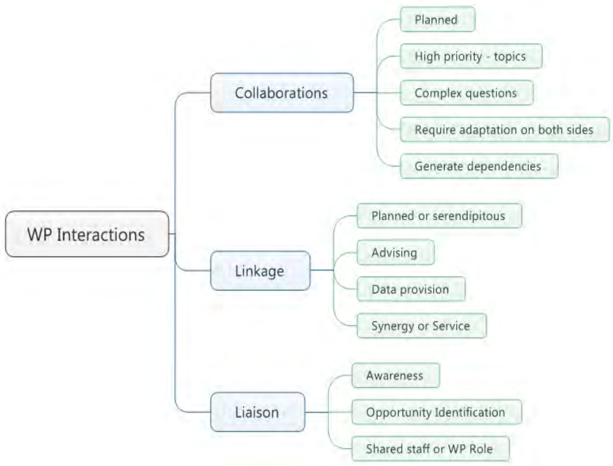


Figure 2: Working with others

Collaborations are areas where there is an *a priori* agreement on teams working together across WP boundaries and where the research undertaken is modified in the light of ongoing interactions. Note that these interactions have a significant overhead cost and imply dependencies, and thus need to be prioritised and planned for. Typically these collaborations should be driven by a specific, clearly identified and high priority end-user requirement or a major strategic science question. Collaborations are specifically identified as such in the RD descriptions. The key collaboration that will be initiated is with Integrated and sustainable management of natural assets (WP1.4) and Communities and Wellbeing (WP3.4) to allow triple-bottom-line assessments of policy options particularly, the instruments such as CAP.

Linkages are less intensive interactions, typically with exchanges of data and knowledge. These are synergistic for the SRP but may not be cost-free for an individual WP where the role is in provision without reciprocal benefits. Such activities will be prioritised and monitored. Mechanisms for crediting underpinning work need to be agreed and, where regularly used, considered for funding under Underpinning rather than the SRP. Where linkages are anticipated then these are identified as such in the RD descriptions. Linkage clearly also requires that the opportunity for exchange is identified and prioritised, requiring investment in between-WP networking, awareness-raising and management processes. These latter activities are referred to as research Liaison.

Liaison - individuals within the WP will be tasked with keeping familiar with activities in other WPs (e.g. at a minimum by attending their meetings and reporting back). The aim is to create awareness of activities and outputs from other WPs that could be used by WP2.4 and to offer WP2.4 inputs where these are appropriate. These liaisons will be undertaken by staff working both in WP2.4 and the other WPs.

The agreed instances of collaborations and linkages (a subset of those specified in the Invitation to Grant Funding, ITGF) are summarised in Figure 3. The figure also highlights where additional (purple) or different (yellow) options for interactions have emerged and been agreed in the proposal writing process.

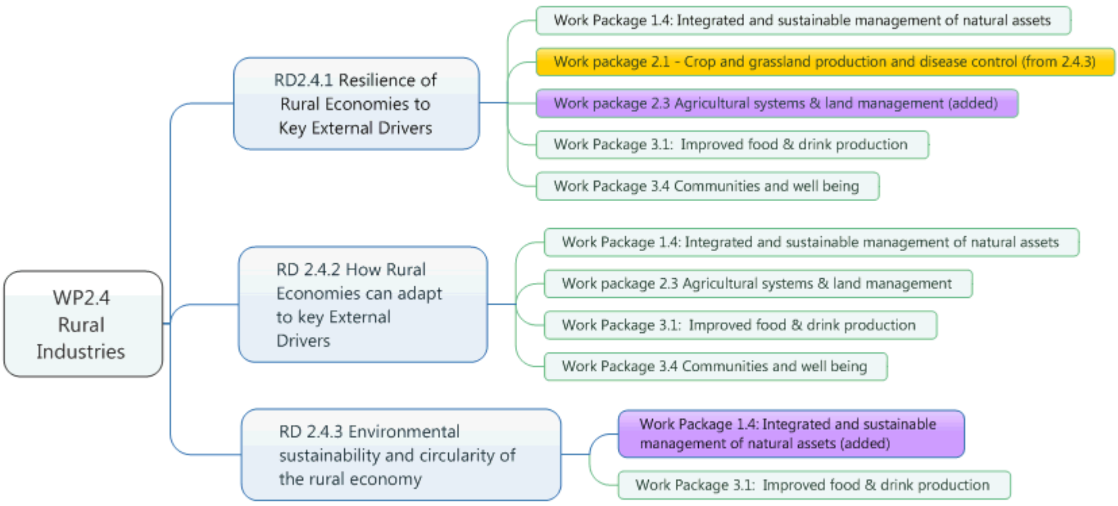


Figure 3 WP2.4 linkages from ITGF

1.2 Working with research partners beyond the MRPs

The research builds on a strong track record of successfully delivering salient and credible research to support major policy initiatives such as CAP reform. The WP will continue to enhance active working relationships with SG policy teams, analysts and other key stakeholders developed over the last 10 years. The key policy questions are well understood by the WP team, as is how research needs to be tailored to best support policymaking. Figure 4 identifies ongoing or anticipated interactions, grouped by the anticipated role for each organisation. Impact/KE is dealt with in Section 3.

Research Collaborators are organisations who see close project-based interactions with the WP on a regular basis, with face-to-face meetings, workshops and regular exchanges of data, and joint authorship or reviewing of research outputs. These research collaborators include both industry/policy experts and academic partners. Transdisciplinary co-construction of research with non-academic collaborators is the norm in the current programme, and will continue to be, a regular feature of the WP, with expertise and deliberation the basis on which any contested issues are dealt. Positive working relationships are also maintained by the WP team with a widening range of UK, European and international academic partners. These interactions will continue to be exploited to increase the expertise available to the WP (in for example life cycle analysis, viability analysis and ensemble modelling of cropping systems), to leverage additional funding to build research capacity (e.g. in Horizon 2020) and to generate reputational benefits by showcasing the excellence of SG funded research in a variety of fora.

Directing Stakeholders are the key group with which there may be frequent interactions either directly or mediated by third parties – e.g. RESAS with SG Policy Teams. These stakeholders have a directing role since they either fund or are strongly influential on the funding of research and thus have a client and evaluative role. With sufficient credibility, researchers may be able to influence direct stakeholders but mainly such groups provide the definitive policy/regulatory context within which the outputs of the WP will be used. Interactions are typically though steering groups, project meetings and participation on stakeholder advisory groups.

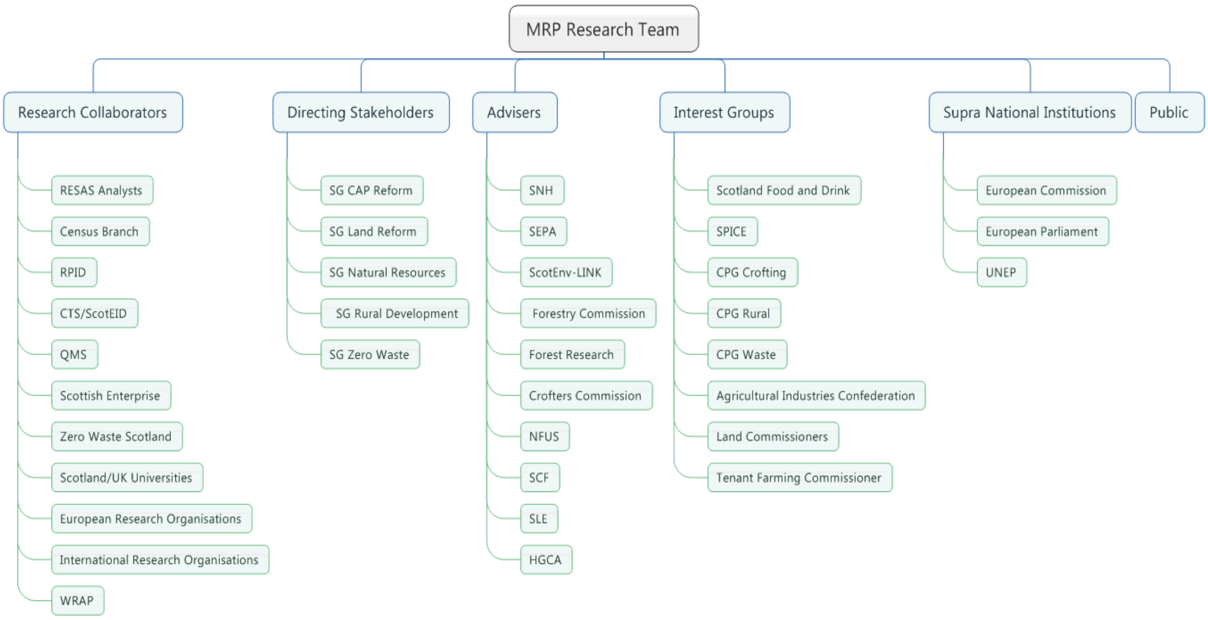


Figure 4 WP2.4 Research Partners

Advisers represent a wider community of organisations wherein research may be being carried out and by whom data is collected for a variety of purposes and which can have considerable value to MRP research. Advisers do not fund the WP research and so are not directing stakeholders. Interactions here are typically less frequent and may entail data, advice on specific issues or review of draft research outputs. Interactions with such organisations also firmly ground the research in the reality of policy implementation on the ground. Advisers can also have an influence on shaping research agendas, meaning that early interaction with them is often advantageous to both sides. Depending on the nature of activity, advisers may move between this role and that of research collaborators.

Interest Groups typically conduct less formal research themselves but may represent significant sources of contextual information and expert comment. Similarly they may be influential in research agendas, particularly when considering representatives within the Scottish Parliament and its committees, or the proposed Scottish Land Commission.

Supranational Institutions more typically provide opportunities for presentation of outputs. However, project-based interactions with bodies such as the EU Commission, United States Department of Agriculture (USDA) and United Nations Environment Programme (UNEP) have added value to past research by providing opportunities for comparative research, horizon-scanning and agenda-setting.

Public is typically seen as a recipient of science outputs. However, well-informed individuals in particular spheres can function as key informants and gate keepers in interactions with wider communities. The latter are regularly used by qualitative social research conducted within the WP. Opportunities for citizen science (particularly for social network data) will be evaluated by the WPMT.

1.3 Underpinning Capacity

Historically, the WP's interactions with Underpinning and related funding streams (e.g. the Veterinary and Advisory Services programme for SRUC) have been through call-down, policy-led research. For example, projects on CAP redistribution, agricultural holdings and regulatory review have been generated through interactions with SG policy teams. With RESAS, specifications have been jointly developed and in some cases delivered through fully collaborative working. These sources have provided additional capacity for particular issues (often with short deadlines), and have been reported by RESAS as having high policy impact. Overall demand for this kind of working has, however, reduced the resources available to invest in strategic research and to generate scientific impact. The WPMT anticipate increased use by SG policy teams of call-down mechanisms within the scope of the WP.

1.4 The Annual Reporting Cycle

The annual reporting cycle provides the key opportunity to revise RDs based on assessment that includes feedback from directing stakeholders, thus serving both an internal and external facing role. The network management structure described in Figure 1 will take responsibility for the WP management of the annual reporting cycle. Compliance with reporting requirements (i.e. metrics and narratives) will be overseen and coordinated by WP, RD and team/project leads within the RDs. This multi-level approach is intended to ensure that all relevant activities and outputs and impacts are collated, evaluated and reported on in ways that ensure achievements are clearly signposted to key audiences. Delayed or failing activities are reappraised at WPMT meetings and remedial action taken in consultation with RESAS / DEC. .

1.5 Additionality

Within the WP we have a mix of highly experienced staff who all bring a track record of adding value to the SRP through international linkages (with other academics), links to the industry (through SAC Consulting, National Farmers Union Scotland (NFUS), Quality Meat Scotland (QMS), Scottish Land and Estates (SLE) and Home Grown Cereals Authority (HGCA) and from building additional capacity and techniques through competitive and collaborative UK- and EU-funded research projects. For example, contributions in kind from other researchers and agencies helped to develop the CAP Intentions Survey (a major survey of business characteristics, practices and plans), and work on farm viability and potato sector analysis. Research in the WP will continue to add value to scientific databases and to datasets gathered for administrative /regulatory purposes. The WP will build on existing FP7 successes to try to leverage external funds through Horizon 2020

(H2020) and other sources so as to increase the depth of analysis possible within the scope of the WP research.

1.6 Delivery Risks

Whilst we are confident in our ability to deliver the kinds of analysis specified in the ITGF to high scientific standards and in a way that responds to SG policy requirements, we have highlighted the most serious risks to delivery and where possible taken steps to mitigate these.

Risk Descriptor	Risk Assessment	Impact	Controls	Risk owner	Update including recommendation for mitigation*
Lack of strategic depth in priority areas for RESAS	High – limited scope to provide adequate analysis for new areas such as land reform, tourism and forestry	Only able to provide limited insights into these policy topics. Disruption to other topics e.g. supporting CAP.	Flexibility in work programme through discussion with RESAS – draw more heavily on PAWSA, Underpinning and CRF resources.	WP/RD	Medium – make strategic case to DEC for investment in these new research areas.
Very high rates of staff turnover	High - in current T4 staff turnover was >100% in four years (some staff replaced more than once).	Delays in replacement limited progress in several key areas.	Expeditious replacement approval	WP/RD	Medium - Escalation to DEC if staff not replaced appropriately
Limited numbers of staff with key skills	High - especially for wider supply chains, rural industries and the circular economy	Delay or dropping of deliverables	The WP will build capability incrementally beyond existing expertise and policy domains	WP/RD	Medium - Exploit other capability sources: studentships, HEI, H2020.
High demand for policy-led analysis	High - in current T4 at least 30% of resource has been devoted to this and this may increase.	Limits ability to do strategic research and develop new capabilities	Prioritise delivery to policy. Where possible increase key capacity in the WP (e.g. socio-economics and spatial analysis).	WP/RD	Medium - Monitor policy led analysis and agree work priorities with RESAS.
Partnership working, with other WPs, policy teams and other stakeholders	High – the WP has many potential linkages and these are resource intensive to maintain	Limited ability to support linkages to other WPs / RDs or engage with new policy teams	Prioritise the resources available and where possible increase key capacity in the WP (e.g. socio-economics and spatial analysis).	WP/RD	Medium - Prioritise linkages that add value to the WP and maintain KE linkages with other socio-economics WPs
Access to datasets	High – the research depends on access to regulatory and industry data, new access agreements are needed.	Delay or dropping of deliverables	Need to devote resources before and at the start of the WP to access and extract appropriate data	WP/RD	Low – Gain SG support for access, early interaction with data holders
Inadequate time for stakeholder consultation in ITGF writing process.	Medium - consultation should be an iterative process with face-to-face communication when establishing new contacts.	Limited stakeholder buy-in beyond RESAS damages salience, credibility and legitimacy	Within time and resources constraints good practice was followed. Revise WP on an ongoing basis.	WP/RD	Low- Opportunities for further interaction will be followed up
Not all relevant policy teams are known.	Medium - the RD is less able to prioritise for policy impact	Need to devote time at the start of the WP to building relations with key policy teams	Use contacts in Zero Waste Scotland as “intermediaries” until appropriate policy contacts are established.	WP/RD	Low – Key policy contacts and priorities will be identified in early stages of WP

* This will be reviewed regularly by the management committee who will take the decision to either: ‘tolerate’, ‘continue to monitor’, ‘take action’ or ‘escalate’ the risk.

2 Impact and KE

2.1 Priorities for Impact

The priority for the WP will continue to be delivery to SG CAP policy teams. Where possible, relationships will be extended to, for example, the SG Land Reform policy team, the Zero Waste policy team and the Forestry Commission Scotland. In the RD descriptions there is detail on delivery to RD objectives. At the WP level it is important to provide a strategic overview of the kinds of research capacity that are being developed (for science impact) and the domains prioritised for impact.

2.2 Key research capacities

Conceptually the WP will build on capabilities and scientific methodologies developed within the previous SRPs, highlighted on the left-hand side of Figure 5 (e.g. geospatial modelling, enterprise, farm and sector models and economy wide models, life-cycle analysis, quantitative and qualitative social research). The WP has an appropriate balance of empirical and model-based quantitative analysis capacity and qualitative social research skills in all RDs. Staff are also experienced in combining these methods to deliver high quality interdisciplinary research. Tools and methods being developed within the current programme will be refined and applied, and new methods developed to assess structural and distributional effects and second-order effects shaped by behaviours and interactions.

Initially these challenges can be addressed by enhancing the enterprise, farm and food supply chain models developed in Theme 4 of the existing programme (e.g. ScotFarm), using behavioural models to improve predictive capacities. Opportunities also exist to gain access to more detailed datasets (e.g. the data that underpin Scottish Input-Output tables, Cattle Tracing System (CTS) and ScotEID). This will enable analysis that more accurately quantifies interactions between farms, their suppliers and markets and that can be used in other economic, geographical and simulation modelling approaches. Distributional and interaction questions will be addressed through the maturing field of agent-based social simulation (ABSS). Over the period of the WP the modelling work (and ABSS in particular) will act as a framework for progressively increasing the integration of existing data, simulations, knowledge and expertise in ways that generate better understanding of the dynamics of the system and policy effects. The WP will provide better estimations of emission factors used to assess the environmental impact of economic growth and will exploit newly available administrative datasets on waste arising and waste management for analysis of opportunities for increasing the circularity of rural industries.

The right-hand side of Figure 5 highlights the intended domains of impact. In policy terms there will be a strong emphasis on studying the consequences of the 2014 CAP reforms for farming systems, farm households, the agri-food supply chain and wider rural society and economy. The interaction of the CAP reforms with other key drivers such as market volatility, EU membership or bilateral trade agreements will also be studied. For farm-households the focus will be on adaptation and increasing resilience through diversification of activities, uptake of innovative practices, specialisation and cooperation. Changes in other key components of the agri-food supply chain will also be analysed (e.g. for haulage, processing and retail sectors). The WP will have an important role in providing evidence for the Greening Review and Areas of Natural Constraint (ANC) reviews and any CAP Mid-Programme Review. Whilst land reform is likely to be a slow process, elements of the WP will address important policy questions *vis-à-vis* different types of tenure (both formal and informal) and associated structural changes and build on non-SRP funded work on land reform issues. On the circular economy we will examine key sectors of interest that will be important for the Climate Change Delivery Plan.

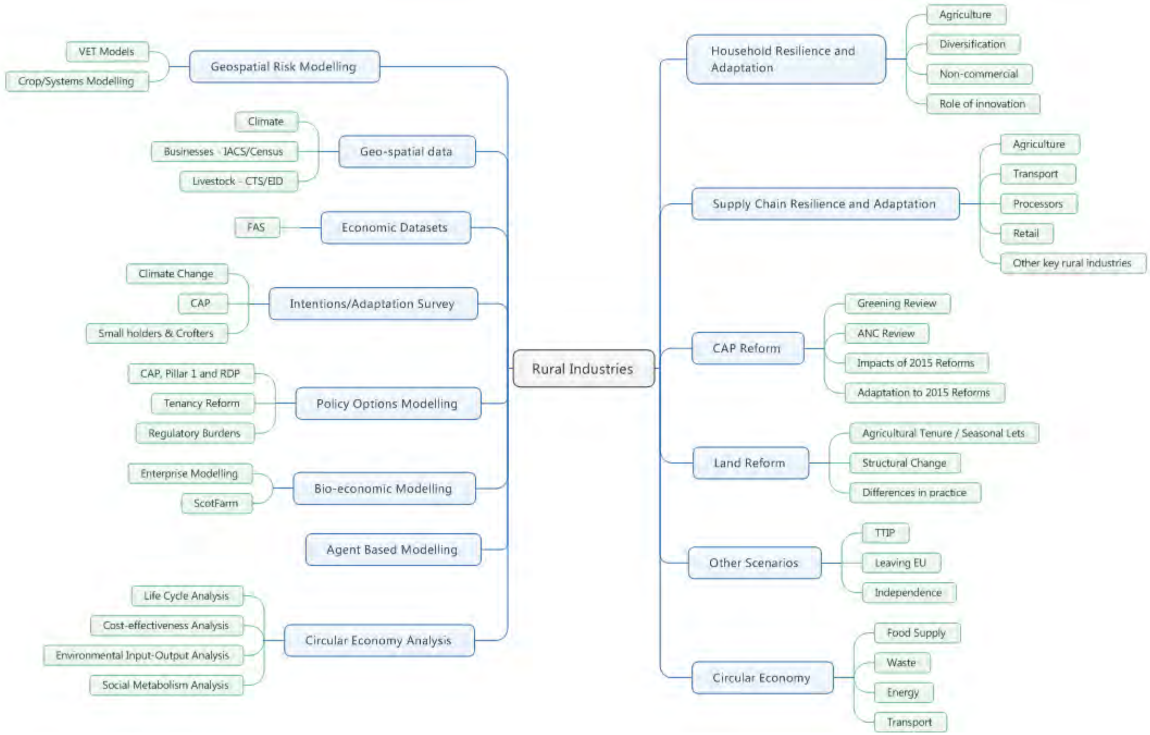


Figure 5 WP2.4 Areas of relevant expertise and impact domains

2.3 Science impact challenge

In the Mid Programme Review (MPR) there was a specific challenge raised for the MRPs. This was how to maintain the excellence achieved in supporting policy teams while achieving greater visibility and impact in science/academic domains and forums. The ITGF specification is narrower than antecedent research and this provided some opportunity to refocus effort, reinforce success and generate strategic science depth. Organisationally, there are fewer and more integrated teams combining SRUC and Hutton staff and these add depth of experience to projects. There is significant continuity of the underpinning science, so science focused outputs should not be disrupted. Throughout there are also opportunities to add scientific value by exploiting resources generated in other research activities (e.g. EU 7th Framework Programme (FP7), H2020) and exploiting these in a Scottish context. Balancing strategic science with policy led requirements, however, remains very challenging.

2.4 Interaction with Central KE resources

A key issue identified in the Mid Portfolio Review (MPR) was that providers perceived the quality and impact of outputs from the SRP as being much higher than the end users did (particularly for policy). A key leadership role in addressing this issue will be through the CKEI (see Figure 1). This centralised KE resource will support delivery of KE impact.

- *Collation, storage and communication of outputs from the components of the SRP, i.e. through a portal or website*: the WP will ensure timely inputs to such a site and the provision of the necessary summary or meta-data such that generating periodic reports is standardised, flexible and conducted efficiently.
- *Identifying research outputs with wider public interests*: providing professional support to scientists in managing their mass media interactions.

- *Branding, design, corporate identity*: here the WP will be making use of central KE services of the CKEI and ensuring that presentational standards are adhered to, particularly emphasising the key role of SRP funding.
- *Hosting and maintaining social media platforms – Facebook, Twitter etc.:* In both these cases the WP has a reactive role of providing content identified as newsworthy but also a proactive role in identifying emerging issues where the MRPs could comment based on current and previous research programmes.
- *Events Management:* The WP will be responsible for making timely and high-quality contributions to major pan-SRP events and providing staff with the knowledge and KE skills needed to ensure that these events are successful.

3 Finance and value for money

Given the importance of socio-economics to underpin SG analysis and policy decisions and to meet the ITGF specifications established by RESAS we will need the full proposed budget allocation. T4 in the current SRP has received very positive feedback from RESAS in terms of delivering impacts in the policy and SG analytical arena and through the adding of value to regulatory databases. Capacities developed under the previous SRPs mean that there is considerable value for money in our approach as many techniques have been developed and will be refined during the programme and linkages to appropriate stakeholders are pre-established.

4 Quality Assurance (QA):

The MRPs and RBGE contributing to this Work Package are dedicated to achieving and maintaining the highest possible standards of quality in order to meet the requirements of their work and the needs of their internal and external customers. To achieve this they will: (1) Comply with the requirements of the Joint Code of Practice (March 2012) on behalf of for quality assurance and the BBSRC Statement on Safeguarding Good Scientific Practice; (2) Operate a quality management system that meets the requirements of the ISO 9001:2008 and which is systematically maintained, reviewed and revised to ensure continuous improvement.

5 Ethical and regulatory issues:

Research involving human subjects is subject to the relevant Research Ethics Committees of the MRPs, which follow the British Sociological Association (BSA) Statement of Ethical Practice. Surveys undertaken as part of the research programme are subject to clearance via the RESAS Research Approvals Proforma.

6 Contribution to the 3R's (reduction, refinement and replacement):

Not applicable to research within this work package.

7 Sustainable Development:

The MRPs have Environmental Policy Statements which affirm that they are committed to adopting and promoting environmental best practice in the aims and operations of their research activities. They are committed to working practices such that the environment is not compromised, and the relevant principles set out in the links provided under the Scottish Sustainable Procurement Action Plan (Scottish Government, 2009). To achieve this they monitor relevant aspects of their activities and make such changes as are deemed necessary to achieve a good environmental footprint. The Institute will operate a waste management strategy which attempts to minimise emissions to the environment and ensures that all relevant legislation is either complied with or exceeded.

RD 2.4.1: Resilience of Rural Economies to Key External Drivers
Research aim and key drivers This research addresses the broad question of how well Scotland's rural industries (e.g. farming, forestry[1] and tourism) can cope with outside pressures such as: more extreme weather events; volatile prices and changes in government(s') policies (e.g. reductions in support for farming from the CAP and land reform). One way of looking at this question is to assess how strongly rural industries can resist change. Another is to assess how capable rural industries are to make changes to their size, configuration or ways of working to continue to deliver the same goods and services but perhaps in different ways. Both characteristics are referred to as resilience by different interest groups, yet they are clearly not the same. The research aims to assess rural industries using both views of resilience so as to better inform debate by identifying vulnerable industries or regions and where new opportunities will emerge. The research links closely to other projects that address related questions: 1) how Scotland's rural industries have and are changing (adapting) in response to the same set of pressures; particularly whether these changes are resulting in more resilient rural industries, and 2) how the land-based industries can be made more circular so that undesirable wastes are minimised or modified to become inputs for other agricultural or industrial processes, thus reducing the burden on the wider environment. The research is being undertaken because there is concern within government about the long-term viability of some rural businesses due to their lack of profitability. There are secondary concerns about rural poverty and environmental damage that can be caused by poor land management practices. It is recognised that for all the key pressures on rural industries there will be either more volatility (markets and weather) or a significant reduction or redistribution of government support (such as from CAP payments). The research will define and test new ways of measuring the resilience of key rural industries. It will use data collected by government and scientists and computer-based research methods to identify sectors and regions where there is limited resilience and explain why this has happened, if it will get worse and what the consequences of such change might be. The research will allow government to be more certain about how external pressures will affect rural areas and how effective any interventions from government might be. The research has been developed in close partnership with SG staff and in consultation with key research collaborators and advisers.
Summary of Work: The focus in this RD is on making forward-looking evaluations of the resilience of rural industries using empirical system characterisations and combining these with model-based scenario analyses and/or specific policy option appraisals. Existing research capabilities developed within the previous programmes provide a strong basis from which to characterise and understand the drivers that change the

[1] Forestry has previously been included in land use modelling and as a management option in adaptation research but the ambition for the WP was to include forestry in sectoral, farm systems analysis. The capacity available to the WP team means this is only possible through trying to align the WP research with that of Forest Research and to exploit linkages (exchanging data and knowledge) and by seeking further funding for collaborative working. See key linkages on page 17.

resilience of Rural Industries (e.g. studies of farm viability). However, it is clear that there are also questions for which existing datasets and methods provide limited answers, particularly in the forestry and tourism sectors. Particular challenges include understanding structural and distributional effects and second-order effects shaped by behaviours and interactions.

The Resilience RD will progressively integrate data, models and knowledge developed in previous SG research programmes and elsewhere (left-hand side of Figure 6) and build evidence on new areas of study (forestry and tourism) to allow the research to better explore and appraise policy scenarios aimed at promoting resilience of rural industries. The four Objectives of this RD are shown on the right-hand side of Figure 6: Objective 1 captures the multiple perspectives on resilience and develops metrics with which to assess them; Objective 2 further develops existing component models and data sources about rural industries. Objective 3 draws on Objectives 1 and 2 to develop integrative agent-based models. Outputs from both Objectives 2 and 3 are used to conduct scenario analysis at the science-policy interface (Objective 4).

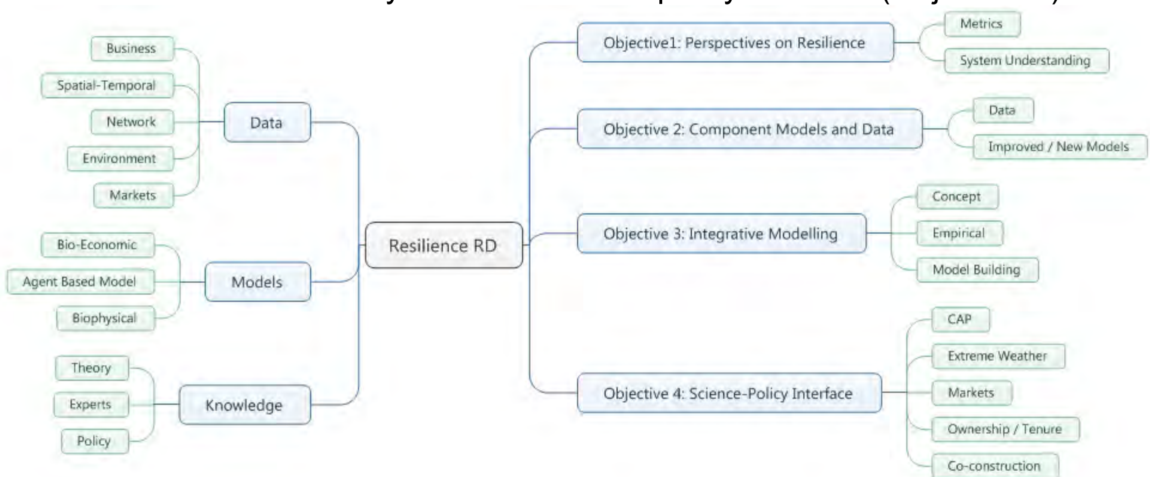


Figure 6. The structure of RD 2.4.1; its sources and components.

Objective 1: Perspectives on Resilience (O1): Resilience can be measured by a range of metrics. This objective will compare measures of resilience generated through the analysis of time series of secondary data sources such as assessments of farm viability within the current SRP to improve our systemic understanding of the alternative perspectives on resilience taken by stakeholders (Barnes *et al*., 2014). Qualitative techniques will be used to examine resilience in rural tourism businesses.

Key Deliverables: how resilience can be characterised and has changed in recent years.

Objective 2: **Component Models and Data (O2)**: This objective seeks to continue the development of existing models and datasets to underpin policy-relevant analyses to be delivered through Objective 4. The component models[2] include approaches to analysing time series of variance in performance and business survival; cropping systems model ensembles and highly resolved, national coverage climatic datasets.

Key Deliverables: new and improved models and integrated datasets that can support the assessment of changes directly or through inputs to Integrative Modelling

[2] The term component models is used here to refer to models that deal with components or parts of the system (e.g. crops, livestock, farm profitability etc.) in contrast to systems or integrated models where function is created through the integration or linking of the components together.

(Objective 3).

Objective 3 Integrative Modelling (O3): This objective focuses on the development of an empirical agent-based model (ABM) of the agri-food supply chain and intra-sector transfers. Work will initially focus on beef production, where existing data are available from which networks of interaction can be derived. This work will initially draw on ABM expertise developed in previous SRPs and on-going collaborations funded by the Norwegian Research Council exploring adaptation to climate change in the beef-dairy value chain.

Key Deliverables: a modelling framework that supports investigation of the changes in resilience (particularly in terms of distribution effects) from behavioural and structural change to inform the analyses being conducted as part of Objective 4.

Objective 4 Science-Policy Interface (O4): This objective has as its focus the delivery of policy-relevant scenario analyses of the consequences of changes in key drivers for resilience of rural industries. Examples identified in the ITGF prioritise reductions in CAP support, markets (e.g. trade agreements such as TTIP), ownership/tenure change and extreme weather events. Over the course of the research programme, further analyses will be developed in cooperation with policy and other stakeholders. This will build on the strong connections of RD staff with a variety of SG policy teams (e.g. CAP, Natural Resources and Rural Development). From this experience we anticipate that outputs from the RD will also be able to underpin other emerging policy-led questions (e.g. on Land Reform).

Key Deliverables - datasets, reports and advice for use with SG analysts and policy makers. Increased participation in SG-led and other stakeholder forums (e.g. by presentations or other interactions).

Technical approach:

The research methods include time series, bio-economic, network, critical incidents, geospatial, cropping-systems and agent-based modelling and analysis approaches to provide multiple complementary assessments of resilience based on existing and new datasets. Interaction with stakeholders and policy-makers in knowledge elicitation, e.g. scenarios of interest and options to appraise, will be through meetings arranged with them, and through enquiries they make of us.

Objective 1. Perspectives on Resilience (O1): There are various aspects to resilience at different levels in rural industry systems. After exploring these, effort will be focused on developing composite indicators of resilience(s) through analysis of time series data and any relationships they have with known ‘shocks’ to the system (such as extreme weather events, changes in CAP, and changes in patterns of demand).

At the individual business level, the assessment of agricultural viability conducted in current WP4.1 will be extended to cover a wider range of factors including biophysical and off-farm income, and to examine rural industrial sectors allied to agriculture. The diversity of resilience will be explored through an analysis of the distribution of income throughout the Scottish farm sector and the influence of tenure. This will extend work on viability, income mobility and efficiency conducted for the Scottish sector (Barnes *et al*., 2014).

Beyond the farm scale, indexes will be developed for resilience of supply chains and rural areas, using measures of total factor productivity for various rural sectors, derived across different industry-specific groupings. New data sources will be sought to develop understanding of rural tourism business resilience (e.g. VisitScotland, Scottish Enterprise, Federation of Small Businesses). This will be augmented by interviews with rural businesses. The impact of shocks will be studied qualitatively with rural business owners (including tourism) and their staff within selected regions and with the focus on specifically identifiable shocks (i.e. critical incidents approach). Two follow up workshops with business owners and enterprise/business support providers will then be held (in appropriate geographical locations) to discuss and cross-check the emerging findings. The resilience metrics will inform component models and integrative modelling in Objectives 2 and 3.

Objective. 2 Component Models and Data (O2): This brings together a number of modelling approaches covering the social and biophysical components of the system, to study the change in resilience of rural industries in response to a number of different shocks. The work will draw on the indicators developed in Objective 1.

There have been a number of disturbances to rural industries over the last thirty years: changes to the CAP in 1992, 1999, 2003 and 2013; the BSE and Foot-and-Mouth Disease outbreak of 2001; the exit of sterling from the Exchange Rate Mechanism in 1992; the financial crisis of 2008 and consequent recession; extreme weather events such as the 2003 heatwave and severe winter of 2011/2. Using time-series data, we will be able to analyse the characteristics and subsequent consequences of these disturbances for rural industries, and the degree to which they may have constituted ‘shocks’ that could potentially have had a significant impact. Using Office for National Statistics, Annual Business Inquiry, Farm Accounts Survey for Scotland, and historical weather data, we will characterise the disturbances across the biophysical and social systems that combine to form shocks at the individual business and system levels. Extreme Value Theory will be applied to this study, along with event and variance-type modelling (such as GARCH and survival analysis). At business level, panel data regression using a variety of non-parametric, semi-parametric and parametric methods will be applied to explore individual farm resilience trajectories before and after disturbances. Markov switching-type regressions will also be applied to the study of changes in farming regime as a whole. Linking with the ScotFarm+ model (in RD2.4.2) will generate indications of payment impact on farm viability series and forecasts.

Shocks associated with extreme weather affects will be given particular attention using geospatial risk modelling. Using a risk framework (vulnerability, exposure and threat from current Work Programme (CWP)4.1), we will study the consequences for rural industries of projected future severity, frequency and changes with respect to past variability of extreme weather events. Spatially contiguous climate projection data for Scotland at 5×5km resolution (HadRM3-PPE) and emerging projections factoring in jet stream interactions with Arctic sea ice and other teleconnections, will be integrated with site-specific and gridded observed data (UK Meteorological Office - MIDAS), the Hutton Soils database and in-house crop management data to simulate primary production using an ensemble of cropping systems models. This will test the resilience of primary production under current management practices to extreme weather events and background climate change. This will use ensembles of crop models run across the whole of Scotland, on a new multi-purpose modelling platform (Alternative management options are addressed in RD 2.4.2 Adaptation). This work builds on analysis within the current Economic Adaptation theme and on-going projects (AgMIP, MACSUR) that explore the changes to current practice that promote individual crop and business-level resilience, and global scale analysis of extreme weather on food security (GFSP Task Force).

Objective 3 Integrative modelling (O3): A spatially-explicit agent-based model will be used as the environment in which to integrate knowledge, data and component models from elsewhere in this RD and WP. Learning from established best-practice in integration from the literature, the agent-based model will be built as an internally consistent integrated model in its own right, drawing on, but not necessarily directly using, models and evidence from Objective 2 and RD 2.4.2. Using thinking from the social metabolism literature, we will represent businesses (or potentially groups of businesses) as individual agents, and model the exchange of goods and services between them. At the heart of the model is a database of activities that rural businesses could choose to do (populated from work in Objective 2), which includes details of the resources, infrastructure and environmental conditions needed, together with the outputs generated by the activity. The choices of the agents are then about which activities they will undertake, how and from whom they will source the inputs, and how or to whom they will sell or dispose of the outputs. These choices create a network of interaction among businesses that is both a flow of money and a network of flow of resources mediated through the transport infrastructure. An environment such as this creates a platform in which scenarios can be explored, exposing potential vulnerabilities and lock-in limitations due to path dependencies. Using ABSS allows us to show the potential distributional effects of such scenarios, from individual business and geographical perspectives, and, where metrics from Objective 1 can be applied to variables in the model, to provide assessments of how the scenarios affect resilience. To be useful to the SG and other key stakeholders, the model will need to be populated in ways that are based on empirical data for Scotland. Though challenging, this presents an excellent opportunity for a cross-MRP exercise that further exploits existing administrative and research-based datasets. Although we envisage a model in which the whole supply chain can be simulated, in the first instance, we intend to focus on the beef agri-food sector, as this is a major area of rural activity anticipated to experience complex patterns of readjustment following 2015 CAP reforms.

Objective. 4 Science-policy interface (O4): This objective recognises the need to invest time and other resources into undertaking translational, co-construction and other activities across the science-policy interface if the research undertaken is to maximise its intended impact. A dedicated science–policy interface objective provides an additional locus for integration and synthesis of activities conducted elsewhere in the RD. Generically we anticipate being proactive in undertaking scenario analyses within the scope defined by the ITGF; that is, we will assess the resilience of rural industries in the face of key policy, market and environmental drivers identified in other Objectives and evaluate the potential role of policy in enhancing such resilience. Experience in the current SRP means that we can also anticipate that the capabilities of the RD team will be drawn on regularly by SG to address emerging policy options questions. To do so in a timely fashion, resources need to be flexibly deployed and these contingencies allowed for within the scope of the strategic work plans.

Beyond policy support, there are also specific needs for knowledge elicitation from stakeholders and policy-makers, including understanding different perspectives they have on resilience, specifying priorities for scenarios to explore, feedback on model design and the key dimensions of concern for extreme events analysis. We propose to handle these chiefly through multi-stakeholder workshops, which will be co-organised with other RDs and WPs as far as possible in order to minimise inconvenience and participant fatigue. As an RD within a transdisciplinary WP, we will continue to co-construct analyses as far as possible while maintaining appropriate independence and rigour. We foresee that interest in the findings and tools developed in this RD will lead to invitations to participate in relevant panels and requests to present the outcome of policy options appraisals to a range of audiences, as has been the case in the current SRP. Such interactions are an important metric for the success of the RD. Finally this Objective provides the resources to support innovation, evaluation and for sharing of good practice within the team and to other RDs and potentially to other WPs.

Detailed Work Plan

The work plans for Y1 and Y2 are set out in the GANTT charts at the end of this document. The section below itemises the deliverables lists in the chart. Key deliverables include: (Numbering system for deliverables relates to Gantt charts listing Deliverables (D#), KE/impact events (KE#), Published papers (KEp#) for Years 1-2). Experience in the current SRP has indicated that, given the high levels of interaction with RESAS, policy teams and others, that the timing of deliverables (i.e. the specific materials that cross the science-policy interface) can be difficult to predict. Therefore the specification of deliverables below indicates a trajectory for the strategic research that we expect to be heavily modified as the RD responds to emerging issues. Where deliverables are anticipated to occur beyond Y2 these are noted as such in the GANTT.

Deliverables

Objective 1 (O1) Perspectives on Resilience

Viability Analysis - compilation of resilience indicators at farm level (D1), resilience indicators within rural industries (D2); efficiency indicators at farm level (D3), productivity indicators at rural industry (D4).

Objective 2 (O2) Component Models and Data

Temporal dynamics of viability (D5), Survival analysis of farm viability (D6), Past policy effects on viability (D7), Drivers of rural industry viability (D8).

Extreme weather events will define and characterise extreme events, develop and compile data structures, build model ensemble capacity (D9) and undertake a knowledge elicitation workshop (KE1); conduct historic trend versus future projection variance analysis (D10); consider the impacts of extremes on primary production (cropping) systems (D11), includes a knowledge exchange workshop (KE2); provide agro-meteorological metrics as indicators of extreme weather impacts from multiple weather variables in communicable forms (D13); combine cropping and agro-meteorological impacts to consider impacts on livestock systems (D14).

Objective 3 (O3) Integrative Modelling

Agent Based Modelling –initial design of the model, with a particular focus on the data structure for storing activities (D15); initial parameterisation of the model, including an initial set of populated activities (D16, KE3); demonstrator version of the model available showing its potential and capabilities (D17); agreed initial scenarios to explore with the model (D18, KE4); parameterisation of the model suitable for exploring the scenarios (D19).

Objective 4 (O4) Science policy interface
This conducts interaction with policy and analysis teams either proactively (KE5, KE6), via workshops and meetings or responding to ad hoc requests for analysis.

Key linkages, interdisciplinarity & collaboration
Socio-ecological systems theory suggests that maintaining long-term, system integrity means promoting flexible adaptation rather than rigidly resisting pressures. This RD will therefore collaborate closely with RD 2.4.2 Rural Economy Adaptation, by sharing datasets, models and staff, and cooperating in terms of presenting outcomes to achieve greater impact, scientifically and with policy. Outputs from RD 2.4.3 Environmental Sustainability/Circularity of the Rural Economy could enhance characterisations of resilience by more fully considering environmental consequences. Resource available, however, mean that a full consideration of the resilient use of natural resources is unlikely to be possible when set against other policy-led priorities. This RD will contribute where possible on this topic in analysis being carried out in RD1.4.2 (Identifying and understanding multiple benefits and trade-offs).
As noted in the work package, we intend to collaborate with work packages WP1.4 (Integrated and sustainable management of natural assets) and WP3.4 (Communities and wellbeing) in the conduct of policy options appraisal and supporting analyses so as to provide assessments of the environmental, economic and social consequences, emphasising the depth of socio-economic analysis possible in the SRP.
Other opportunities for interdisciplinary linkages via exchanges within the SRP are with WP3.1 (Improving Primary Production) drawing on simulations by the crop model ensemble (particularly barley) and RD 2.3.11 (Trade-offs between productivity) where information on farm viability from this RD may be valuable. Interaction between farm and non-farm incomes (at household and regional scale) will be jointly pursued with RD3.4.1 (Demographic change in remote areas). With RD2.1.8 (Novel Crops) there is some potential to explore options for exchange of knowledge and data and to cooperate on emerging policy questions. This linkage is mainly with the extreme weather events analysis in Objective 2 of this RD but may also have value for the ScotFarm+ modelling in RD2.4.2.
Forestry is included in land use modelling and behavioural analyses in this RD and RD2.4.2. It would be highly desirable to incorporate a more sophisticated representation of forestry across the work package. This is true both for analyses at business scale (adding farm woodlands and on-farm use) and for the macro analyses (adding forestry companies as components of sectoral and regional analyses). To better address forestry within the limits of the capacity available, the best available option is to align the WP with the research programs of Forest Research (particularly their socio-economic and ecosystem services led programmes). WP leads met with senior FR staff and identified more than a dozen topics in which there were immediate potential benefits from cooperation, with both WP and FR sharing the same objectives of improving resilience. It was agreed to initiate improved liaison with the intention to exploit together existing data and other research outputs and to seek funding that will

make cooperation on initiatives possible (e.g. from Year 2 HEI funding in the SRP). Further opportunities are present in current H2020 bids (e.g. Water 2b Nexus, CEDOC) and ongoing projects e.g. New Path (Norwegian Research Council) (NewPath). A joint PhD studentship between the University of Nottingham and SRUC on farm-level modelling and microsimulation with FAS data will feed into RD2.4.1. Linkages with BioSS will be through their consultancy services particularly on extreme event modelling, data mining and simulation model output summarising.

Added Scientific Value

The focus of the research in terms of Scotland and SG policy means that the research conducted tends not to overlap other initiatives but there are complementary interactions. Research in the current SRP has seen significant interactions with other SG-funded activities. For policy-led research there have been "call down" projects within Veterinary and Advisory Service[3] (VAS) for SRUC, via Policy Advice with Supporting Analysis (PAWSA) within Underpinning for James Hutton Institute, and in the Centre of Expertise for Climate Change. In these cases strategic capacity developed within the current SRP has been deployed in a timely way to address issues with immediate policy interest. Such capacity has also been deployed regularly through SG's contract research fund (e.g. Pack Inquiry on Future Support, Agricultural Holdings Evidence Review, Woodland Expansion Advisory Group).

Research within the RD will benefit by having access to data, expertise, methods and capacity from staff's previous participation in EU and UK government-funded international research – Defra (e.g. the review of PES), FP7 (e.g. GILDED and LoCAW), FACCE-JPI, AgMIP, MACSUR. Such interactions will continue in this RD.

KE, Audiences and Impact

Audience - As set out in the WP description, there are clearly identified stakeholders who will benefit from research. In terms of timing of impacts, it is anticipated that, since this RD is largely an evolution of existing research programmes, benefits for stakeholders in terms of useful outputs and other interactions will occur in Year 1 and continue throughout the lifetime of the programme.

Research Collaborators will benefit from interactions with the research teams through shaping successive research cycles – initiation, execution and reporting. For CAP-related work we anticipate continuing to work with the extensive network of contacts we have developed within RESAS and Rural Payments and Inspections Directorate (RPID). The new programme offers opportunities to develop new working relationships with HGCA, QMS, CTS and ScotEID, VisitScotland, Federation of Small Businesses as providers of knowledge and data for various agricultural sectors. RD staff also have well-established links to model developers such as DSSAT, APSIM etc.

Direct Stakeholders are those policy teams within government that can make direct use of the research outputs. For this RD, these include CAP, Rural Development Policy and Ready Scotland. They will benefit from both the development of the strategic research capacity within the RD in contributing to foresight but will also the specific instances of research being undertaken since they have the leading role in defining the ITGF and its subsequent reshaping in the light of emerging priorities. This reshaping

[3] It should be noted that with the introduction of the Farm Advisory Service that will replace the VAS programme in 2016 there is currently no alternative model for SRUC to conduct short policy "call down" research.

process means that direct stakeholders will benefit from being able to draw on the expertise base within the RD to inform policy options – e.g. Greening, ANC, post 2020 CAP and Land Reform.

Advisers and Interest Groups will interact with the RD through processes of expert review and dissemination. These organisations typically have more intensive interactions near the completion of research cycles but can also see event-driven and ongoing interactions e.g. participating in the Future CAP stakeholder group, providing information to the proposed Land Commissioners and Tenant Farming Commissioner.

Supranational Institutions provide forums within which outputs from the RD can be internationalised showcasing outputs and processes of science-policy engagement. RD staff have active networks of contacts and we will prioritise with RESAS when participation is appropriate e.g. the GFSP Extreme Event Task Force.

Public are primarily interacted with through the facilities of the Central KE resources of the CKEI with the intention that there is an ongoing process of KE through a variety of online and other media that raise awareness and demonstrate value for money from the SRP. The RD will provide timely and appropriate inputs to this process.

Science Community will see interaction with the RD through peer-review publication and presentation at appropriate forums. The WP leads will seek to maximise the science impact of the RD by careful targeting and prioritising of journal publication and through coordination with other RDs to raise the profile of the SRP at events.

Impact - The types of impact anticipated for the RD are identified below with the intention that specific outputs will be flexibly delivered in response to interactions between the RD team and the stakeholders identified above (ongoing co-construction). The RD will be proactive in seeking audiences for new research results emerging from the strategic aspect of the RD while reacting positively to requests for particular analysis particularly from directing stakeholders. The mechanisms and management of this process is described in the WP text since this is generic to all RDs in the WP but can be summarised as conducting research in ways that generate salient, timely outputs that are credible, legitimately derived and viewed as impartial by stakeholders.

Instrumental – the RD will make specifically identifiable contributions to policy development, implementation and evaluation (prioritising the instruments of the CAP and Land Reform issues). The impact of the research will be measured through the utility of outputs being acknowledged by SG analysts, officials, ministers, MSPs and representatives. In antecedent research on CAP, farm regulation and agricultural tenure instrumental impact has been achieved by regularly providing new, improved or recombined datasets and evaluations or syntheses of existing evidence bases. WP staff have also made appraisals of specific policy/regulatory options, usually reactively but in some instances using the “creative space” of the SRP to demonstrate the potential of alternative approaches. A key role for researchers is in assiting interpretation of the outputs of analyses with stakeholders and participating in forums where options are debated (e.g. Future CAP Stakeholders and Scottish Farmed Environment Forum). This activity grounds researchers in the reality of policy making and the consequences of policy making for stakeholders. WP staff will also have a role in prototyping administrative processes (e.g regionalisation or spatial targeting) used in the implementation of agreed measures working with RPID staff. The expectation is that all these activities will continue and that the research conducted will be used directly by analysts and policy makers in the full range of forums from consultative to decision making. Instances of known policy developments where instrumental impacts are sought are itemised in the science-policy objective in this RD. There are also broader policy questions that while they have no client at this stage are anticipated by RESAS analysts and for which preparations can be made. These could include the consequences for rural industries of: (a) the potential exit from the EU, with or without a further referendum on Independence; (b) land reform matters (e.g. succession laws, tenure issues) that can build on ongoing work examining diversity of land ownership.

Conceptual – the RD will also generate through seeking instrumental impact, new and influential understandings and awareness of the factors underpinning the resilience of the rural industrial systems; deliberated on in high-profile scientific and stakeholder forums (both those organised by the WP and by others). Conceptual change was seen as difficult to achieve in the CAP case-study of the Mid-Programme Review, yet testing the prevailing narratives is arguably an essential part the role for science in policy development. The challenge for the WP is to better engage with key opinion formers within and beyond government in ways that foster willingness to look again at issues and policy options (e.g. in the work undertaken for the Doing Better review of red tape in farming). This probably needs to be in Chatham House type forums where participants have more freedom to move from publically stated positions. Options for such events hosted by RD/WP staff will be explored.

Attitude/Culture – the RD staff will be required to ensure that, in addition to being rigorous and appropriately innovative, their research is conducted in a way that maximises its utility to policy and government. This will mean investing time in understanding the timelines that dictate when inputs are needed, the forms that outputs need to take to be usable, and the social processes within which they are used. This approach to research is a vital precursor to conceptual and instrumental impact and means senior research staff, familiar with policy processes, will be active in raising awareness of the opportunities for engagement, shaping the conduct of research and ensuring that all research conducted has clear policy relevance.

Enduring Connectivity – the RD will maintain and improve its staff's connections into government and industry to facilitate exchanges of knowledge and data. The RD staff will also seek to develop mutually beneficial connectivity with research organisations beyond Scotland as part of the drive to internationalise the SRP (e.g. through AgMIP, GFSP). See Key Linkages and Added scientific value sections above.

Capacity-Building – the RD will more fully exploit and leverage existing capability and capacity through developing supporting research proposals from other funders and investing in the strategic capacity needed to tackle emerging issues identified with our directing stakeholders.

RESEARCH DELIVERABLE NUMBER: 2.4.1
Work planning and timetable for Year 1

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 - resilience indicators at farm level								D1		KEp1		
O2 - resilience indicators within rural industries												D2
O2 - temporal dynamics of viability												
O2 – extreme weather, definition, data sources, model-ensemble building					D6 KE1						D7	
O2 - historic versus future analysis												
O2 - cropping systems impacts												
O3 - Agent Based Modelling, model design and implementation				D15							D17	KEp3
O3 - Model parameterisation									D16			KE3
O4 - Science Policy Interface, proactive engagement									KE5			
O4 - responding to ad hoc analysis requests												

(RESEARCH DELIVERABLE NUMBER: 2.4.1

Work planning and timetable for Year 2

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 - efficiency indicators at farm level						D3						KEp2
O1 - productivity indicators at rural industry level											D4	
O2 - temporal dynamics of viability				D5								
O2 - survival analysis of farm viability						D9						
O2 - past policy effects on viability										D10		
O2 - drivers of rural industry viability												D11
O2 - historic versus future analysis					D8							
O2 – cropping systems impacts								D12		KE2		
O2 – agro-metrics for extremes												D13
O2 – livestock systems impacts												D14
O3ABM model design and implementation												
O3-ABM model parameterisation							D19					
O3 -ABM scenario analysis					D18					KE4		KEp4
O4 - proactive engagement									KE6			
O4 - responding to ad hoc analysis requests												
Year 1 Annual report to RESAS			R1									

Name of RD: How rural economies can adapt to key external drivers

Research aim and key drivers

This research will assess recent and anticipated adaptive responses to environmental change, the CAP and other policy and market shifts; identify processes of innovation, diversification and collaborative action in agricultural household adjustment and assess future influences on the adaptive capacity of segments of the agriculture sector (e.g. size and tenure, commodities and supply chains, geographical regions).

The 2014-2020 CAP reform package will deliver the most fundamental change for over a generation in how Scotland's farming sector are supported. As the CAP moves away from historic towards regional payments, there will be a significant redistribution of support payments within the industry (and regions), with those farmers that were historically intensive being hardest hit. By 2020, the farming sector and its ancillary industries will also be faced with: exchange-rate fluctuations; general and Scottish elections; consequences of dairy quota abolition in the EU; land reform and agricultural holdings legislation reforms; the review of ANC; the Greening review; and future CAP reforms (including a new Multi Annual Financial Framework).

The context in which farm households and rural businesses are adapting is already in transition: in 2005 the Fischler reforms of the CAP introduced a step change in how support was delivered to farmers through decoupling of support payments. Significant business rationalisation in the hill, upland and island sheep sector followed, although the impacts on the beef sector were far less reaching. Since 2005 farmers have also been faced with considerable fluctuations in the exchange rate, abolition of set-aside, input prices inflation, increased market returns in the red meat sector, wide fluctuations in dairy returns, rising land values and the introduction of incentives for renewable energy and heat production. The adaptive responses of some farmers to these drivers have led to improved market-awareness with greater focus on technical efficiency and increasingly diversified income streams.

In addition to CAP the new land reform agenda will likely have impacts on agricultural tenure and on land ownership (e.g. review of succession, community right to buy) that rural industries will have to adapt to. Whilst this is a relatively new area of study the research team can draw on their growing experience in the subject to answer forthcoming questions relating to land reform that may come from policy leads or the proposed land commissioners and tenant farming commissioner. Experience includes the agricultural tenancy evidence review and projects on diversity of ownership, economic impact of estates, seasonal grazing lets and land-use assessment of 432:50 (where 432 owners hold 50% of the land area). This will lead to a more informed debate amongst key stakeholders and the wider population

The research team have developed substantial databases and models which are already delivering across the science-policy interface. New research will:

- Update and improve on the geospatial datasets available for research by linking with the SG's Futures Platform, CTS and Scot EID systems.
- Assess the innovative capacity and diversification trajectories of Scotland's land-based businesses, building on the 2013 CAP intentions survey with novel mixed-methods approaches, and a follow-up CAP Impacts survey in 2017/2018.
- Improved understanding of industry linkages through social network analysis of

livestock movement data.

- Predict adaptive changes of farm households and selected supply chains to a range of future policy and market scenarios
- Inform the science-policy interface through co-construction of analysis.

Summary of the proposal

The Adaptation RD will integrate data (e.g. IACS, JAC, intentions surveys, livestock movements, and bio-climatic data), models (e.g. ScotFarm and cropping systems ensembles) and existing knowledge (left-hand side of Figure 7) to allow: (a) an assessment of how the farming sector, and ancillary industries, adapt to CAP reform, other policy and market signals; (b) identification of enabling mechanisms to support innovation, diversification, collaboration and specialisation; and (c) prediction of how the sector is likely to respond to future scenarios. A range of innovative methods for assessing change processes will be developed and tested: 1) combining innovation theory with network analysis; 2) using mixed methods analysis; 3) structural modelling of the impact of multiple stochastic shocks on farm business diversification; 4) extending economic models to integrate dynamic biophysical processes and observed behavioural elements; 5) creating multi-level geospatial datasets and 6) applying social network analysis to regulatory datasets.

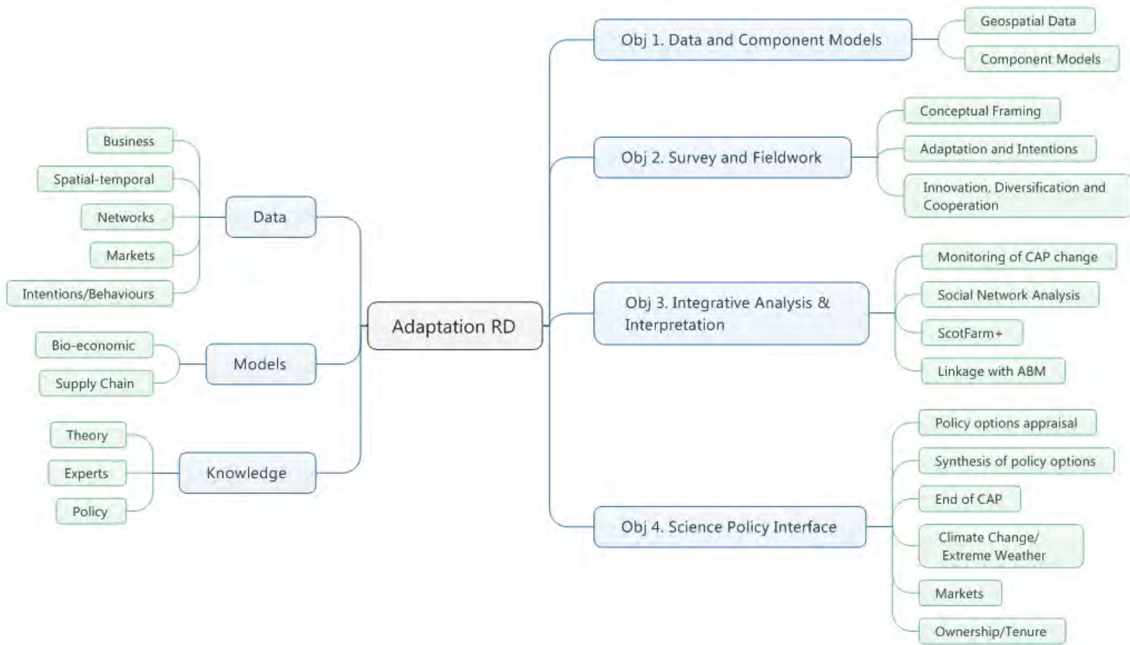


Figure 7. Diagram outlining the structure of this RD; its inputs and outputs

The four Objectives of this RD are shown on the right-hand side of Figure 7.

Objective 1: Data and Component Models (O1): Further develops datasets and models used for analysing and modelling adaptation in farming and related sectors. Datasets include: IACS (with interaction with the new CAP Futures programme a key new focus), June Census, climate and livestock movements data. Component models include bio-economic models such as the ScotFarm and dynamic programming approaches to long-term farm planning that will include new grass growth and behavioural components.

Key Deliverables: new and improved models and geospatial datasets.

Objective 2: Survey and Fieldwork (O2): Generates data and information on the past and future adaptive responses of the farming sector to its operating environment and how it innovates, diversifies and co-operates. The research will identify indicators of innovation and diversification from the 2013 CAP Intentions survey, assess the adaptive capacity of Scottish farmers and inform the selection of two sub-national 'hotspots' of innovation and diversification for more intensive analysis. Qualitative research into innovation pathways and knowledge networks will identify drivers and barriers to innovation and business diversification, as well as mechanisms for capacity building, in different regional contexts and for businesses of multiple scales and tenures. A second major (CAP Impact) survey of farm businesses will follow in (2017/18).

Key Deliverables: national coverage analysis of innovation, diversification and specialisation of land-based businesses at multiple scales; and sub-national comparisons of diversification trajectories (specialisation, agri-renewables, agri-tourism) and underlying networks and enabling mechanisms. New empirical data on farmers' attitudes, behaviours and responses to change used in other objectives.

Objective 3 Integrative Analysis and Interpretation (O3): This will 1) develop farm business models that allow for differentiated behavioural responses; 2) analyse farmer social networks and 3) monitor historic and ongoing adaptation through combinations of administrative data and surveys of farm behaviour. The ScotFarm model will be linked to an external partial equilibrium model to better analyse farmer adaptive responses to change such as market pressures and technological opportunities. ScotFarm will also be linked to a microsimulation model to provide improved geospatial representation of predictive adaptation responses. Social network analysis of integrated livestock movement and JAC data will improve knowledge of farmer linkages in the livestock sector and adaptations over time that will be used to inform the Agent Based Modelling in RD2.4.1. Analysis of integrated databases will be undertaken to monitor adaptive responses to CAP reform and other shocks, including farmers' adaptation pathways compare to stated intentions.

Key Deliverables: Quantitative analysis of farm adaptations and intentions to inform policy evaluations (*ex-post* and *ex-ante*) backed up by an integrative modelling environment that supports investigation of the predicted adaptive changes by farm households. Network models of farmer interactions to support ABSS (RD2.4.1).

Objective 4 Science-Policy Interface (O4): Delivery of policy-relevant scenario analyses examining the predicted adaptive responses to drivers in the agricultural sector (e.g. changes in CAP support, changing market conditions, trade agreements such as TTIP, ownership/tenure change, and extreme weather events). Further analyses will be developed in cooperation with policy and other stakeholders. The objective also provides the resources and environment in which particular policy questions can be addressed (e.g. assessment of CAP payment redistribution in the current SRP).

Key Deliverables - datasets, reports and advice that are used by SG analysts and policy makers. Increased participation in SG-led and other stakeholder forums (e.g. by presentations or other interactions).

Technical approach

Objective 1: Data and Component Models (O1) - This objective aims to further develop geospatial data sets and bio-economic models and to use them directly in the assessment of adaptive responses to key drivers (e.g. through Objective 4) and through underpinning work elsewhere in the WP and the wider research programme (see linkages below). The geospatial data acts as a framework for sampling or extrapolation in the conduct of qualitative social research (e.g. in Objective 2).

Work will improve, update, maintain, quality-control and disseminate geospatial datasets derived from administrative and scientific sources through processes of data integration, synthesis, spatial and network analysis. With the new RPID information system "Futures" which will replace IACS as the main source of land use and ownership data, new processes and data structures will be needed that maintain continuity in the time series. Accessing an improved up-to-date suite of climate datasets (beyond HadRM3-PPE UKCP09) will improve analysis of the extreme weather events in RD2.4.1 and climate change as drivers of adaptation. Analysis of livestock movement data (from CTS and ScotEID) will provide new insights into farmers' interactions with others (e.g. traders, markets, processors) by geography, farm size, occupier type, etc. These datasets will also be structured and analysed to shed light on other adaptations in management practices (e.g. breeds, calving periods, crop and system ideotypes etc.). Having initiated the addition of behavioural questions to the FAS dataset and generated a behavioural typology (see Barnes *et al*. 2011), the new data will underpin new components within the ScotFarm model.

Farm-level economic dynamic models, such as ScotFarm developed through the current SRP, are useful tools for examining economic adaptations under different policy and other changes. However, most of these models have restrictive assumptions about farmers' behaviours and wider farm household income in their predictions of adaptation. The work will extend the ScotFarm model by developing cropping and grass modules and farmer behaviours (potentially including the role of off-farm income). The predictions of farm-level adaptive responses to policy and other scenarios will inform analyses that are delivered through Objective 4.**Objective 2: Survey and Fieldwork (O2) -** This objective will use qualitative and quantitative methods separately and together to assess how the farming industry (including other land-based businesses and wider up-stream and down-stream supply chains) adapt to current and future changes. National-level quantitative analysis to assess farmers' adaptive responses will make use of secondary data sources (e.g. from Objective 1) and combine these with data from the 2013 Farmer Intentions Survey and 2015 Innovation Survey to facilitate direct comparison of stated intentions with real actions as CAP reform is implemented.

Further geospatial analysis of the 2013 and 2015 surveys and secondary data sources (e.g. EU Farm Structure Survey) will also inform identification of differential transition pathways (e.g. between different scales, tenures and locations of businesses), and enable selection of two sub-national 'hotspots' of innovation and diversification for targeted qualitative research. This research will combine network analysis with innovation-theory led qualitative research to identify drivers, barriers and underlying enabling mechanisms (such as collaboration and information exchange) of business specialisation, and diversification into renewable energy, tourism, in contrasting locations (remote rural and peri-urban). Analysis will identify differential adaptation strategies based on tenure and scale (e.g. crofts, estates, tenants, community ownership) and how these are influenced by key drivers (e.g. CAP reform, commodity markets, land reform, succession and new entrants). As such, the research brings together and builds on the expertise developed in the current programme on agricultural transition pathways, diversification, new entrants, and collaboration, with a consolidated focus on innovation and adaptive capacity. Findings from the qualitative research will be used to further develop the 2017/2018 CAP Impacts survey. This will update empirical evidence of farmer attitudes, adaptive behaviours and future intentions, including the role of off-farm income streams. The survey informs work in all objectives in this RD and parts of RD2.4.1.

Objective 3 Integrative Analysis and Interpretation (O3) - Through integration of existing models and datasets and interpretation of their combined outputs (also drawing on the qualitative research in Objective 2), there are significant opportunities to develop new research capabilities. These will provide more complete understanding of processes of adaptation which in turn will better support scenario and policy options analysis (in Objective 4). Integration can be in terms of new combinations of datasets, linkage of models or comparison of their outputs and reinterpretation of their underlying assumptions, structure or parametrisation. The common challenge is to better represent the diversity of Scotland’s rural industries so that we are better able to understand the dynamics of adaptation by explicitly representing within the modelling distributions of natural resources, infrastructure, knowledge, finance, government support and most significantly differences in values, attitudes and behaviour.

Mathematical programming models of Scottish beef and pork supply chains will be further developed to assess adaptation to policy, market, disease, weather, etc. that will support policy decision-making and enhance understanding of the adaptability and resilience of different supply chains (e.g. the vulnerability of the pork supply chains and lack of adaptability were exposed in 2013 with the closure of Halls of Broxburn). These models will provide an economic analysis framework within which to assess the resilience of important Scottish livestock supply chains (in RD2.4.1).

Linkage of ScotFarm with a partial equilibrium model (e.g. FAPRI/CAPRI/AgLink-COSMO) will also be established to account for price volatility in the model. The ScotFarm model will also be linked to a micro simulation models like SMILE (Spatial Microsimulation of the Irish Local Economy) to improve the geospatial dimensions of the modelling results (joint PhD studentship with Nottingham University). This new ‘ScotFarm+’ model will be used in RD2.4.1 to create spatial representation of Scottish farming resilience and how this may change under policy and market scenarios.

To adequately ground the agent based modelling of the flows of materials and value in the agri-food supply chain (developed in RD2.4.1) will mean using most of the geospatial datasets to which the teams have access (through Obj 1), investigating new sources (such as CTS and ScotEID) and representing data in new ways (as networks and flows). There will also be opportunities to generate new insights though interaction between the evolved ScotFarm+ and ABSS models (for example in testing behavioural assumptions and secondary effects between productive and consumptive sectors.

Objective 4 Science-policy Interface (O4): As noted in the RD2.4.1 it is anticipated that with appropriate investment in co-construction many outputs (such as scenario analyses) from the strategic research within this RD will also be directly policy relevant, for example feeding into developing policy agendas such as the land reform, community empowerment, succession, agricultural holdings, as well as scheduled government reviews such as the Report on the Economic Condition of Crofting due in 2018, Greening and ANC reviews and the next CAP reform discussions from 2019. The science-policy interface objective, however, also recognises the need to go beyond the scope of the ITGF as written in 2014 and to build in flexibility and capacity within the RD to customise analyses and/or conduct new policy-led analyses to address emerging issues. As noted in the WP we will seek opportunities to achieve impact but will do so in a coordinated way prioritising activities with RESAS and SG policy contacts.

In addition to assessing particular policy options as they arise, the RD will undertake a synthesis of policy actions to assess their effects on overall adaptive capacity of the sector. This objective provides the environment within which the research team as a whole can undertake a synthesis that draws together relevant outputs and insights from this RD, other RDs in the WP and aspirationally from other WPs with relevant insights. Such a synthesis could be based on assessment of policy and other drivers on a variety of underpinning capitals – natural (with WP1.4), financial, technical (with WP2.3), human and social (with WP3.4). The within-WP synthesis is potentially very valuable since combining research-based insights on resilience and adaptation could (and arguably should) influence how these ideas are conceptualised within policy processes.

Detailed work plan

The work plans for Y1 and Y2 are set out in the GANTT charts at the end of this document. The section below itemises the deliverables lists in the chart. Key deliverables include: (Numbering system for deliverables relates to Gantt charts listing Deliverables (D#), KE/impact events (KE#), Published papers (KEp#) for Years 1-2 only). Experience in the current SRP has indicated that, given the high levels of interaction with RESAS, policy teams and others, that the timing of deliverables (i.e. the specific materials that cross the science-policy interface) can be difficult to predict. Therefore the specification of deliverables below indicates a trajectory for the strategic research that we expect to be heavily modified as the RD responds to emerging issues. Where deliverables are anticipated to occur beyond Y2 these are noted as such in the GANTT.

Deliverables

Objective 1 (O1) Data and Component Models

- Improvement of geospatial data – will integrate CTS (D1), update land use and users data from SG Futures (D2) and integrate ScotEID (D3).
- Evolve the ScotFarm model through development of additional modules: Grass growth module for Scottish conditions (D3); Crop rotation and crop growth module for Scottish conditions (D4), and; Estimation of risk parameters and behavioural module for Scottish farmers (D5)

Objective 2 (O2) Survey and Fieldwork

- Analysis and mapping of 2013 CAP Intentions Survey will finalise the analysis of the 2013 CAP Intentions survey and follow-up 2015 Innovation survey, yielding reports on innovation in Scottish agriculture (D6), non-commercial farming (D7) and farm business diversification (D8). These reports will include maps demonstrating the spatial distribution of the phenomena.
- Field research will be undertaken in two subnational 'hotspots' of diversification (site selection D9), and data collection completed (D10).
- Analysis of field research will yield initial results in the form of a report for participants and stakeholders (D11). Findings will feed into an up-dated CAP Impact Survey to provide an evidence base for further CAP reform.
- CAP Impact Survey designed and submitted for approval (D12).

Objective 3 Integrative Analysis and Interpretation

- Links ScotFarm+ model to external partial equilibrium model (D13) and to microsimulation model (D14).
- Analyse social networks of Scottish cattle farms (D15).
- Monitor adaptive responses of farmers to CAP reforms and other factors (D16, D17).

Objective 4 (O4) Science policy interface

- Link with policy and analysis teams proactively via workshops and meetings (KE2 & KE3).
- Respond to ad hoc requests for analysis.

Key linkages, interdisciplinarity & collaboration

Adaptation and resilience are closely linked aspects of the dynamics of rural industries. As outlined in the Resilience RD (2.4.1), both issues will be addressed in a coordinated way so as to maximise the potential for scientific and policy impacts. Metrics of sustainability/circularity from RD 2.4.3 Environmental Sustainability / Circularity of the Rural Economy could be used to provide an additional perspective on the consequences of adaptations especially with regard to any intensification of activities.

As with the Resilience RD, we envisage that to maximise the potential for policy impact and to promote the quality and depth of socio-economic analysis being undertaken within the SRP, we would collaborate closely with WP 1.4 (*Integrated and Sustainable Management of Natural Assets*) and WP3.4 (*Communities and Wellbeing*). WP1.4 considers the management of natural assets in more depth than is possible within this WP. WP3.4 addresses issues of community cohesion and livelihoods which dovetail well with this WP in assessing spill-over effects and alternative income streams from other sectors. Both of these WPs could potentially benefit from the in-depth consideration of farm systems adaptation and agriculture policy in this RD. This collaboration also has potential to deliver support to policy developers beyond CAP, for example informing decisions on land reform through better understanding the spatial patterns in the environmental, economic and social outcomes of alternative tenure arrangements.

Opportunities for interdisciplinary collaborations or linkages via exchanges of data and knowledge will be explored in line with suggestions from the ITGF. These include:

RD 2.3.10 (*Data Sharing Across the Supply Chain)* drawing data from new sources such as CTS and ScotEID within social network analysis and the ABSS in RD2.4.1 and RD3.1.2 (*Improving Food and Drink Production*) where we would collaborate on the development of supply chain models. There is also an opportunity to use ScotFarm in RD2.3.5 (*Improving Existing GHG Reduction Measures*) linked with crop models to examine the cost-effectiveness of GHG mitigation measures. Opportunities to assess the Beef Efficiency Scheme will be developed with RD2.3.12 (Increasing uptake of best practice) linking to O1 (data) and O2 (intentions survey). Interaction between farm and non-farm incomes (at household and regional scale) will be jointly pursued with RD3.4.1 (Demographic change in remote areas).

A joint PhD studentship is being finalised between the University of Nottingham and SRUC on farm-level modelling and microsimulation that will feed into RD2.4.2 and RD2.4.1. New links have been established with partners in Brazil (i.e. EMBRAPA and University of São Paulo), and it is anticipated that the RD2.4.2 models will play a crucial role in future collaborative research in the context of Brazilian agriculture. Collaborations such as the joint European Association of Agricultural Economists seminar on *The spatial dimension in analysing the linkages between agriculture, rural development and the environment* arranged by SRUC and Teagasc in Edinburgh, Oct 2015, are expected to continue.

Collaboration with BioSS will be through their consultancy services particularly in the analysis of CAP Intentions and Impacts surveys and the integrated analysis of FAS and bio-physical datasets.

Added Scientific Value

The focus of the research in terms of Scotland and SG policy means that the research conducted tends not to overlap other initiatives but can see complementary interactions. Research in the current SRP has seen significant interactions with other SG funded activities. For policy-led research there have been responsive-mode "call down" projects (VAS, PAWSA, CXC) where strategic capacity developed within the current SRP has been deployed in a timely way to address issues with immediate policy interest (e.g. Redistribution of CAP scenarios, Pack's regulatory review, seasonal grazing analysis). Much of this work adds value to regulatory datasets and research capacity has also been deployed regularly through SG's contract research fund (e.g. Pack Inquiry, Agricultural holdings Evidence Review, WEAG).

In the current SRP, farm level models have been used to inform technical and policy questions of organisations such as the SG, Defra, BPEX, EBLEX, QMS, DairyCo, FSA and European Science Foundation. With international collaborations the models are being jointly developed and used with Norwegian University of Life Sciences (under MACSUR), MTT Agrifood Research Finland, Teagasc and Nottingham University. A book titled 'Farm level modelling: Technique, Application and Policy' is being edited by RD members drawing on contributions from around 20 scientists. These strong collaborations will continue.

The Social Network Analysis (SNA) undertaken here will focus on transactions between businesses rather than (as has been the case to date) taking an epidemiological perspective that focuses on individual animals interactions. The work will build on SNA expertise developed through NERC funded project on translation of barley integrated pest management research to the barley supply chain.

The research in this RD will draw on expertise and datasets created through leadership or participation in modelling knowledge hubs (e.g. AgMIP, MACSUR), several FP7 and H2020 projects. These FP7 projects include FarmPath (on sustainability transitions in agriculture), ProAKIS (on the role of knowledge networks and advisory services in agricultural innovation), Animal Change (on future of the livestock sector under climate change), SmartSOIL (on sustainable farm management aimed at reducing threats to soils under climate change) and the EIP Agri Focus group on New Entrants to Farming in Europe.

KE, Audiences and Impact

Audience – the WP description has set out the typology of stakeholders and the nature of the interactions anticipated. Since this RD is so closely aligned in policy terms with RD2.4.1 (Resilience), the nature and benefits of interactions will be very similar. As this RD also builds on a significant body of existing research, and there are ongoing policy processes to which the work is relevant, we can expect that useful outputs and interactions with SG policy teams will occur from Year 1 onwards. As progress is made towards greater integration of the research methods and teams, it is likely that this will generate higher-profile scientific outcomes but these are more likely to be realised in Year 3 or later.

Research Collaborators are closely involved in all phases of the research. Again CAP and related policy teams will be key partners. Ongoing interaction with RESAS analysts and RPID officials will continue. This RD, however, also offers opportunities to develop new relationships with a wider range of industry-related bodies that represent interests within the agri-food supply chain e.g. hauliers, auctioneers, processors and retailers.

Direct Stakeholders are those policy teams within government that can make direct use of the research outputs. We will contribute to foresight, using outputs from the programme directly and reshaping the research as priorities and circumstance change.

Advisers and Interest Groups will interact with the RD through processes of expert review and dissemination. As this RD builds upon ongoing research we anticipate KE interactions from an early stage. Ongoing interactions are often event driven (e.g. presentations to NFUS Committees, Forestry Commission Industry Users Group, etc.) and focus on practitioners (e.g. NFUS, SLE, Scottish Crofters Federation (SCF), Forestry Commission Scotland (FCS)). It is anticipated that KE to these industry audiences will continue. With more emphasis on the wider supply chain, we anticipate developing interactions with Scottish Food and Drink.

Supranational Institutions provide forums within which outputs from the RD can be internationalised both showcasing outputs and that RD staff have active networks of contacts. WP management will prioritise with RESAS when participation is appropriate.

Public are primarily interacted with through the facilities of the Central KE resources of the CKEI with the intention that there is an ongoing process of KE through a variety of online and other media that raise awareness and demonstrate value for money from the SRP. The role of the RD will be to provide timely and appropriate inputs to this process.

Science Community will see interaction with the RD through peer-review publication, books and presentation at appropriate fora. The WP leads will seek to maximise the science impact of the RD by careful targeting and prioritising of journal publication and through coordination with other RDs to raise the profile of the SRP at events.

Impact - The types of impact anticipated for the RD are identified below with the intention that specific outputs will be flexibly delivered in response to interactions between the RD team and the stakeholders identified above (ongoing co-construction). The RD will be proactive in seeking audiences for new research results emerging from the strategic aspect of the RD while reacting positively to requests for particular analysis particularly from direct stakeholders. The mechanisms and management of this process is described in the WP text since this is generic to all RDs in the WP.

Instrumental – the RD will make specifically identifiable contributions to policy (prioritising CAP and Land Reform and practice (prioritising providing new data and methods available within RESAS/RPID) with the utility of outputs acknowledged by SG analysts, officials, ministers, MSPs and representatives. RD2.4.2 analysis in these highly politicised topics contributes to the available evidence base and provides the capacity to undertake timely and specific options appraisals. Based on experiences in the current SRP (e.g. in the agricultural tenure evidence review and CAP direct payment regionalisation) this will have substantial value in facilitating a transparent and evidence informed discussion with stakeholders around the policy choices available.

Conceptual – the RD will generate influential new understandings and awareness of the factors underpinning adaptation of the rural industrial systems and a synthesis that identifies the influence of the policy actions; deliberated on in high profile scientific and stakeholder forums.

Attitude/Culture – the RD staff will be required to ensure that in addition to being rigorous and appropriately innovative their research is conducted in a way that maximises its utility to policy and government. This will mean investing time in understanding the timelines that dictate when inputs are needed, the forms that outputs need to take to be usable and the social process within which they are used.

Enduring Connectivity – the RD will maintain and improve its staff's connections into government and industry to facilitate exchanges of knowledge and data. The RD staff will also seek to develop mutually beneficial connectivity with research organisations beyond Scotland as part of the drive to internationalise the SRP.

Capacity-Building – the RD will more fully exploit and leverage existing capacity through developing supporting research proposals from other funders and investing in the strategic capacity needed to tackle emerging issues identified with our direct stakeholders.

RESEARCH DELIVERABLE NUMBER:

Work planning and timetable for Year 1

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 - Improving of geospatial data									D1		D2	
O1 - ScotFarm module development										D3		KEp1
O2 - analysis and mapping of 2013 CAP Intentions Survey					D6			D7		D8		KEp3
O2 – Field research											D9	
O3 - ScotFarm+ linkages											D13	
O3 – Network Analysis												
O3 – Adaptation Monitoring										D16		
O4 - proactive engagement									KE2			
O4 - responding to ad hoc analysis requests												

RESEARCH DELIVERABLE NUMBER:

Work planning and timetable for Year 2

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 - Improvement of geospatial data									D3			
O1 - ScotFarm module development				D4					KEp2		D5	KE1
O2 – Field research						D10						
O2 – Analysis of field research												D11
O2 – CAP Impacts Survey										D12		
O3 - ScotFarm+ linkages												D14
O3 – Network Analysis							D15					
O3 – Adaptation Monitoring										D17		
O4 - proactive engagement									KE3			
O4 - responding to ad hoc analysis requests												
R1 Year 1 Annual Report to RESAS			R1									

Name of RD: 2.4.3 Environmental sustainability and circularity of the rural economy

Research aim and key drivers

This research will assess the environmental sustainability of different sectors of the rural economy and identify trade-offs and opportunities for the production and use of bio-materials in a circular economy. It will identify ways for rural industries to co-operate and exploit synergies to reduce their environmental impact and become more circular – especially with regard to bio-materials. The work will also include identification of impact and performance measures more broadly to better understand changes in environmental sustainability.

Global demands for key bio-materials are forecast to increase significantly over the next 20 to 30 years. The economic opportunity presented by these trends has been recognised by the private sector, which is responding with strategies to increase production, e.g. a target of £16.5 billion turnover and £7.1 billion in exports from the Scottish food and drink sector by 2017. The imperative is to find means to achieving these targets in ways that are consistent with other policy goals, such as the EU growth strategy, the OECD principles of green growth and the recent EC communication on the circular economy (COM/2014/0398).

The research will improve, and use with stakeholders, methods to analyse the sustainability and circularity of economies at a range of spatial and organisational scales. There are a number of alternative activities which are consistent with promoting a more circular economy including: improved resource use efficiency; substitution; eco-design; and changed delivery models and consumer choices. Opportunities to introduce circular economy approaches arise at multiple points along supply chains; however, not all interventions will have a net benefit. Furthermore, food and drink supply chains are complex, and change can lead to unintended consequences. For example, improved crop drying can reduce storage losses but may lead to an increase in the energy consumption and emissions per kg of grain produced. The challenges are therefore to: (a) provide scientists and policy makers with data, tools and metrics that better enable them to understand the functioning of complex social-ecological systems particularly in terms of changes in their sustainability, (b) identify feasible and efficient measures to improve sustainability and circularity, and (c) understand how such measures might impact on the wider economy.

Interactions between researchers and policy teams in this domain are at an early stage but the current research programme has highlighted potential interest from a variety of SG analysis and policy teams. A draft of the concept note for this research has been sent to the Food and Drink team at Resource Efficient Scotland and preliminary discussions held. Potential research collaborators, advisers and interest groups in industry and the third sector have been identified and consulted.

Summary of the proposal

The driver for the research is to provide scientists and policy makers with data, tools and metrics that better enable them to understand the functioning of complex social-ecological systems particularly in terms of changes in their sustainability (dependence on non-renewable or imported resources) and their circularity (the degree to which energy or materials are lost from cycles of use often in ways that result in damage to the environment or human health). The outputs from these tools are relevant to a wide range of policy decisions, clearly issues of waste management and environmental protection but also higher level policies that consider the macro-scale functioning of economic policy and how this translates into well-being for citizens (for example the “beyond GDP” initiatives being pursued by various states). Whilst interactions between science and policy in this domain are at an early stage within the SRP, the current programme highlighted potential interest from a variety of SG analysis and policy teams.

The research is structured as 3 Objectives that each draw on existing data, methods, models and knowledge (left hand side of Figure 8) and combine these in a more integrated way than previously so as to generate greater capacity and new capability. Objective1 Bio-material Flows will identify and quantify flows of materials, energy and value, and identify hotspots of resource consumption or potential environmental impact. Objective 2 Integrative Analysis and Interpretation is where the consequences of specific changes for circularity and the use of bio-materials can be assessed against a variety of economic, environmental and social criteria. This objective will also see further development of system-wide performance metrics. Objective.3 the Science-Policy Interface is where scenario analyses, policy option appraisal and other interactions with stakeholders will occur. These objectives are further elaborated below with their key deliverables. The three Objectives of this RD are shown on the right-hand side of Figure 8

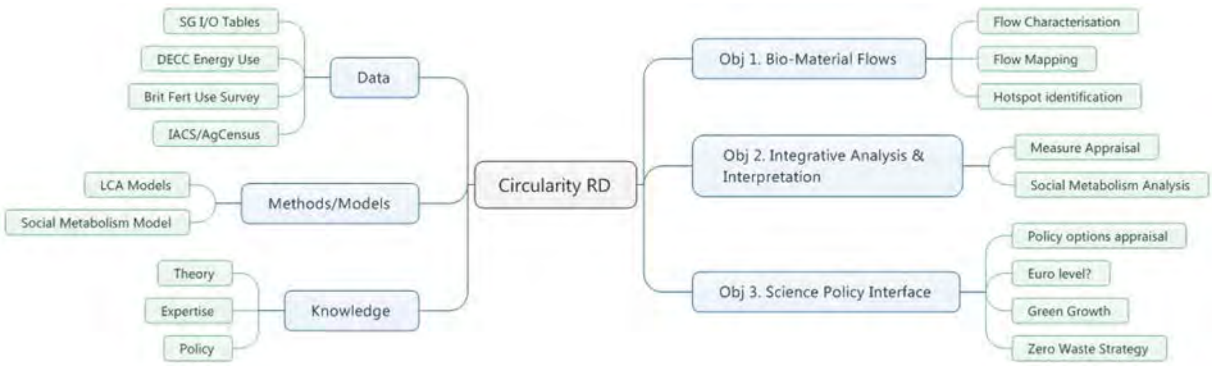


Figure 8 Diagram outlining the structure of this RD; its inputs and outputs

Objective 1: Biomaterial Flows (O1) – This will identify and quantify the main material, energy and financial flows arising from the production and consumption of biomaterials within Scotland. The main flows of materials, energy and money will be characterised using flow diagrams and spatially mapped to identify and describe key process, sectoral or locational hotspots. This will provide the basis for integrative analysis and interpretation (Objective 2).

Key Deliverables: Excel-based model quantifying the main material and energy flows, and their spatial location, arising from the production and consumption of biomaterials within Scotland.

Objective 2: Integrative analysis and interpretation (O2) – Appropriate technical and policy measures for improving the efficiency of biomaterial production and consumption via increased circularity will be identified from the flow modelling in Objective 1. A subset of these measures will be selected and appraised in terms of technical feasibility, cost-effectiveness, and acceptability to stakeholders (producers, consumers and government). Social metabolism analysis tools developed in the current SRP will be refined and updated in partnership with stakeholders and applied to assessing the performance of the agricultural sector between 1990 and 2015. The feasibility of using these metrics within agent-based social simulation models will be

explored to create a more functional analytical framework for *ex ante* policy assessment that can address the extents and intensities of resource use, the mix of resource types and the trade-offs between production and environmental burden. Outputs from this development will be delivered through linkage with RD2.4.1 with the improved tools and methods supporting scenario analysis in Objective 3 of this RD.
Key Deliverables: Short technical reports describing: key supply chains and hotspots (i.e. processes and/or locations that have high rates of production or consumption of biomaterials or high environmental impacts); and options for improving the efficiency of biomaterial production and consumption via increased circularity. Deriving time series of social-metabolism based system performance metrics and using them with key stakeholders to better understand trajectories of change and responses to external system shocks such as the 2008 banking crisis. Integration of social-metabolism analysis methods with agent-based social simulation models.
Objective 3. Science Policy Interface (O3)– Interaction with appropriate research collaborators and stakeholders to consider policy options, or other incentives that could be used to achieve greater uptake of the measures appraised in Objective 2 to increase circularity. Analysis of likely uptake rates of technical and policy measures and the likely impacts arising.

Key Deliverables: Research briefs for a subset of measures that can improve circularity outlining their technical feasibility, cost-effectiveness, and acceptability to stakeholders (producers, consumers and government). Report outlining the potential use of improved sectoral and regional carbon intensity measures to help support the monitoring and delivery of Scotland's Carbon Reduction Plans (as will be updated in RPP3). This will be focused on agriculture where progress in efficiency has been reported as significant but is perhaps not being well reflected in inventory methods.

Technical approach

The work builds on existing work of developed in the current SRP and other projects. The team has expertise in the proposed topic (resource efficiency) and proposed methodologies (life cycle analysis, cost-effectiveness analysis and social-metabolism analysis).

Objective 1. Biomaterial flows (O1).

The main biomaterial, energy and financial flows will be quantified and mapped for key supply chains. The focus will be on activities that fulfil one, or more, of the following criteria:

- produce significant amount of biomaterials (e.g. arable farming, fisheries, forestry);
- consume significant amounts of biomaterials (e.g. livestock farming, aquaculture, food and drink manufacturing);
- have potential for biomaterials to be substituted for non-biomaterials, e.g. energy (biomass for fossil fuels), construction (wood for steel), arable farming (organic N for synthetic N).

Material intensities, such as the amount of material input or output per unit of gross value added (GVA) for key inputs (e.g. water, energy, nutrients, protein), co-products (e.g. crop residues, distiller's dry grains and fish trimmings) and waste streams (e.g. low-grade heat, grey water, CO_2) will be determined based on published datasets. These datasets include: industry environmental reporting, Government-collected data (such as the British Survey of Fertiliser Practice and Farm Accounts Survey) and other relevant studies. Unpublished data may also be extracted from existing economic and physical supply chain models. Where appropriate, a range of material intensities will be given to reflect anticipated spatial and temporal variation (e.g. arising from changes in feed conversion ratios or energy efficiency). The total key material inputs and outputs will be calculated for sub-sectors by combining the forecasts of economic activity with the material intensities.

Metrics for identifying hotspots will be developed and applied to these data, and may include:

- Total consumption of input types (e.g. fossil fuels)
- Total production of selected outputs (e.g. abattoir waste not fit for human consumption)
- Rates of consumption/ production of certain inputs and outputs, e.g. kgCO2e per unit of GVA.

Objective 2. Integrative analysis and interpretation (O2).

Circularity Measures Appraisal

The barriers to circularity and the opportunities to overcome them depend on the product and process in question. In essence, a circularity measure needs to be:

- Technically feasible - i.e., it could in principle be applied and there is reasonable certainty of effect;
- Cost-effective and economically efficient - i.e. the costs are less than the benefits and the cost effectiveness is better than alternative measures.
- Acceptable – i.e. there needs to be no significant barriers to industry uptake, (such as the risk of undesirable unintended consequences).

Increased circularity may pose risks for industry in terms of product safety, quality or image that need to be managed accordingly. For example, alternatives to fishmeal in salmonid aquaculture have different risk profiles that may need consideration from regulatory and public acceptability perspectives.

An initial list of measures for increasing circularity, and potential barriers to uptake, will be developed based on peer reviewed and grey literatures and the team's expertise. These measures will be discussed with a range of industry and policy stakeholders to identify:

- Current levels of uptake of the measures.
- Projected levels of uptake in a business-as-usual scenario.
- Opportunities for increasing uptake via policy, initiatives, product differentiation (sustainability), etc.

Through this consultative process a short list of measures will be established to further assess technical feasibility, cost effectiveness and public acceptability:

- Identify the main (one-off and recurring) cost elements.
- Identify the main direct and indirect effects on material intensities.
- Undertake initial quantification of the costs (positive and negative) and physical effects of the measures.

Social Metabolism Analysis (SMA)

Realising the potential of social-metabolism analyses to support policy-making requires further development in a scientific and technical sense of the existing tools and methods but also investing in a process of interaction with key stakeholders to raise awareness of the potential of the methods and to refine how they can best be used in practice. Figure 9 highlights the deliverables on the right-hand side of the figure with aspects where research and development are required on the left.

Figure 9 Social Metabolism Analysis

- In order to improve the credibility of SMA conducted under current SRP, tools will be developed that are more robust, user friendly and present the data in ways that are more accessible to stakeholders.
- Further assessment (conceptually and practically) of how best to represent flows of more intangible assets (e.g. services, information, culture).
- To further improve credibility, generate more complete time series, rather than snap shots, so that trend analysis is more coherent and can be better integrated with knowledge of other drivers where lags may occur.
- The data capture process will be streamlined and automated, perhaps also drawing on versions of administrative datasets at a pre-aggregated level (for example better understanding the data underpinning GVA calculations).
- Highlight opportunities that are emerging for the research to interact with so-called Nexus Studies – at UK, Europe and International level.

Objective 3. Science-policy interface (O3).

Through interactions with collaborators, stakeholders and advisers and reviews of the policy environment, an options appraisal (including relative strengths and weaknesses) will be undertaken to highlight policy instruments that could improve uptake of circularity measures (e.g. self-regulation, education and information, incentive–based structures, classic command-and-control regulation). The scenario analysis will predict uptake rates of measures and associated impacts and scenarios and will also demonstrate the effect of changes in key drivers on the future feasibility of circularity measures and policy instruments, such as commodity prices and the EU regulatory framework (e.g. changes in waste regulations or REACH requirements).

The integration of SMA methods with agent-based social simulation models will provide a framework for *ex ante* policy assessment that can address adaptive responses and environmental trade-offs to policy scenarios.

Methods Proposed

Life cycle analysis (LCA) is an analytical approach rather than a tool *per se*. Its defining feature is that it quantifies the impacts arising over the life-cycle of a product or service. In theory, LCA should include the impacts arising across the entire life-cycle, from “cradle to grave”, including the manufacture of inputs (such as steel or electricity), the production of the commodity, and its subsequent transport, sale, use and disposal. In practice, LCA often focuses on part of the life cycle, e.g. agricultural commodities are often “cradle to farm gate”.

Environmental Input Output (EIO) analysis is an established methodology to analyse the socio-economic and environmental performance of the economy and its sectors. Based on statistical data on the inputs used and outputs produced by the different sectors in the economy, and augmented with environmental impact coefficients, the method can provide *ex-ante* assessment of policies. The work will be based on the

EIO modelling previously developed for SG.
Cost-effectiveness analysis (CEA) can be used to quantify the costs of measures in different approaches: (a) bottom up cost-engineering; (b) micro-economic modelling, exogenous prices; (c) regional/sectoral using supply-side equilibrium models. The approach will depend on the research question.
Spatial analysis will be undertaken where appropriate (e.g. for mapping spatial patterns of biomaterial production and consumption). Specifically, links can be made here with the natural asset register mapping work being undertaken in RD1.4.1 (Natural Asset Inventory and Natural Capital Accounts). Such spatial analysis may offer insights into both barriers and opportunities for the circular economy.

Social metabolism theory argues that social-ecological systems can be better understood by their representation as an organism that acquires, uses and alters resources and its environment to maintain, grow or change. SMA identifies key stocks and flows, dependencies on resources that cross the system boundary and consequences for the environment. The radically different natures of the flows within such systems and the regularity of transformations generate considerable complexity and mean that maintaining internal consistency within an SMA is challenging. This is compounded by the need to generate a limited number of metrics that to communicate the state, dynamics and trade-offs. In this regard, the use of *emergy*[4] as a unit of exchange provides a way forward by structuring the relationships between such flows in terms of both the quantity and quality embodied energy.

Detailed Work Plan

The work plans for Y1 and Y2 are set out in the GANTT charts at the end of this document. The section below itemises the deliverables lists in the chart. Key deliverables include: (Numbering system for deliverables relates to Gantt charts listing Deliverables (D#), KE/impact events (KE#), Published papers (KEp#) for Years 1-2 only). Experience in the current SRP has indicated that, given the high levels of interaction with RESAS, policy teams and others, that the timing of deliverables (i.e. the specific materials that cross the science-policy interface) can be difficult to predict. Therefore the specification of deliverables below indicates a trajectory for the strategic research that we expect to be heavily modified as the RD responds to emerging issues. Where deliverables are anticipated to occur beyond Y2 these are noted as such in the GANTT.

Deliverables

Objective 1 (O1) Biomaterial Flows

- Flow characterisation - Excel-based model quantifying the flows (D1)
- Flow mapping – Spatial representation of key commodity flows (D2)
- Hotspot identification - Short technical report describing key hotspots and potential options for improvement (D3), Workshop to disseminate and discuss findings of FC1 and HI1 (KE1).

Objective 2 (O2) Integrative analysis and interpretation

- Measure appraisal - Functional analytical framework (D4), Research briefs for a subset of improvement options (D5), Workshop to discuss measures and policy options for specific sub-sector (KE2).

[4] Emergy uses as a common unit the solar equivalent joule (seJ) with other flows converted into this using factors that recognise the utility of the widely differing flows as an energy hierarchy from solar via vegetative, mineral and manufactured forms and ultimately to services.

- Social metabolism analysis - Report outlining changes in agriculture sector GHG intensity measures (D6).

Objective 3 (O3) Science Policy Interface
This conducts interaction with policy and analysis teams either proactively (KE3) via workshops and meetings or responding to ad hoc requests for analysis.

Key Linkages, Interdisciplinarity & Collaboration
This RD will work closely with the others in the WP with the common goal of better understanding the responses and consequences of change in rural industries. It will not be dependent on any other RDs, but will draw on, and contribute to, related RDs where possible.
As noted in the other RDs within WP2.4 we see considerable potential for collaborations and linkages from this WP to WPs 1.4 (Integrated and Sustainable Management of Natural Assets) and WP3.4 (Communities and Wellbeing) since each shares a strong socio-economic core. Cooperation and coordination will aid in achieving efficiency of delivery, stimulating new strategic research opportunities and greater visibility for the SRP at national and international events. This RD will, where possible, make use of the natural asset register mapping work being undertaken in RD1.4.1 and contribute to the development of models of material flows in sub-sectors of the rural economy (RD1.4.2). WP staff will continue to deploy capability developed within the WP through the Centres of Expertise – particularly ClimateXChange and EPIC.
This RD shares the goal of identifying options to improve production efficiency and avoid waste with several RDs in WP 3.1 (Improving Primary Production): RD 3.1.1 (Improving Scottish primary production), RD 3.1.2 (Improving Food & Drink Production) and RD 3.1.4 (Preventing Food Waste). Therefore, where possible, this RD will liaise closely with others to avoid duplication of effort in data gathering and will, where appropriate, hold joint thematic meetings.
This RD will utilise the input-output methods developed by Centre of Excellence on Climate Change (CXC) to estimate the economy-wide effects of wider measure adoption.

The research team presently have peripheral involvement in studies that take a multi-scale social metabolic approach to analyse of the trade-offs in land, water and energy use at global/national scales, e.g. with FAO. There are upcoming opportunities in the EU H2020 rounds and elsewhere for RD staff to participate in and leverage additional resources and expertise that would add value to the SRP.

Added Scientific Value
Detailed research has been undertaken by the private and public sector on specific topics, but significant data gaps currently remain, particularly in the rural dimension. This work builds on research undertaken within the current SRP theme, in the FP7 project SMILE and through ongoing collaborations with leading researchers in the domain within European universities.
We believe this RD adds value by:

- Making use of existing data sets (e.g. data on waste arising held by local authorities and government agencies) and studies (e.g. SG's Circular Economy Evidence Building Programme, UK Circular Economy Task Force and the Ellen Macarthur Foundation) and complementing them with targeted additional data gathering.

- Bringing together staff with an understanding of the Scottish rural economy, allied to broader international experience.
- Using LCA-thinking and social metabolism analysis to provide insights into potential displacement of production (and related flows) to other parts of the supply chain and/or territories.
- Developing models to illustrate the effects of the circularity measures on key parameters.

KE, Audiences and Impact

Audience – the WP description has set out the typology of stakeholders and the nature of the interactions anticipated. This RD is at an earlier stage of development that others within the WP. The listing of audiences and the types of interactions are those that would be desirable, are planned for and need to be resourced. The process of engagement with policy and research collaborators will follow that successfully developed by other areas of the WP but the eventual configuration relationships will depend on how well the research and stakeholder interests can be aligned. Given the resources available to this RD (<20%) of the WP there will have to be realism in terms of what can be delivered with the need for careful prioritising in cooperation with RESAS and directing stakeholders.

Research Collaborators are closely involved in all phases of the research. There are opportunities for the research to exploit and add value to data sources within SG (e.g. from Zero Waste Scotland/Resource Efficient Scotland and WRAP) and also from local authorities (through COSLA). Collaboration with industry private sector organisations is also possible for specific industries e.g. Marine Harvest for aquaculture and Scots Whiskey Association (or Morangie Group) for distilling.

Directing Stakeholders are those policy teams within government that can make direct use of the research outputs. For this research we have identified potential direct stakeholders as being the SG Zero Waste policy team, Climate Change and Agriculture team and Office of the Chief Economic Adviser (for linkage to the wider use of social metabolism metrics). The cross cutting nature of the research means that there are several policy teams that could make use of outputs but given the resources available we will need to carefully prioritise where outputs can be delivered in a timely fashion that maximises impact.

Advisers and Interest Groups will interact with the RD through processes of expert review and dissemination. Here we anticipate interactions with the SG Circular Economy Evidence Building Programme, COSLA and potentially with the UK Circular Economy Task Force. The nature of these interactions will be to provide advice on technical, regulatory and other legal aspects. Wider industry representatives also have the potential to provide advice on feasibility and acceptability issues (e.g. Agricultural Industries Confederation and the British Retail Consortium). The third sector is also active in this domain so we would seek to engage appropriately with key players such as the Ellen MacArthur Foundation and the Green Alliance.

Supranational Institutions provide forums within which outputs from the RD can be internationalised both showcasing outputs. RD staff have active networks of contacts and WP management will prioritise with RESAS when participation is appropriate e.g. the European Commission (e.g. through the developing Communication on Circular Economy) and the SAVE FOOD initiative (led by FAO, UNEP, and the Messe Düsseldorf Group).

Public are primarily interacted with through the facilities of the Central KE resources of the CKEI with the intention that there is an ongoing process of KE through a variety of online and other media that raise awareness and demonstrate value for money.

Science Community will see interaction with the RD through peer-review publication, books and presentation at appropriate fora. The WP leads will seek to maximise the science impact of the RD by careful targeting and prioritising of journal publication and through coordination with other RDs/WPs to raise the profile of the SRP events.

Impact - the types of impact anticipated for the RD are identified below with the intention that specific outputs will be flexibly delivered in response to interactions between the RD team and the stakeholders identified above (ongoing co-construction). The RD will be proactive in seeking audiences for new research results emerging from the strategic aspect of the RD while reacting positively to requests for particular analysis particularly from direct stakeholders. The mechanisms and management of this process is described in the WP text since this is generic to all RDs in the WP.

Instrumental: The RD will produce specific policy briefs and will seek to develop these with input from their intended audience in order to maximise their usefulness.

Conceptual: The RD will improve understanding of the circular economy by developing models and using them to quantify and map flows. It will use life-cycle thinking, social metabolism approaches and other methods to shed light on the wider implications of circular economy measures and policies.

Attitude/Culture: Engagement with stakeholders will be required throughout this RD in order to build trust and make efficient use of existing data and knowledge. This will be achieved through a combination of *ad hoc* informal contact and periodic formal meetings bringing together stakeholders to address specific themes.

Enduring Connectivity: the RD will maintain and improve its staff's connections into government and industry to facilitate exchanges of knowledge and data. The RD staff will also seek to develop mutually beneficial connectivity with organisations beyond Scotland in order to learn from best practice in this field.

Capacity-Building: This RD represents an opportunity to apply existing skills within the MRPs (in LCA, CEA, social metabolism analysis, EIO) to the questions raised by the circular economy challenge. In so doing, staff expertise in their own methods will be increased, and their understanding of other methods used in the RD developed through cross MRP working.

RESEARCH DELIVERABLE NUMBER: 2.4.3 Work planning and timetable for Year 1

Year 1: 2016/17	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 - Flow characterisation									D1			
O1 - Flow mapping												
O1 - Hotspot identification												
O2 - Measure appraisal												
O2 – Social metabolism analysis												
O3 - Science Policy Interface, proactive engagement												
O3 - responding to ad hoc analysis requests												

RESEARCH DELIVERABLE NUMBER: 2.4.3 Work planning and timetable for Year 2

Year 1: 2017/18	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1 - Flow characterisation												
O1 - Flow mapping			D2									
O1 - Hotspot identification					D3	KE1						
O2 - Measure appraisal		D4							D5	KE2		→
O2 – Social metabolism analysis												D6 →
O3 - Science Policy Interface, proactive engagement									KE3			→
O3 - responding to ad hoc analysis requests												→
R1 – Year 1 Annual report to RESAS			R1									

Appendix A: HEI bids associated with Theme 2 activity

Project number	Project title	Links to WPs/ RDs (primary link(s) in bold)	MRPs involved	Approx. Year 1 cost (£k)	Location of costs
1	Structure-function relationships of pathogen effectors and surfaces	RDs **2.1.3**, **2.1.6**	Hutton, SRUC	96	Theme 2
2	Bere barley adaptation to Scottish Island low input agriculture	RDs **1.1.1, 1.3.1,** 2.1.3, 2.1.6	Hutton, SRUC	60	Theme 1
3	A systems-wide approach to the control of *Campylobacter* in the food chain: exploiting genetic variation	RDs **2.2.3**, **3.1.3**	MRI, RINH, SRUC	277	Theme 2 (UoE); Theme 3 (UoA)
4	Inferring genetic and other individual variation in population and dynamic models	RDs **2.2.3**, **1.3.3**, 2.3.3, 2.3.10	BioSS, Hutton, SRUC, MRI, potentially RBGE	108	Theme 2
5	Monepantel: anthelmintic resistance and the development of	RDs **2.2.4**, 2.3.12	MRI, SRUC, BioSS	112	Theme 2

Project number	Project title	Links to WPs/ RDs (primary link(s) in bold)	MRPs involved	Approx. Year 1 cost (£k)	Location of costs
	tools for sustainable use				
6	Linking agricultural and ecosystem models with economy-wide models. Understanding the contribution of agriculture and related ecosystem services to the wider economy	RD **1.4.2**, WP 2.3, RD 1.4.1	Potentially all	107	Theme 1
9	Disease management options: Insights from comparing forestry and agriculture	RDs **2.1.4**, 2.3.12	Hutton, SRUC	60	Theme 2
10	Microbiome and metagenomic study of the rumen microbial population and their microbial enzyme genes	RDs **2.2.9, 2.3.1**	SRUC, BioSS, RINH	154	Theme 2