SCOTTISH GOVERNMENT
RURAL AFFAIRS, FOOD AND ENVIRONMENT PORTFOLIO

STRATEGIC RESEARCH PROGRAMME
1 April 2016 to 31 March 2021

Submission
Theme 1 – Natural Assets

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

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 Friday 6 November 2015** the date fixed for receiving tenders, until the Award of Grant.

Signature	
Name	PROFESSOR COLIN CAMPBELL (BLOCK CAPITALS)
Designation	CEO, JAMES HUTTON INSTITUTE

Theme 1 – Natural Assets

Name of Theme Co-ordinator: Robin Matthews (Hutton)

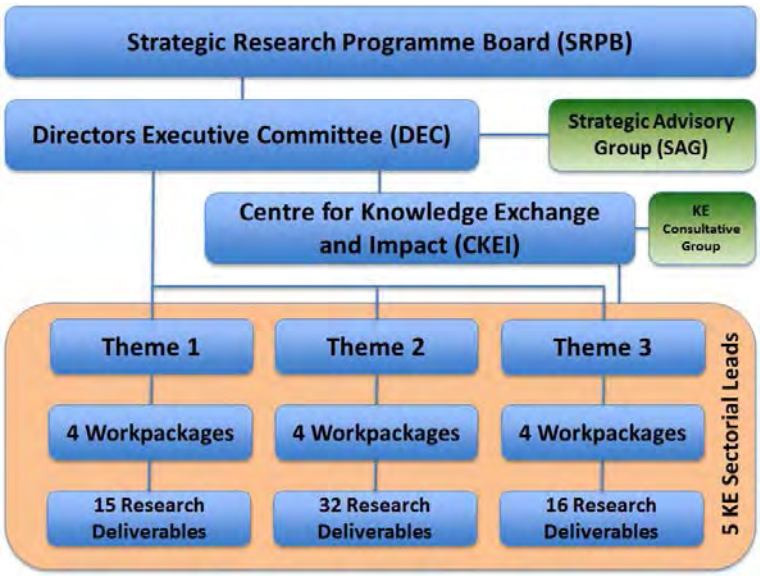
Executive summary

The 2021 vision for the Natural Assets Theme is to be recognised worldwide as a leader in understanding and management of natural resources, facilitating sustainable use of these resources in a manner that is resilient to future pressures. The benefits of achieving this vision will be to enable our natural assets to support sustainable growth of the Scottish economy, our sense of place, and our overall health and quality of life. Our work from 2016-2021 will provide and integrate the evidence base informed by our scientific understanding of the way our natural assets function to underpin the development and implementation of policies in the areas of climate change, land use for multiple benefits, and food security.

Specifically, we will undertake work to understand better the processes contributing to the resilience of our soils, waters and biodiversity, which will contribute to the development of a register of natural assets. This will provide the basis for detailed analysis of (a) how individual natural assets work together to create overall ecosystem resilience, (b) trends in these natural assets and whether safe boundaries are being approached, and (c) the trade-offs and synergies that may occur under different management options seeking to enhance ecosystem resilience. Best management practices will be tested in specific case studies that will demonstrate to stakeholders how our 2021 vision of sustainability may be achieved. Throughout the process, our research will provide evidence for policy development aiming at better stewardship of our natural assets.

A.1: Programme governance

The overarching vision for the Strategic Research Programme (SRP) is to support the Scottish Government's (SG) 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 five Main Research Providers (MRPs) plus RBGE, 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 (see Figure) 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. The Strategic Research Programme Board (SRPB) convened by RESAS will oversee all scientific activities and impact from the SRP.

2. The Directors Executive Committee (DEC), 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 Centre for Knowledge Exchange and Impact (CKEI).
3. A Strategic Advisory Group (SAG) 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, environment, and communities, will coordinate KE activities across the SRP. The KESLs will interact with the SRP Themes, CoEs, Innovation Platforms and Underpinning Capacity (UC) services, coordinate stakeholder engagement, and help implement CKEI activities through the relevant MRP communications teams. 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 1 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 its 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 MRP 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 MRP Director.

Programme Advisors

1. Assisting Theme Coordinators in identifying new opportunities or changes in policy foci, monitoring scientific progress within Themes and at SRP level.
2. Responsibility for overall coordination and oversight of the reporting process on behalf of DEC with designated MRP representatives for metrics.
3. Forming specific linkages with KESLs and RESAS Science Advisors.
4. Stakeholder engagement in liaison with the KE Director.
5. Identifying cross-Theme opportunities for both research and KE, through attendance at DEC meetings and membership of the KE core team.
6. Representation role for SRP at key KE events, liaising with the KE 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. Chairing *Theme Management Group* (TMG) meetings, at least 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, reporting on problems with delivery of Theme to DEC and providing advice on contingency plans to address such issues.
6. As empowered by DEC, responsibility for implementing changes to Theme delivery/resource allocation.
7. Highlighting 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 within 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 (to which 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. Discussing 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.

A.2: Theme overview

A.2.1 Strategic relevance (Plain English statement)

Scotland's ecological footprint has been calculated to be 5.4 ha capita^{-1}, more than twice the 2.2 ha capita^{-1} if all the available land in the world was shared out equally (Chambers *et al.*, 2004). Similarly, a recent analysis of the 'Scottish doughnut' (see diagram right) concluded that the country's impact on key planetary processes was much beyond that justified by its population, specifically in relation to GHG emissions, nitrogen and phosphorus flows in the landscape and ocean, contribution to ozone depletion, and air pollution (Sayers *et al.*, 2014). Moreover, large inequalities in wealth distribution also meant that several social indicators, such as unemployment, fuel poverty, and food unaffordability, scored low, despite average wealth being relatively high. Jackson (2009) has highlighted the urgent need to evaluate how changes in natural assets and ecosystem functioning impact on economic stability. The challenge is to ensure that Scotland continues to be a prosperous country, but with more equitable distribution of this prosperity, and that its natural assets are enhanced rather than degraded.

Recognising this, the purpose of the SG is "to focus government and public services on creating a more successful country, with opportunities for all of Scotland to flourish, through increasing sustainable economic growth" delivered through the National Performance Framework. To achieve this, policies are focused on five Objectives: a (a) Wealthier & Fairer, (b) Healthier, (c) Safer & Stronger, (d) Smarter, and (e) Greener, Scotland. To facilitate these, the SG Economic Strategy, refreshed in March 2015, has four strategic priorities: (a) Investing in People, (b) Innovation, (c) Inclusive Growth, and (d) Internationalisation.

The work in Theme 1 will contribute to the overall SG Purpose by addressing four of the Objectives by making the most of our natural assets to support livelihoods (Wealthier & Fairer), deliver recreational and other health benefits (Healthier), provide knowledge for better land use decision making (Smarter), and supply ecosystem services to pave the transition to a sustainable future (Greener). It will also provide underpinning evidence for several of the 50 national indicators used to measure progress towards the SG Purpose (e.g. reducing Scotland's carbon footprint). Additionally, it will contribute to the strategic priorities of the SG Economic Strategy by providing evidence for decisions on *Investment* in natural capital, resource efficiency and low carbon futures, and will contribute to *Internationalisation* of Scottish knowledge and expertise through helping the SG fulfil some of its international commitments, particularly in relation to GHG emission reductions (UNFCCC), biodiversity conservation (CBD), protection of water resources, and the UN

Sustainable Development Goals (SDGs). Of particular relevance to the Theme are SDG13 “to take urgent action to combat climate change and its impacts” and SDG15 “to sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss”. Nationally, work in Theme 1 will contribute to the CAMERAS Theme “Catchment management for water resources” (WP1.1, WP1.2), to the CAMERAS Theme “Ecosystem resilience to climate change” (WP1.1, 1.3), and to CAMERAS Theme “An integrated approach to land use” (WP1.4). It will also contribute to the CAMERAS Environmental Monitoring Steering Group including the Soil, Water, Biodiversity, Landscape Monitoring Action Plans, and to the Scottish Hydro Nation agenda.

To achieve this we will build on the work of the 2011-15 Strategic Research Programme and the National Ecosystem Assessment by addressing the following research questions (referred to throughout the following document as RQs):

RQ1. How do Scotland’s natural assets function, how healthy are they, what are their trends, and what are ‘safe’ limits to their sustainable use?

RQ2. How resilient are Scotland’s natural assets to climate change and other risks (invasive non-native species (INNS), pollution, etc.), and what are the key interventions to make them more resilient or to protect them from further harm?

RQ3. What are the key ecosystem benefits we derive from Scotland’s natural assets, how are they distributed, how are they related to one another, are our natural assets declining as socio-economic capital increases, and how do we manage trade-offs between them?

RQ4. How can we improve the management of our natural assets to support sustainable land-based industries and vibrant communities, how can we improve existing instruments, and what other instruments could be applied to support social and economic entitlements and a just distribution of outcomes?

References: (1) Chambers, N. et al., N., 2004. Scotland’s Footprint: A resource flow and ecological footprint analysis of Scotland. Viridis, Oxford, UK. 80 pp. (2) Jackson, T., 2009. Prosperity without Growth: The Transition to a Sustainable Economy. Sustainable Development Commission. 133 pp. (3) Sayers, M., *et al*., 2014. The Scottish Doughnut: A Safe and Just Operating Space for Scotland. Oxfam. 83 pp.

A.2.2 Theme management activities and structures

A.2.2.1 Coordination and management

Theme structure

Theme 1 consists of three work-packages focused respectively on soils (WP1.1), waters (WP1.2), biodiversity and ecosystems (WP1.3) and a fourth that integrates outputs from these in the context of managing our natural assets for multiple benefits (WP1.4). The relationships between these are shown in Figure 1. Within each of the first three WPs, work focuses on (a) a basic understanding of ecosystem function, (b) the ecosystem processes that contribute to ecosystem resilience and service provision, and (c) how knowledge of the key characteristics contributing to ecosystem resilience can be managed to achieve desirable outcomes. Each of these common threads then contributes to the development of a Natural Assets Register, an analysis of trade-offs and synergies between different ecosystem services under different management options, and the testing of best practice options in selected case studies. Each WP will provide evidence in its own right for policy development in that area (e.g. Soils to the RPP4), but will also contribute outputs which will be synthesised in WP4 for more integrated policy development such as the Land Use Strategy or CAP Reform.

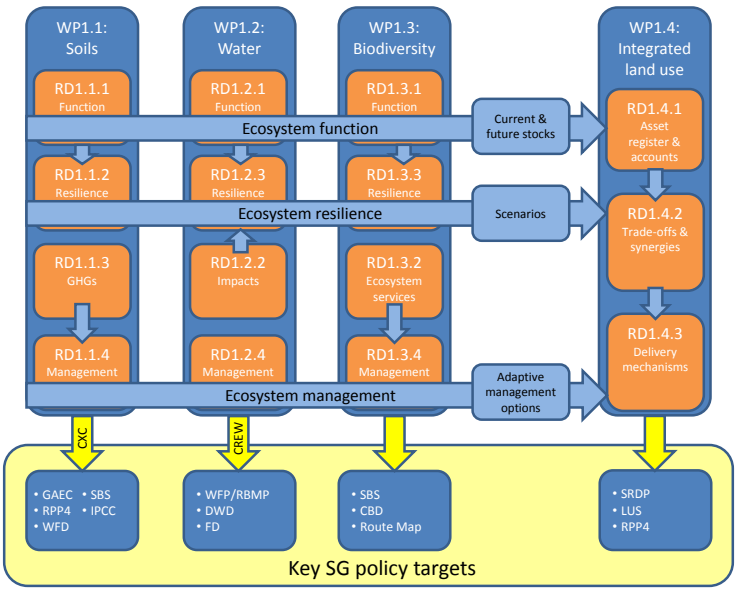


Figure 1: Structure of and main flows of information in Theme 1. (GAEC=Good Agricultural and Environmental Condition; RPP4 = Low Carbon Scotland Report on Policies and Proposals (Revision 4); WFD=Water Framework Directive; SBS=Scottish Biodiversity Strategy; IPCC=Intergovernmental Panel on Climate Change; DWD=Drinking Water Directive; FD=Flooding Directive; CBD=Convention on Biological Diversity; SRDP=Scottish Rural Development Programme; LUS=Land Use Strategy)

Theme coordination

The Theme will be managed by a Theme Management Group (TMG), comprising the following:

• Natural Assets Theme Coordinator (Chair) • Natural Assets Theme WP Coordinators (4) • KE Director and/or relevant KESLs (2)	• MRP Theme 1 Representatives (where not represented by WPC) • Programme Advisors (to provide linkages across Themes) (2) • RESAS Science Advisors • Natural Assets Theme Administrator

The TMG will be the principal decision-making management body of the Theme, and will meet twice annually. It will be responsible for:

1. The strategic direction of the work;
2. Contributing to a shared vision within and between Themes and across the SRP;
3. Providing overall co-ordination (financial, administrative, and intellectual);
4. Monitoring progress of research against the Deliverables agreed in the Tender;
5. Co-ordinating and ensuring consistency and excellence in the science;
6. Communicate with and to a wider stakeholder community through integration with the relevant CKEI Sectorial KE Leads; and
7. Providing arbitration where decisions within the Theme are required but cannot be reached by other means. Where issues persist, the DEC will be the final arbitrator.

The Risk Register (see below) will be a standing item at TMG meetings, to enable assessment of current and emerging risks. The TMG will liaise with the individual MRPs through the MRP Theme Representative on any issues of data management and Intellectual Property which arise, in line with the Data Management and Intellectual Property Plan (Appendix 1). Management of the Theme will comply with the Joint Code of Practice for Research (Appendix 1), with any issues requiring resolution to be raised with the DEC and relevant MRPs as appropriate.

Within the Theme, each Work-package will be managed by a WP Management Group (WPMG), comprising the following:

• WP Coordinator (Chair) • RD Coordinators • MRP nominated WP representative • Appropriate Sectorial KE Leads	• Natural Assets Theme Coordinator (as required) • Programme Advisors (as required) • RESAS Science Advisors (as required)

RD Coordinators will report on progress at WPMG meetings. If any issues arising cannot be resolved at the RD level, they are referred to the WPMG for resolution. WP Coordinators will report on progress to the TMG, which the Theme Coordinator will use for briefing the DEC and for six-monthly and annual reporting. Any issues that cannot be resolved at the WP level will be brought to the TMG.

Collaboration and networking with wider science communities

Theme interactions with wider scientific communities will use a variety of approaches:

- Scientific networks: PIs will be encouraged to maintain and join networks relevant to their fields (e.g. SFSA, CECHR, and ESCom, Resilience Alliance, International Society for Natural Resource Management).
- Conferences and meetings: Funding is allocated to each PI to attend one national or international conference/workshop per year to present WP work. Priority will be to meetings focusing on integrative science.
- Host leading symposia: Opportunities will be sought to host or (co)organise high profile international meetings on cross-Theme issues, methodological or topic-specific workshops with invited scientific and stakeholder participants.
- Theme seminar series: Leading authorities in natural asset management across soils, water, biodiversity and land will be invited to present in MRP's seminar series, using webcast tools to widen participation.
- Presence on committees of influence: Support will be provided to PIs to participate in international or national scientific or technical committees to help shape scientific discussions around sustainable use of natural assets.
- Publication strategy: WPs will take the 'green' route to open access, with a budget to publish 1-2 of each RD's most important papers per year as open access, and so increase the visibility and scientific impact of the research.

Interaction with Underpinning Capacity

Theme 1 will make extensive use of a range of UC services, specifically those of long-term monitoring sites (e.g. Environmental Change Network: Glensaugh, NE; Allt a'Mharchaidh, Cairngorms; Sourhope, Scottish Borders), the National Soils Archive and soils databases, and national collections. Individual PIs or RD Coordinators will negotiate access to the relevant UC Service (e.g. collection, dataset, advice), managed by the MRP provider (including RBGE). Any access or support issues will be raised with the relevant MRP contact on the TMG.

BioSS will support statistical design, analysis methods and data quality control. Theme staff are active in the supervision of current PhD students, recruitment for wider strategic initiatives (e.g. SFSA), supported through UC. The Theme will also be enabled to lever collaborative UK or international research funding through the underpinning support of platforms (e.g. unique long-term datasets) and the new science developed through 'seedcorn' funding. As well as through the CoEs, requests for policy advice can be made directly for areas of Theme relevance, and will be directed to expert staff.

Managing the 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 TMG 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. This will ensure that cross-Theme referencing is complete, consistent, and accurate. By monitoring progress, the TMG will identify narratives that are suitable to be included in the Theme level reporting, and individuals will be identified to draft the details as required for reporting. Final editorial responsibility for narratives and their submission will lie with the Theme Coordinator and the relevant Programme Advisor. Progress will be classified as being on schedule, slight delay, or significant delay. 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 areas of (a) policy relevance, (b) industry/innovation, (c) scientific excellence, (d) leveraged external funding, and (e) collaboration and interdisciplinary working.

Management of risks to delivery (Theme level)

Theme-level risk management will link to WP risk management strategies. A risk register will be developed, and at WPMG and TMG meetings, the status of current risks will be assessed, emerging risks will be identified and added to the register, mitigation strategies will be identified taking account of implications for cross-programme links and external collaborations including those with stakeholders, and responses will be agreed (e.g. tolerate, monitor, take action, escalate). The TMG will receive risk register updates from WPs. The risk register will describe the risk, its assessment, impact, controls, the risk owner in terms of RD, WP or Theme level coordination, and the recommendations and course of action proposed of the TMG.

Table 1: Key risks, where the overall risk status is indicated in terms of Amber or Green, for medium and low risks, respectively

Key Risks	Risk Assessment	Impact	Controls	Risk Owner
Significant budget reductions	Medium	High	Work programmes renegotiated with SG, and impacts agreed with partners on cancelling work areas, or reorganising priorities.	DEC
Staff turnover	Medium	Low-High (post dependent)	Ensure early discussions with relevant project and management teams for new staff members to familiarise with the research.	RD, WP, Theme Coordinator
Divergence in priorities between Underpinning and SRP	Low	Low-Medium	Ensure communications between relevant Underpinning capacity and SRP activities. Accountability links through individual MRPs, with utilisation and issues arising in SRP identified at Theme Management meetings.	WP, Theme, MRP
Divergence in stakeholder and research priorities	Low - Medium	Medium	A Consultative Group will be used to agree why and where priorities may need modified (e.g. changing in public sector priorities), or if findings conflict with stakeholder positions. The CKEI will participate in the CG. The CG will be asked to recognise the independence of research and policy. Early identification of issues, monitored by the CKEI, actions taken to engage and resolve issues, and reported to DEC.	WP, Theme, KE Director

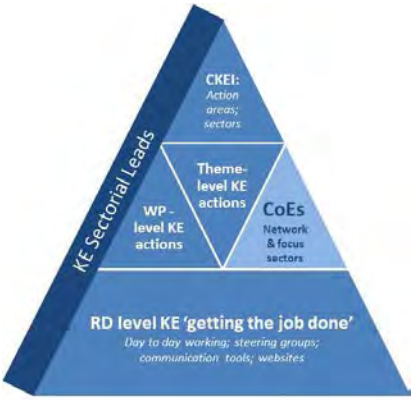
Divergence in priorities between partner MRPs	Low	Medium-High	Regular Theme Management meetings to ensure communication, early identification of potential for issues to arise. Reporting to DEC for resolution of prospective issues identified at Theme level. Adherence to project plan and schedule of Deliverables, with alerts to RESAS via annual/six–monthly reporting.	RD, WP, Theme, Coordinator

A2.2.2 Knowledge exchange and impact

Knowledge exchange structures

The aim of Knowledge Exchange in Theme 1 is to enable the creation of impact from the research to a range of beneficiaries with responsibilities for policy, practice, industry and in civic society, to maximise the impact of the research in the priority areas of the SG Economic Strategy of investment, innovation, inclusive growth and internationalisation. As such, KE will take place at the levels of the RDs, WPs, Theme, Centres of Expertise, and the CKEI.

RD: At the RD level, KE will be aimed at "getting the job done", principally face-to-face meetings with the relevant stakeholders and individuals, building on existing relationships in the current Programme. Further details are in the individual RD descriptions below.



WP: At the WP level, interaction with stakeholders will be through a Soils Stakeholder Group (SSG) and a Biodiversity Focus Group, both of which will cut across several WPs. In addition, there will be interaction with the Biodiversity and Land Use Policy Unit (BLUPU), particularly for WP1.3 and WP1.4. WP1.2 plan to form small steering groups on specific topics. KE will include both informal and formal meetings, and the use of IT tools to deliver short bulletins. Further details are in the individual WP descriptions below.

Theme: Engagement will, where appropriate, focus on global *fora* which address strategic interests in the research of the Theme (e.g. side events at the annual UNFCCC Conference of the Parties, FAO Global Soil Partnership, Global Water Partnership, biannual Convention on Biological Diversity CoP), facilitated by the CKEI (see below). At the Theme level, messages from the four WPs will be combined and presented at major meetings (e.g. the SRuC-SEPA bi-annual conference).

Centres of Expertise (CoEs): The CoEs (CXC, CREW and EPIC) synthesise relevant evidence from the SRP and other sources for use by the appropriate SG policy teams, and as such will be a major route of engagement with this group of stakeholders. Much of this work is by 'call-down' in which the policy teams request information within a specified time frame, typically 3-6 months. There are also a number of projects on specific topics designed to address longer term policy questions (e.g. woodlands, peatlands, renewables, behaviours, etc.), which will link with research in WP1.1 (Soils), WP1.3 (Biodiversity), and WP1.4 (Integrated Land use), while CREW will draw on work in WP1.2 (Waters). The Theme will work closely with the CoEs to ensure alignment of relevant research activities for delivery to these beneficiaries. Further details are in the tenders for CXC, CREW and EPIC.

Centre for Knowledge Exchange and Impact (CKEI): The CKEI will provide the overarching KE strategy for the SRP. The Theme will contribute to the proposed CKEI activities in a number of ways:

	CKEI Indicative Activity	Example contributions from Theme 1
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	Co-organisation of side-one event per year at a relevant international meeting (e.g. UNFCCC-CoP, CBD-CoP, etc.)
5	Annual showcase event	Provision of speakers for plenaries and breakout group organisation on specified topics
6	Think Tank: science without boundaries	Proposal of Think Tank topics – e.g. Scotland's contribution to planetary boundaries
7	Practitioner workshops and staff training opportunities	Training workshops in e.g. soil management, farm biodiversity management; integrated land use management in practice
8	Leadership programme for early career researchers	Identification of suitable junior staff, and contribution to leadership training of senior staff
9	Work shadowing, secondments, residencies	Identification of staff for all of these in specific policy areas
10	Responsive opportunity fund	Contribution to innovative ideas for KE engagement, both within and across Themes

Linkage between CKEI and Theme 1 will be via the appropriate Sectorial KE Leads, who will be members of the TMG and will work with WP Coordinators to ensure shared awareness of policy and industry environments and opportunities for high impact KE.

Ensuring additionality and impact

Additionality and impact will be achieved by (a) ensuring all of our work is relevant to societal challenges, (b) doing excellent science, (c) working in partnership with the appropriate stakeholders, (d) collaborating with strong external research teams, and (e) promoting our work to wider audiences. Within the Theme, additionality will be achieved by organising workshops and seminars on topics that cut across all WPs, such as resilience, environmental decision-making and management. The Theme will also maintain ongoing communications across all the types of beneficiaries of the research, sharing early findings using approaches tailored to individual stakeholder groups. It will also be alert to emerging agendas and interests requiring links to be established with new communities of interest (e.g. reflecting evolving policy or changed societal and environmental responses). New ways of enhancing impact, such as social media, podcasts and e-newsletters will be used where appropriate.

KE impact will be trackable and reportable, and will contribute to an accessible and useable legacy of the 2016-2021 Programme. As 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, RCUK, 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: 1.1 Soil

1. Work package overview

Soil is a valuable but vulnerable natural asset which is vital to ecosystem goods and services while at risk from numerous drivers of change (Fig.1). In Scotland, given societal demands, our soils are required to support a number of functions from the same land and landscapes. For examples, agricultural soils are not only required to produce crops but also to play a role in limiting diffuse pollution to waters and reducing GHGs to mitigate climate change.

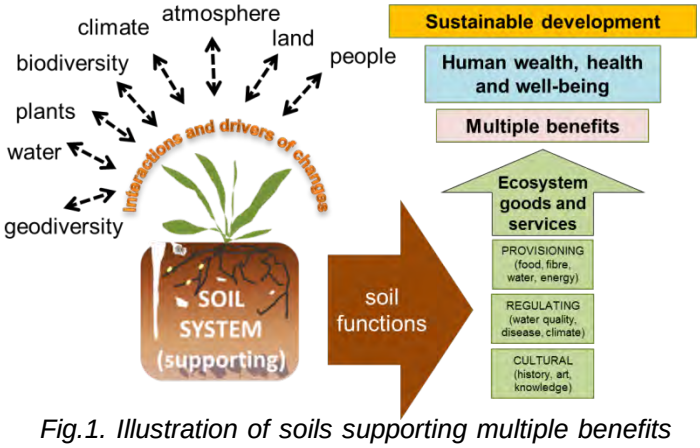


Fig.1. Illustration of soils supporting multiple benefits via diverse ecosystem services and wide ranging interactions. Adapted from NERC/DFID ESPA

Our vision for 2021 is to increase the area of Scotland under sustainable soil management practices and under restoration of degraded soils to enhance and safeguard the multi-functional capacity of Scotland's soils under changing a climate and other drivers of change. This principle of sustainable soil use and management for multiple functions is set out in the Scottish Government's Soil Monitoring Action Plan (2012) and the preceding Scottish Soil Framework (SSF) *(2009).*

Our research will support this vision by producing new tools and information for decision makers and by increasing the awareness of opportunities for wide ranging benefits to society by sustainable soil management and restoration. WP1.1 outcomes will contribute to Theme 1's vision to enhance Scotland's natural assets (RQ1-4) by producing improved information on the functions of soils to link with other natural assets thus reduce Scotland's ecological footprint and supporting the UN Sustainable Development Goals.

WP1.1 consists of four linked research deliverables (RDs) as illustrated in Fig. 2. A cross-scale and cross-system approach runs across WP1.1 with research reflecting the functioning of soils from gene to landscape and across Scottish ecosystems (peatland, montane, woodland, moorland, grassland, Machair, low-input arable - in collaboration with Theme 2). This will enable WP1.1 to build up an improved representation of individual and interacting soil functions across spatial scales, from plant to landscape to national. We have identified a number of common approaches to facilitate the development of generic understanding, ensure the integration of data and maximize added value. These include common sites (e.g. Hutton and SRUC farms) and common management (e.g. woodland expansion, peatland restoration and grassland

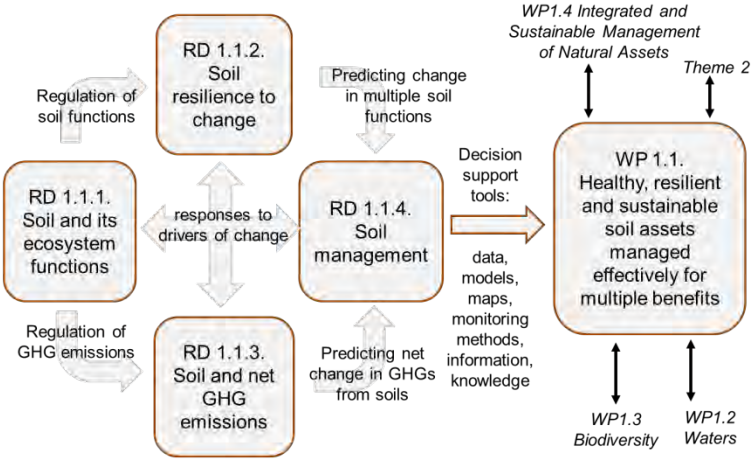


Fig.2. Diagram illustrating the primary linkages between research deliverables (RD) that come together to address the overarching outcome from WP1.1. Soil

liming) reflecting various policy issues including SRDP 2014-2020 aims to enhance the quality of Scotland's soils and peatlands.

At the outset, RD1.1.4 will use new approaches to improve existing decision support tools e.g. innovative digital soil mapping to produce high resolution spatial soil data that will be used to underpin the Natural Assets register and modelling of multiple benefits in WP1.4. RD1.1.2 and RD1.1.3 will work to improve our ability to predict change in soil functions that will feed then into RD1.1.4 to produce new decision support tools. RD1.1.1 will improve understanding in the regulation of soil functions which will in turn improve modelling in RD1.1.2 and RD1.1.3 and ultimately tools from RD1.1.4. The production of new data, models and tools will involve close collaboration with Theme 2 (in particular RD2.3.4) to bring together complementary information from intensive and extensive systems. Reflecting the significant multi- and interdisciplinary research challenges for WP1.1, the research team includes ecologists, microbiologists, soil scientists, economists, social scientists, statisticians, mathematical modellers, spatial analysts and GIS specialists.

WP1.1 will generate new and improved knowledge on: (i) how soil functions and associated ecosystem services are regulated by soil chemical, physical and biological properties; (ii) the sensitivity and resilience of soil and its functions to drivers of change and (iii) changes in and scaling of soil functions across space and time. Technical advances will be made with (a) new and improved tools to measure, map and monitor soils, (b) innovative modelling approaches predicting how soils function and respond to drivers of change and (c) user-friendly approaches to communicate and make soil information available to stakeholders e.g. via the web-based communication platforms SEweb and Scotland's Soils.

WP1.1 focusses on research with strong policy imperatives with relevance to a number of stakeholders and which will significantly advance Scotland's capacity for sustainable soil management to meet multiple objectives by 2021. The proposed Soil Stakeholder Group (SSG) will provide a forum to review priorities in response to emerging issues and outstanding areas, including invasive non-native species, soils as records of past environments and wind erosion. The SSG will assist WP1.1 in identifying alternative approaches to tackling outstanding areas e.g. research collaborations with HEIs through access to sites, PhD studies and collaborative projects. The RD allocation of research in WP1.1 reflects efficiencies in research effort. For example, mapping of soils as natural assets is addressed in 1.1.4 to reflect research on scaling and Digital Soil Mapping which will improve mapping (as opposed to 1.1.1, as outlined in the ITGF). In response to the review feedback, WP1.1 has increased emphasis on: extensive grassland research; SRDP measures with shared experiments across Theme 1 and interactions with Theme 2 and; increased modelling efforts to investigate management and risk and to support the development of new decision support tools.

2. Coordination and management

2.1 Work package management and coordination within the SRP

Within WP: Research management and coordination will be via the structures of (i) Objective leaders – for day to day administrative and scientific exchanges. There will be Objective leaders from RINH/UoA, SRUC and Hutton will ensure cross MRP representation; (ii) RD coordinators within each RD for delivery and budget tracking, coordination between projects and managing annual reporting. RD coordinators will have a pivotal role in communicating and coordinating with Objective leaders, amongst RD coordinators and with the WP coordinator. RD coordinators will organize regular RD catch ups to review progress, research planning and

integration; (iii) Work Package Management Group for overarching management and coordination between RDs and with or WPs in Theme 1 (see below).

WP Management Group (WMPG): This will consist of the WP coordinator and the four RD coordinators, or deputies. The WPMG will hold regular open meetings (monthly initially leading to quarterly) to review progress, planning, any requirements for remedial action and horizon scan future opportunities. Outcomes from these meetings will be fed back to the WP research team via RD coordinators and regular WP update emails from the WMPG. To address matters arising, WPMG will maintain regular contact via email, phone and skype. The WPMG will:

- Act as the primary contact point for RESAS and SG Policy units.
- Maintain communication and consultation with RESAS scientific advisors
- Provide overarching financial, intellectual and administrative management
- Assistance with planning and implementation of research projects
- Review and support change management e.g. staffing changes
- Monitor resourcing, progress and priorities
- Co-ordinate synergies between RD and other WPs in Theme 1
- Co-ordinate synergies with Theme 2 soils research, Underpinning projects (e.g. Soils and CSC) and the Farmland Biodiversity Initiative (see WP1.4)
- Ensure outputs are communicated and disseminated effectively, including good use of websites such as Scotland's soils, SEweb and UKSO
- Provide a forum for the mediation and resolution of conflicts
- Communicate with and report to the Theme Coordinator
- Provide guidance on knowledge exchange and pathways to impact
- Foster communication, networking and engagement with stakeholders
- Foster engagement with the Centres for Expertise (CREW, CxC, Plant Health)
- Develop collaboration with compatible research activities e.g. RCUK.
- Maintain regular RD and WP meetings and other forms of communication
- Monitor and facilitate collaborations and networking

Across the SRP: WP1.1 will work closely with other WPs in the Natural Assets Theme including sharing data, methods, modelling and outputs while working collaboratively on common management topics and shared study sites. There are substantive links for: WP1.2 - soil-water interactions; WP1.3 - above-below ground interactions with shared experiments and WP1.4 - co-construction of frameworks to investigate multiple benefits across spatial scales. There are significant interactions with Theme 2 which has parallel soil research objectives for intensive agricultural systems. We will actively engage with Theme 2 to provide the cross-Theme SRP soils research that will produce the fully integrated national perspective. At the WP level this engagement will be coordinated via WPMG e.g. and the RD specified shared activities with shared outputs.

2.2 Mechanisms for networking and collaboration

The research team has extensive experience and success in networking and collaboration at all levels. Each level will be extended as the WP develops, with example mechanisms set out below:

Local

- WP1.1. will host an annual cross-Programme soil workshop, as an extension of the WP meetings, to ensure close working between Theme 1 and Theme 2.
- In support of RD2.3.8, 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, 2.3.8 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.

- Participation in, and assistance with, the Soils Stakeholder Group in partnership with WP1.4, Scottish Government and other stakeholders. WP1.1 has allocated staff time to SSG together with WP1.4
- Participation in CAMERAS Soil Monitoring Action Plan with key outputs from WP1.1 addressing the objectives of the soil MAP. Staff time has been allocated to support the Soil MAP Working Group.
- Participation in the CAMERAS Environmental Monitoring Steering group – linking soil monitoring to wider monitoring activities
- Centres for Expertise (CoEs: CREW, CxC, Plant Health, and EPIC). CoEs have a pivotal role in policy networking and impact. WP1.1 will maintain regular communications with CoEs and provide project updates and technical support for CoEs project activities. In return WP1.1 will benefit from the CoEs up-to-date knowledge of stakeholder priorities and emerging issues. WP1.1 staff directly involved with CoEs will help foster this engagement.
- Continuing local collaborations initiated during the International Year of Soil 2015 e.g. Soil Association Scotland, National Farmers Union Scotland.
- By direct practitioner working through catchment and field site based activities e.g. Centre for Sustainable Cropping, Balruddery; Farmland Biodiversity Initiative at Hartwood and Glensaugh, NFUS and LEAF events.

Regional

- Continued strategic engagement with RCUK and wider UK research community. WP1.1 researchers are directly engaged with NERC Soil Security (funded projects and steering group), NERC/DFID ESPA (funded projects), BBSRC SARISSA (funded projects) and NERC/BBSRC STARS (joint PhDs). Further opportunities will be considered as they become apparent
- By memberships of committees and other UK activities. MRP scientists are directly involved in Innovate UK, reviewing for the EA and EU in Horizon 2020.
- By engaging with UK Learned Societies e.g. British Society of Soil Science, Geological Society, and British Ecological Society. With broad membership these societies are excellent networking opportunities and have been used to great success in the current previous RESAS programmes.

International

- Participation in the FAO supported Global Soil Partnership through Hutton institutional membership, membership on the steering group for the European Soil Partnership and participation in the activities of the GSP Plenary.
- Contributions to consultations on IPBES, UNCCED desertification, IPCC, COP and SDG as they relate to soil, land degradation and climate change.
- Through existing and expanding scientific networks using RC-UK EU (FP7 and Horizon 2020) and international projects e.g. EU FP7 SMART SOIL.
- Through existing links with international institutes and networks such as the World Agroforestry Centre, Integrated Carbon Observation System, Royal Society/DFID Africa Capacity Building Initiative and Global Research Alliance.

2.3 Interactions with underpinning capacity (UC)

Soils. WP1.1 researchers are directly in the UC soils activities and will be using National soils data, archived material from the National Soils Archive for WP1.1. Shared staff will aid effective use and exchange of data and tools between WP1.1 and UC soils. WP1.1 will develop new approaches and data that will be used to augment the National Soils data in UC, e.g. digital soil mapping improvements from 1.1.4 will ultimately help populate data sparse areas. WP1.1 will improve existing and new spatial datasets and maps that will be delivered through the

Scottish Soils Website and other portals. UC soils will inform WP1.1 approaches.

BioSS. Inputs of a collaborative or advisory nature will be provided through UC Function 7, "Provision of Biomathematical & Statistical Consultancy Services". WP1.1 supported via a BioSS WP1.1 contact, who will attend WP meetings, involved in annual reporting and KE activities.

Centre for Sustainable Cropping. Experimental work linked to Theme 2 will take place at the CSC Balruddery to add value to CSC by generating new data and equally have access to CSC information to support modelling and interpretation.

Environmental Change Network. All three Scottish ECN sites provide fundamental datasets of long term change in soils, climate, deposition chemistry and biodiversity which will be used to inform baselines and for model development.

2.4 Enhancing additionality

Data, information and tools for decision making. These are a major route to add value from WP1.1 and we will be working closely with our stakeholders, through SSG, CoEs and CKEI, to ensure that these are tailored, accessible, useful and easy to use. Working with Underpinning Capacity Soils projects, we will ensure that the appropriate data and sample archiving establishes a legacy that has open access. In the first instance, we will be working to release data and metadata through Scotland's Soils website and SEweb, and also wider through UK Soil Observatory and other suitable international portals.

Research findings. Key here will be the communication of research results to both established audiences and also new audiences where soil information and knowledge can create new impacts. WP1.1 in partnership with the CKEI, KE Sectorial Leads and SSG will review research findings and work to identify the relevant audiences (e.g. local authorities, environment and health; community action groups, SMEs in the bio-economy) and suitable approaches in communicating findings to these audiences.

Table 1. Projected key risks for WP1.1, where the overall risk status (likelihood x occurrence) is indicated in terms of **Amber** or **Green**, for medium and low risks.

Risk Descriptor	Risk Ass.	Impact	Controls	Risk owner
Significant budget reductions	Med	Limitations on the delivery of research	Objectives and deliverables will be modified in consultation with RESAS to ensure best possible delivery within any reduced resource	DEC & Theme Coord.
Unexpected or high staff turnover	Med	Reduced or delayed delivery/ over- commitment of remaining staff	Coordinated response required across MRP team. Early discussions on response. Research objectives, deliverables and timelines will reviewed with RESAS	Theme, WP & RD coords
Inappropriate phasing of activity to fit with policy timelines	Med	Reduction in impact and fit with policy requirements.	Close liaison with policy groups to review research against impact timelines. Regular intelligence gathering (e.g. SSG, CoEs, CKEI) to maintain rolling 2 yr timeline window	WP Coord. / RD coords
Restricted field access: weather or disease.	Low	Reduced or delayed delivery	Fieldwork timelines modified; Research objectives, deliverables and timelines will reviewed with RESAS	RD coords & PIs
Divergence in stakeholder and research priorities	Low	Research uptake lower than expected	Agreed TOR of stakeholder groups. SSG will be used to agree why and where priorities may need to change, or if findings conflict with stakeholder positions.	WPcoord. RD coords & PIs

Research funding. WP1.1 will build on the significant successes of previous SRP research which led to significant added value from EU FP7, NERC, BBSRC and Innovate UK funding, and recently with the UK-China Newton Funding for Critical Zone Observatories. With collaborative funding, our strategy will be to extend WP1.1 integrative research to new systems beyond Scotland to explore the broad utility of our approach and new tools. In parallel we enhance local insights

through new HEI collaborations on WP1.1 experimental platforms and modelling.

2.5 Work package risk management

WP risk management will be a component of Theme-level risk management. The WPMG will establish a risk register and review the risks in Table 1 on a regular basis, updating and adding to the risk table as necessary. Emerging risks will be identified and mitigation strategies identified taking into account the implications for cross-programme links and collaborations including implications for stakeholders. The WPMG will provide a risk register update to the Theme Management Group.

3. Impact and KE

3.1. Multi-functional approach to KE

Soils research in Scotland is acknowledged internationally for its innovation and impact on policy, awareness raising and improved management. RESAS research linking soils to ecosystem services has informed the UN Year Book 2012 chapter on the Benefits of Soil Carbon, the 2015 updated UN FAO World Soil Charter, the successful EU FP7 SMART Soil project and the identification of a tiered approach for peat monitoring to support the Scottish Government Green Stimulus Peatland Restoration Package. Much of this is based on our integrative (holistic) approach and imaginative knowledge exchange (e.g. hosting the European Soil Awareness Conference 2013; joint activities with EU JRC for IYS2015 at Milan EXPO 2015, and the soil trail at Royal Highland Show 2015). We will expand awareness of innovative and integrative SRP soils research at appropriate international venues and developing further novel KE in partnership with SSG, CKEI and international partners. Such an approach is a challenge for WP1.1 as it works to ensure that research outputs are relevant and useful while balancing differing demands for soil information from multiple stakeholders. It necessitates working across science disciplines, policy areas and stakeholders. To address this, a key component of WP1.1 KE will be on-going dialogue with stakeholders to aid communication, identify requirements and establish priorities for soils data, information, and tools to support different decision making needs.

To build impact of Theme 1, WP1.1 will have a key role in delivering new soil information to WP1.4 to support development of the Natural Assets Registers and support decision making across policies. We will continue to be ground-breaking by demonstrating opportunities to expand sustainable soil use and management across Scotland soils using user friendly tools suitable for diverse types of stakeholders. By this approach, Scotland will be one of the first countries to directly address the principles and actions outlined in the new World Soil Charter endorsed by UN FAO nations in July 2015. It will align WP1.1 soils research with the 2020 Aichi Biodiversity Targets including Strategic Goal D to “Enhance the benefits to all from biodiversity and ecosystem services”. Sustainable soil management is also required to address cross compliance in Good Agricultural and Environmental Conditions (GAECs) and Statutory Management Requirements (SMRs), and to address Water Framework Directive requirements to improve overall health of surface water environments by 2027, given the well establish links between sediment and nutrient transfers from soils to water bodies.

3.2. Improving Pathways to Impact

WP1.1. Pathways to Impact will involve (i) existing pathways with diverse demands for soil information and tools across a number of policy / end-user areas and (ii) new pathways where it is recognised that soils information and tools would be beneficial but where specific needs and mechanisms for engagement are not well understood or defined. In discussion with SG, SNH, and SEPA stakeholders, it

became clear that on-going review and prioritization across end-users with different expectations and needs would benefit WP1.1 and help support implementation of the Soil Monitoring Action Plan (MAP). WP1.1 will work with SG Soil Policy, RESAS and CAMERAS organisations, through the SF and Soil MAP, to explore and improve Pathways for issues of importance to Scottish Government and CAMERAS. In the first instance, we will gain insight from successful impact e.g. the use of peatland soils information to support the National Peatland Plan, and explore how this can be applied to other areas including: diffuse pollution/water quality; biodiversity / Aichi Targets; planning; waste management.

3.3. A KE structure to enable impact

WP1.1 KE structures, as part of the Pathways to Impact, will work to communicate and engage with stakeholders to identify, support and improve impact. This will include activities to: (i) maintain and foster existing stakeholders; (ii) identify new beneficiaries (with CKEI), (iii) deliver simple and clear communication and translation of research activities and outputs, and (iv) foster co-construction and prioritization of research. As elsewhere in Theme 1, our overall approach to KE can be illustrated as a pyramid of activities (Fig. 3).

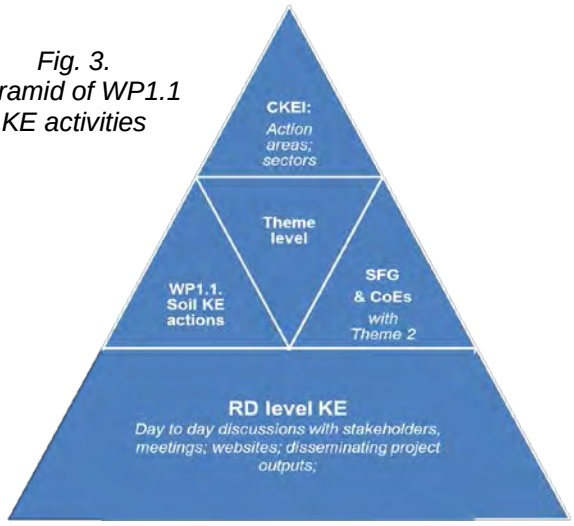


Fig. 3. Pyramid of WP1.1 KE activities

RD level KE: At this level, there will be a variety of KE outputs from research papers, conference presentations and the delivery of specific tools to end-users to direct communication with stakeholders. A key requirement will be for clarity of messages from the research being communicated to different audiences. Externally, the SSG, CoEs and KE Sectorial Leads will play an important role in advising on different KE needs and providing essential feedback to the RDs for future KE requirements. Internally, KE will entail exchange of data and skills between RDs in Theme 1 and Theme 2, supported by cross RD activities. RD-level KE deliverables are included and budgeted in the RD plans and their delivery will be monitored by RD coordinators. They link to WP- KE through topics and issues.

WP to Theme KE: This requires collectively strong, clear messages across (i) RD outputs at WP level, and (ii) between Themes 1 and 2 where outputs have linked messages for managing and restoring soils. Integrative aspects include: combining messages at major meetings (e.g. SRUC-SEPA conference) and coordinating practitioner engagement e.g. Open Farm events. As part of clear messaging of 'what, why, for whom and when', broad stakeholder engagement will be required with on-going mapping of timelines of collective outputs against policy needs and timelines for our key stakeholders. A number of flagship KE activities cut across all RDs, including the Royal Highland Show, European Geosciences Union Congress, World Soils Congress and the annual World Soil Day (5th Dec), coordinated via WPMG with CKEI.

Centres of Expertise (CoEs) for Waters (CREW; Climate Change, CxC and Plant Health): WP1.1 research will provide data, knowledge and capacity building foundations (evidence, knowledge, tools, frameworks and maintaining skilled staff resource) for delivery of projects to short term needs through the CoEs. For example, a draw-down of service is available to CREW partners SEPA, DWQR,

Scottish Water, and SNH. In turn, CREW and other CoE structures inform the needs of the SRP by various mechanisms e.g. synthesis work, improved understanding of stakeholder (regulatory/policy/industry) needs through co-construction of project specifications and targeted events with key stakeholders.

Soils Stakeholder Group. The SSG will play an important role in WP1.1 KE. WP1.1 will work in partnership with WP1.4 and Scottish Government to run and organise the SSG. It is placed between WP1.1 and WP1.4 to complement running the *Biodiversity and Land Use (BLUPU) KE process* which has cross-policy engagement. The objective is to learn about and share practice from cross policy groups. SRP engagement in SSG will be managed by dedicated support from WP 1.1 / WP1.4, and RD Coordinators in Themes 1 and 2. WP1.4 has a staff budget to support this activity. It is envisaged that SSG will host events to bring relevant stakeholders together to review needs and uses of soil information and tools for specific issues e.g. climate change, planning, water quality. SSG will discuss SRP soils research progress, upcoming research outputs and their audience and acts as a "heads-up" on relevant initiatives to which the WP should respond.

WP1.1 will work with other WPs and the SSG to establish effective communication of data, knowledge, expertise, methods and information that can be used to inform on the broad range of benefits and issues associated with soil management and restoration. Since changes in soil management or threats to soils will have significant implications beyond soil itself, WP1.1 has strong research linkages across Themes 1 and 2. Building on the successful approach initiated during IYS2015, WP1.1 will work with SSG stakeholders and the CKEI to hold annual World Soil Day events (5th Dec) to raise awareness about soil issues with other stakeholders including the public and schools. Scotland's Soils and the SEweb websites will be important routes in making soil information accessible and available and to raise awareness on sustainable soil use and management.

CKEI: The KE Director and CKEI will provide guidance on best practice, QA, evaluation and training. WPMG will liaise with the KESLs to ensure appropriate contributions to and integration with CKEI-led activities by:

Activity 2: *Branding, design, corporate identity,* the WP will make use of central KE services and ensuring that presentational standards are adhered to particularly the key role of SRP directly and as support.

Activity 4: Annual campaigns, the WP will utilise its intelligence gathering structures to feed into theme-level suggestions for high impact topical storylines.

Activity 5: Annual showcase event, as we have supported collective programme events before (e.g. SEPA-SAC bi-annual conference) we will strongly support these events with individual and synthesis contributions.

Activity 6: We will contribute ideas and scientists with particularly good intelligence and connections into the *Think Tank approach*, transferring learning from CREW's Think Tank approaches to other activities.

Activity 7: Practitioner workshops, we develop new ways of working with practitioners via SSG, CAMERAS EMCG, Farm Open Days, BSSS/BES events.

Activity 8: Staff KE development, we will identify key individuals for such training and link it to using CoE and SSG to assist in WP staff becoming more effective scientific communicators.

Activity 9: Secondments, work shadowing & placements, we will suggest staff that would benefit from close engagement with agency or policy teams. Key targets may be Scottish Government Soil Policy, SNH or SEPA.

Activity 10: We will seek to make best opportunity of the proposed *Responsive Fund* by seeking to align this with topical issues and co-supporting funds.

Table 2. Summary policy priorities for key stakeholders of WP1.1 with proposed impact routes, decision timelines and primary contributing RDs.

Policy priorities	Impact routes	Audience	Time-line	RDs			
				1	2	3	4
Greening Stimulus National Peatland Plan	Updated advice on restoration priorities and methods	SG Soil / Env Qual; SNH; CAMERAS	2017-2019+		✓	✓	
	New monitoring and evaluation tools for peatlands	SG Soil / Env Qual; SNH CAMERAS	2017-2019+	✓	✓	✓	
	Improved estimates for C sequestration and Net GHG emissions	SG Env Qual; CAMERAS	2017-2019+		✓	✓	
Rural Affairs, Food and Environment decision making across multiple policies	Improved and new soil information to update the Natural Capital Asset Register	SG; SNH	2018+			✓	✓
	Improved soil function data for Natural Capital Accounts	via WP1.4 to SG and UK Gov.	2020+			✓	✓
	Release of new soils information via websites	CAMERAS; SG; local auth	2016-2021	✓	✓	✓	✓
Scottish Biodiversity Strategy	New soil information to support the monitoring and reporting against CBD Aichi Targets re. sustainable management, restoration for carbon	SG; SNH; CAMERAS EMSG	2020	✓	✓	✓	✓
	Soil mapping to support revised Ecosystem Health Indicators for SBS (e.g. soil sealing,)	CAMERAS; SEPA	2017-2018				✓
	Updated functional mapping of soils to improve capability mapping e.g. LCA, GHGs	SG; CAMERAS	2017+			✓	✓
Land Use Strategy	Higher resolution soil information to assist with targeting of existing AECS measures	SG (NATRES)	2017-2018			✓	✓
Scottish Rural Development Plan / CAP	Support for compulsory soil testing and insights into potential outcomes from compulsory soil testing	SG ARD	2016-2021	✓	✓	✓	✓
	New monitoring tools to support GAEC assessments	SG ARD; SEPA	2020	✓			✓
	New options for sustainable land (soil) use and management	SG ARD	2020	✓	✓	✓	✓
	New measures or combinations of measures for SRDP 2021+	SG (NATRES)	2017-2018				✓
	New measures to support SMR and GAEC requirements	SG ARD	2020	✓	✓	✓	✓
	Improved soil information to support review of LFASS or appraisal of ANC methodologies	with WP14 to SG and EU	2018+				✓
	increasing land managers awareness on reducing diffuse pollution through soil use and management	SG; SEPA; land managers	toward 2027	✓			✓
WFD via River Basin Management Planning / Rural Diffuse Pollution Focus Areas	Providing improved information on soil erosion risk to support Sustainable Land Management initiative for diffuse pollution and DOC	with 1.2 to CREW; Scottish Water, SEPA	toward 2027	✓			✓
	Improved and new approaches to monitoring soil erosion and soil nutrient loads to inform diffuse pollution management	SG; SEPA CAMERAS; land managers	toward 2027	✓	✓		✓
Scotland's digital future (RAFE subgroup on digital services)	Provision of free-to-use digital soil data and information via Scotland's Soils and SEweb websites to contribute to Scotland being a world leading digital nation by 2020	Scottish Government	2020	✓	✓	✓	✓
Scottish Planning Policy	Improved spatial information on soil carbon and peatlands to support planning and development management	SG; CAMERAS	2016+			✓	✓

4. Quality assurance (QA).

MRPs associated with WP 1.1 will adhere to the QA directives outlined at the Theme level. All staff 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 BBSRC/Defra/FSA/NERC Joint Code of Practice for QA 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 MRP Institute include: (a) Quality performance monitoring through internal and external auditing relating to the pertaining ISO standard. (b) Understanding of specific quality objectives and targets to staff. (c) Planning and developing of standard work processes by means of Standard Operating Procedures, where required. (d) Appointment of competent personnel to co-ordinate, implement and review quality management directives [existing MRP QA managers]. (e) Ensure adequate allocation of resources to achieve quality objectives and targets. (f) Obtain and act upon feedback from key stakeholders and the Scottish Government (g) Develop competency of all staff through the provision of tailored training and the clear communication of QA requirements.

5. Ethical and regulatory issues

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. 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. SRP research involving people will complete the RESAS Research Approvals *pro forma* for clearance. There are no planned animal experiments. Farm livestock in grazed fields will be handled as per normal farm practice.

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

This is not applicable for the work proposed in this WP.

7. Sustainable development

The Main Research Providers associated with WP 1.1 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. We seek to:

- Regularly assess and review our environmental aspects and impacts
- Implement operational control procedures and monitor environmental performance through management reviews of environmental issues, meetings and audits
- Comply with all relevant environmental legislation and other requirements
- Operate an environmental management system which is systematically maintained, reviewed and revised to ensure continuous improvement. Some institutes currently operate to the ISO 14001 standard
- Set environmental objectives and target, including CO_2 emissions reduction
- Allocate sufficient resources to achieve its environmental objectives and targets within budgetary constraints
- Senior management within the MRPs and RBGE receive advice from Environment Committees or their equivalent.

Name of RD: 1.1.1. Soil and its ecosystem function

Research aim and key drivers: The primary aim of this RD is to make significant improvements in our understanding of how soil functions are delivered by the interactions of soil physical, chemical and biological properties. Healthy, resilient and multi-functional soils are essential to living within planetary boundaries and to achieving Scotland's economic and social goals. Current understanding recognizes that complex interactions exist in the soil-service-benefit chain (Figure 1). However, as yet, there is minimal mechanistic understanding of how soil properties and processes deliver individual and inter-linked functions and therefore how soils support varied goods and benefits. Narrowing these knowledge gaps will lead to improved modelling and mapping of soil functions across ecosystems and ultimately lead to improvements in managing soils for multiple benefits. Globally, major knowledge gaps lie in the role of soil biodiversity in function, particularly in carbon and nitrogen dynamics, while the regulation of soil erosion and nutrient retention have significant regional and local policy significance. For these reasons, these issues form the initial focus for 1.1.1 and will directly address the Theme level RQ1 *"How do Scotland's natural assets function, how healthy are they, what are their trends, and what are 'safe' limits to their sustainable use?"*

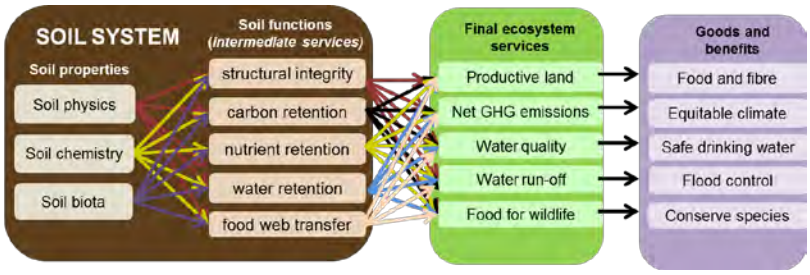


Figure 1. Diagram illustrating the complexity of interactions in soil systems supporting ecosystem services and

New data and knowledge generated by RD1.1.1 will contribute directly to improving the modelling of soil systems in RD1.1.2 and RD1.1.3 and thus contribute towards the understanding of ecosystem and ecosystem service resilience identified in the 2020 Challenge for Scotland's Biodiversity and support the National Peatland Plan and the Scottish Soils Monitoring Action Plan.

Who has been consulted in developing this proposal: There has been extensive consultation with Scottish Government and CAMERAS through Theme 1's shared consultation approach. For 1.1.1, SG Soil Policy, RESAS, SNH, SEPA have given significant feedback and useful information for this submission as part of overall WP1.1 discussions.

Summary of the proposal: This RD will produce new insights into the fundamental mechanisms by which soil functions are regulated by intrinsic soil properties in a number of Scottish ecosystems (grassland, peatland, machair) and how management (e.g. SRDP measures) can influence soil properties and functions. This research will address the characterisation of soil biodiversity and identifying its key roles in ecosystem processes in particular carbon and nutrient cycling in priority habitats and semi-natural systems; the contribution of soil physical and chemical properties and processes to ecosystem functions and the role and importance of soil in sustaining above-ground biodiversity in different systems and habitats. The soil functions of interest to policy are outlined in the Scottish Soil Monitoring Action Plan (2012) which is underpinned by the complex interactions within the soil system (Figure 1) of which 1.1.1 will address a subset (Figure 2).

The challenge for this RD is to demonstrate causative relationships between

properties and function. To meet this challenge 1.1.1 will develop a number of new tools to investigate and measure function at a range of scales, from molecular to field. Methods developed in intensive agricultural systems under the current SRP will be adapted and tested for application in semi-natural systems. We propose six research objectives (Figure 2) that will address interactions between soil properties and functions from gene (using metagenomics) to national scale (using the National Soil Inventory for Scotland). Objectives 1 to 4 are focused on the role of soil biodiversity in soil functions. Few processes in soil do not involve soil organisms but there remain major knowledge gaps in the interactions between biota, processes and function. Using techniques refined in the current SRP (e.g. tracking carbon via isotopes and soil-root imaging) along with new approaches (e.g. novel use of $^{16}O/^{18}O$ isotopes), we aim to identify and quantify the role of key soil biota (fungi, microbes, nematodes). Objectives 5 and 6 address key questions around the structural stability of soil and the availability of phosphorus in Scottish soils. Both are critical in tackling diffuse pollution to waters. Soil structural integrity is linked to sediment and nutrient pollution from soil erosion as well as to net GHG emissions, ground-water recharge and plant growth while limiting soil erosion (GAEC 4 & 5). We aim to improve methods for assessing soil structure *in situ* and thus enabling investigation of links between structure and plant growth. Whilst being a vital plant nutrient, P is also a significant diffuse pollutant. New knowledge generated in 1.1.1 on the distribution and availability of organic P will improve understanding of nutrient leaching risks from Scottish soils (1.1.4).

Outputs from this RD will directly contribute to improving the system models that are being developed in RD1.1.2 (O4), to inform process modelling approaches such as BBN, ECOSSE, PALM, DNDC, INVEST in RD1.1.3, RD1.3.3, RD1.4.2 and function mapping in RD1.1.4. By 2021, we aim to have identified key aspects of soil biota that need further consideration to improve the modelling of soil functions. Research in RD1.1.1 from Year 3 will be informed by Years 1-2 results from model development and application in RD1.1.2, RD1.1.3 and RD1.1.4, with RD1.1.1 evolving to address emerging knowledge gaps.

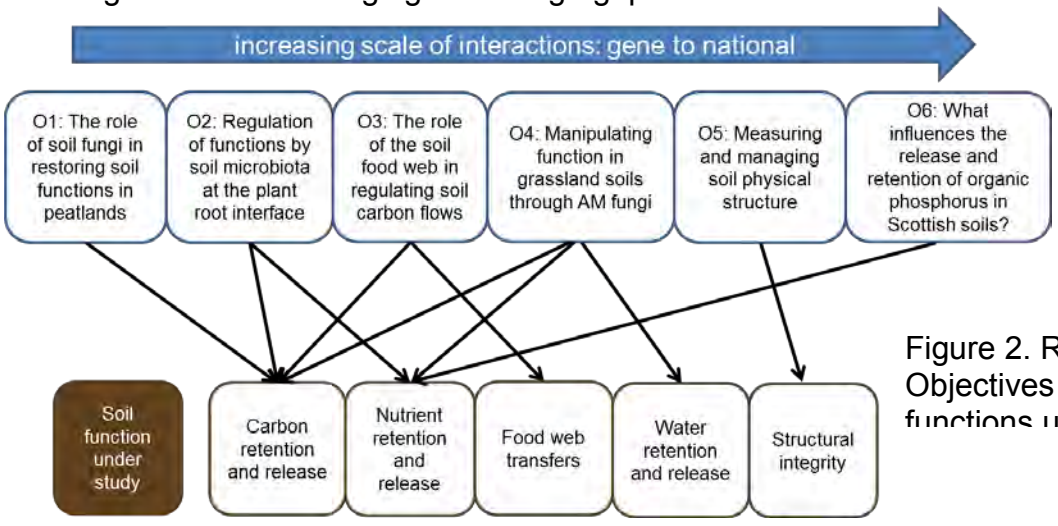


Figure 2. RD1.1.1 Objectives and soil functions under study

Detailed work plan: Objectives (O), milestones (M) and deliverables (D)

O1: The role of soil fungi in restoring soil functions in peatlands

Building on existing SRP research on the well characterized peatlands of the RSPB-owned Forsinard Flows (Annex 1 Atlantic blanket bog) used in RD1.1.2, we will in years 1 & 2, investigate the active soil fungal community and vegetation structure across an established globally unique peatland restoration chronosequence. This will explore whether restoration management results in a predictable shift in the

composition of both above-ground vegetation and below-ground (partially associated) fungal community. Both will influence the restoration of carbon sequestration in peatlands **M1.1.** Resample the entire peatland restoration chronosequence, with samples prepared for downstream analyses (**D1.1**, Year 1); **M1.2.** Establish protocols for metagenomic analysis to facilitate the undertaking of a small scale metagenomic experiment (**D1.2**, Year 2), providing RD1.1.2 with data to parameterise models (**D1.3**, Year 2).

O2: Regulation of functions by soil microbiota at the plant-root interface

Using the novel and unique transparent soil system developed in the current SRP, this objective aims to understand and characterise the mechanisms of establishment of microbiota in the rhizosphere, and in turn quantify their impact on plant growth and nitrogen retention. Two strands of work will be established: a) investigate the activity of free living nematodes and their feeding behaviour, and in turn how their feeding will impact on the rhizosphere interactions with soil biodiversity, nutrient flow and plant biomass; b) explore nitrification and denitrification processes and how root activity influences the functions of nitrifiers and denitrifiers in soil which are fundamental to the release of N for plant growth, leaching from soils and regulating N_2O emissions. **M2.1.** Develop a soil microcosm platform to assess mechanisms of plant–soil–microbiota interactions, with optimization and validation of the system. The platform will be available for other research in WP1.1 and Theme 2 to test specific hypotheses (**D2.1**, Year 1); **M2.2.** Develop quantitative imaging tools for microcosm systems, with optimization and validation of the tools (**D2.2**, Year 2); **M2.3.** Analyse and collate (**D2.3**, Year 2) image data derived from quantitative imaging tools; **M2.4.** Conduct preliminary modelling interactions between plant roots and soil microbiota, test model assumptions (**D2.4i**, Year 2), calibrate models for activity of soil microbiota in the rhizosphere (**D2.4ii**, Year 3), estimate key model parameters (**D2.4iii**, Year 4), identify factors that influence activity of rhizospheric microbiota (**D2.4iv**, Year 5).

O3: The role of the soil food web in regulating soil carbon flows

Root deposition represents the dominant input of C to soil, countering losses through soil organic matter (SOM) decomposition and providing energy to food-webs to drive the cycling of nutrients and elements in soil which are the foundation of soil functions (e.g. nutrient cycling, C storage and net GHG emissions). However, the ability to quantify this crucial biotic interaction is constrained by methodological limitations. Building on existing knowledge and using soils from contrasting common experiments, low-input (1.3.1) and intensive systems (2.3.4) with cutting edge C isotope techniques, we will: a) confirm that a predominance of C-flows through fungal, as opposed to bacterial, channels of food-webs are associated with slower, but more conservative (less leaky) nutrient cycling that occur in low-input systems in Scotland; b) the relative abundance of bacterial, fungal and root feeding nematodes is a measure of the activity in soil food-web pathways in the different systems; and therefore is an informative indicator of soil nutrient cycling. **M3.1.** Synthesize existing data to determine the impact of rotational (grasslands, fallow and arable) management in Machair soils on soil nematode (Output – scientific paper, **D3.1i**, Year 1), arbuscular mycorrhizal communities (Output – scientific paper, **D3.1ii**, Year 2) and identify drivers of change (Output – scientific paper, **D3.1iii**, Year 2); **M3.2.** Evaluate proxy soil food web indicator of C and N cycling in grassland and contrasting low-input and intensive arable soils from common experiments, (**D3.2i**, Year 2), and validate against soil C and N process measurements (**D3.2ii**, Year 2); compare with natural abundance isotopic proxies for C and N processes (**D3.2iii**, Year 3) and spectroscopic proxies for C and N processes (**D3.2iv**, Year 4; Output – scientific paper, **D3.2v**, Year 4). **M3.3.** Establish nutrient pathway index based on

soil food web structure for Scottish soils, and map using supporting information from Scotland's soils database (**D3.3i**, Year 5).

O4: Manipulating function in grassland soils through AM fungi

We will conduct a series of field and glasshouse experiments to investigate the role of arbuscular mycorrhizal (AM) fungi in multiple soil functions through interactions with plant yield, water retention, P availability and soil C content and investigate how management (e.g. nutrient inputs, plant type and genotype) can be used to manipulate this relationship to enhance function. We will conduct a) paired greenhouse experiments to assess the impact of management on AM fungi and associated soil functions; b) a field experiment using existing grassland sites associated with the Farmland Biodiversity Initiative (1.4.3) to indirectly manipulate the soil community via nutrient inputs and multiple plant species and assess the impact on soil functions. **M4.1.** Initiate sampling to facilitate selection (**D4.1**, Year 1) of genotypes for subsequent testing in greenhouse studies; **M4.2.** Temporal monitoring to ascertain the impact of nutrients, host plant and host plant genotype on AM fungi and associated soil factors (Output – scientific paper, **D4.2**, Year 2). M4.3. Assessment of changes in AM fungal function as a consequence of differing soil interventions (Output – scientific paper, D4.3, Year 3); M4.4. Identify drivers of change in grassland plant-soil functions e.g. biodiversity pool, water relations and C dynamics (Output – scientific paper, D4.4, Year 4); M4.5. Identify the relative importance of AM fungal vs. plant genetic diversity maintaining soil function in grasslands, and the implications for land management (D4.5, Year 5).

O5: Measuring and managing soil physical structure

We will develop a new user-friendly tool to measure shear resistance of soil. Shear resistance reflects the stress levels in a soil and is therefore a measure of structural integrity which influences the filtering/buffering of water, plant growth and soil erosion. Using an existing grassland experiment at Glensaugh, established in the current SRP, we will use the tool to investigate the contribution of roots to soil stability under different grassland management regimes which parallels the woodland studies in 1.1.2 and will explore the use of the tool to inform on and minimize erosion in a Theme 2 RD linked experiment at Balruddery. **M5.1.** Develop *in situ* shear resistance measurement tool for grassland systems, tested and refined in-field (**D5.1i**, Year 1) with field measurement of root shear strength in different grazing management systems (**D5.1ii**, Year 1), temporal assessment of soil stability in contrasting grassland grazing systems (**D5.1iii**, Year 2), ascertain if re-vegetation with different species yields similar data (**D5.1iv**, Year 4); **M5.2**. Underpinning laboratory experiment establishing grass in intact field sampled cores to understand impact of grazing on root decomposition (Output – scientific paper, **D5.2i**, Year 5) with development of outline guidance for land managers (**D5.2ii**, Year 5). **M5.3.** Synthesis of existing data on the impact of soil erosion due to winter rainfall events on fallow fields and concomitant effect on soil function (Output – scientific paper, **D5.3**, Year 1); **M5.4.** Apply tool to assess impact of over-wintering crops on soil compaction and soil erosion with development of preliminary guidance to land owners on over-wintering soil management (**D5.4**, Year 2).

O6: What influences the release and retention of organic phosphorus in Scottish soils? There is little information about (i) the occurrence and distribution of organic P resources in Scottish soils; (ii) organic P compounds as a significant conduit for P supply in natural/semi-natural soils and (iii) whether soil organic P composition is similar to mineral P in that it can be linked to plant community status. To address this, soils from contrasting and common field experiments in Uist (1.3.1), Orkney (1.3.1), Balruddery (2.3.4), Glensaugh (1.1.1) and the National Soil Inventory for Scotland (NSIS) will be collected and analysed for the following. ^{31}P

NMR will be used to assess P composition and specification of bulky organic fertilisers (BOFs) (seaweeds and composts). In a novel approach, we will utilise $^{16}O/^{18}O$ measurements in phosphate to elucidate the activity of different phosphatase enzymes in soil to aid in the identification of P turnover processes. **M6.1.** Characterisation of P in soils by ^{31}P NMR and micronutrients soil by sequential extraction to identify the phosphorus species in organic soils of Scotland (Output – scientific paper, **D6.1i**, and presentation at the International Organic P conference, **D6.1ii**, Year 1); **M6.2**. Characterisation of $^{16}O/^{18}O$ in HCl extracts of soils informing decision on whether to measure $^{16}O/^{18}O$ in other soil fractions (**D6.2i**, year 2) and describe the isotope ratios ($^{16}O/^{18}O$) of phosphate in Scottish organic soils of Scotland (Output – scientific paper, **D6.2ii**, Year 2); **M6.3.** Determine the mechanisms of cycling of P in semi-natural soils including grasslands, using novel techniques e.g. 2D NMR (**D6.3i**, Year 3), analyse data and assess how P is cycled in different soil fractions (**D6.3ii**, Year 4), to communicate to stakeholders the implications of the research findings as they relate to diffuse pollution, P availability for habitats and crops e.g. via the Soils Stakeholder Group and CREW (**D6.3iii**, Year 5).

Technical approach:

O1: The role of soil fungi in restoring soil functions in peatlands

Using a resampling of the entire peatland restoration chronosequence, 5 years after the first sampling, we will test, whether a) predictions about the trajectory of vegetation/below-ground community recovery are accurate and b) link recent GHG emissions data collected across four restoration areas to both observed fluxes and the dynamics of the above-ground community structures and the associated functional carbon and nutrient cycling capacity in the belowground community. We will also conduct a small scale metagenomic experiment to test the hypothesis that successional changes in above-ground vegetation structure under restoration activities result in a predictable shift in the functional capacity of the soil fungal community. We will target fungal genes specifically involved in C and N cycling and will utilise genomic and transcriptomic reference databases for relevant soil fungi from our past collaboration with the Joint Genome Initiative. Secondly, we explore links between transcription in mycorrhizal roots to successional changes in vegetation structure, thereby elucidating above-belowground linkages. As the fungi in question here have an important role in nutrient release to their ericaceous plant hosts, we anticipate that such changes may also elicit feedbacks to the nutritional quality of vegetation thereby influencing long-term restoration trajectories of the vegetation composition and hence long-term restoration of the peatlands. Data generated here will inform experimental and modelling work in RD1.1.2 and RD1.1.3 (Y 3-5).

O2: Regulation of functions by soil microbiota at the root interface

This RD will investigate the fundamental mechanisms of root-microbe interactions using model microcosm systems established in laboratory where microscale processes can be observed, quantified and modelled with great accuracy. The research will use a range of model plant species (e.g. lettuce, barley, *Medicago*, *Petunia*), microbial species (nitrifiers, denitrifiers and other rhizobacteria), free-living nematodes and soil conditions (e.g. particle size, aerobic/anaerobic) with the objective that we can identify processes that are ubiquitous to arable, horticultural and grassland soils. Novel experiments will make use of recently developed transparent soil in combination with modern live microscopy such as Confocal and Light Sheet Microscopy, Biospeckle imaging and Optical Tomography. Glass chambers will be built in-house to contain transparent soil, plant and micro-organisms. Containers will consist of window with rubber joints where water,

nutrient, dyes and Refractive Index matched liquid will be injected. Seeds will be germinated in Agar, and various combinations of plant / bacteria / nematodes will be introduced into the system. Time lapse imaging will be performed through the glass wall of the glass chambers. Images will be collected at single or multiple time point, in depth. We will develop image processing programs and software to extract quantitative measurement of key processes in the rhizosphere and their respective locations. A combination of algorithms will be used, for example skeletisation or tracing of roots, particle analysis for nematodes and bacteria. Generated data will be used to parameterise models that explain the factors that contribute to colonisation of the soil surrounding plant roots. Models will be developed at the single root level using classical root growth kinematics concepts. Root growth equations will incorporate root elongation rate and size of the meristematic zone, and will also describe the carbon exudation profile. Models will also include microorganisms as moving particles along the root using a technique known as Smooth Particle Hydrodynamics. Calibrated models will then be used to analyse what factors contribute most to colonisation of the soil by microbiota and hence the localization of soil processes. Data generated here will inform experimental and modelling work in 1.1.2 (Y 3-5).

O3: The role of the soil food web in regulating soil carbon flows

This objective has the overarching aim to quantify root-derived inputs to soil, their impact on C and N cycling processes and to identify useful biological indicators of the regulation of these processes providing key data for RDs 1.1.2, 1.1.4, 1.3.1, 2.1.7 and 2.3.4. Using soils from common experiments (RDs 1.1.1, 1.3.1, 2.3.4) we will apply $^{13}CO_2$-labelling to the plant-soil mesocosm systems, allowing quantitative partitioning of plant- and SOM-derived C fluxes through soil C-pools, the soil biota and to losses in soil CO_2 efflux. A ^{15}N pool-dilution approach will be used to quantify gross N mineralisation, plant N-uptake and denitrification losses from soil. The biotic composition of the soils will be assessed at a coarse level by phospholipid fatty acid (PLFA) profiling and at a fine level via dT-RFLP, including targeting of N-cycling functional genes. Therefore, potential biotic indicators of soil functions will be assessed in experiments where the corresponding processes are explicitly quantified. Initially (Y1,2) this will be applied to barley and grass systems, to establish impacts of management (fertilisation, tillage and cultivar selection) on C and N cycling linking with work in RD1.3.1 and RD2.3.4, in parallel with RD1.1.1 (O5). Subsequently (Y3-5), the approach will be extended to assess the utility of biological indicators in a wide range of soils and land uses, complementing and being informed by Y1-2 model development in RD1.1.2. This will complement efforts to utilise isotopic and spectroscopic measures of SOM quality to predict soil functions (1.1.4). This would both exploit existing spatially explicit databases of soil properties (National Soils Database) and support modelling activities to predict nutrient and organic matter cycling in soil, and their vulnerability to change at a national scale (RD1.1.2/RD1.1.3/RD1.1.4). The research will deliver increased understanding of soil C and N release and retention and their controls which can be used to inform upscaling to map soil functions and their vulnerability to change. The research will also develop biological indicators of these functions and assess their wide application across Scottish soils. Data generated here will inform experimental and modelling work in RD1.1.2 (Y 3-5).

O4: Manipulating function in grassland soils through AM fungi

We will establish a grassland experiment where plant genetic diversity is manipulated at the plot scale to follow interactions with soil function. Twenty genotypes of four plant species (*Plantago lanceolata*, *Centaurea cyanus*, *Trifolium repens*, *Lolium perenne)* will be planted in 40 grassland plots. Half of the plots in

each area will be fertilized. Plant biomass and seed set (yield), bulk density, P content, AM fungal spore abundance and morphotype diversity, extraradical hyphal abundance, and soil carbon will be measured in each year of the experiment. Seed from each plot will be collected and used in the following year. This experiment will be repeated for five years in order to assess how changes in plant genetic diversity and climate influence soil functions (production of biomass or yield, water content, phosphorus delivery into plants, biodiversity pool, and soil carbon). Within the same plots insect community response to the experimental factors will be assessed by work in 1.3.1 and 2.3.8. Also comparative data from intensive arable sites will be generated in 2.3.8. In the first greenhouse experiment we will grow AM fungi with plant communities varying in diversity and expose them to different nutrient and disturbance regimes. We will measure AM fungal spore abundance and diversity, AM fungal extraradical hyphae (as an indirect measure of AM fungal soil exploration and delivery of phosphorus), and plant biomass. We will repeat this experiment over five generations (5 months/generation) to assess impacts of soil management factors over time, and to produce genetically distinct AM fungal lines. Later greenhouse experiments will manipulate soil community diversity and plant genotypic diversity to assess how these factors influence plant tolerance to abiotic and biotic stresses. Data generated here will inform experimental and modelling work in 1.1.2 (Y 3-5).

O5: Measuring and managing soil physical structure

Using an existing experimental site at Glensaugh, a 11 ha field will be divided into 22 x 0.5 ha plots with sheep rotated between plots until the sward height reaches ~100 mm (the optimal height for grass recovery following grazing), approximately every 3 weeks. Adjacent to these plots will be a control field where sheep will remain in one area throughout the grazing period allowing comparison of the impact on rooting between the 'rotational grazing' system and the 'conventional' system. Anecdotal evidence has suggested that a rotational system will improve soil structure, and therefore root penetration and root growth. This will be examined through temporal and spatial sampling using both the developed field tool and sampling of soil cores to assess root volume. Root decomposition may potentially differ between management systems due to air and water filled pore spaces within the soil. Such an effect will be examined through the spraying of grass sub plots within the 22 rotational plots, and control field, for examination of changes in soil strength based on decomposition rates and management system. Un-vegetated areas will be re-sown after 2 years allowing increasing contribution of roots to soil stabilisation to be assessed. Sampling will be performed in both treatments at random locations in the 'control' field and sub plots (based on GPS co-ordinates) at regular intervals. Experimentation will allow both the negative influence of grass removal on soil stability and the positive influence of revegetation to be quantified. To ascertain whether measures within CAP Greening and SRDP will reduce soil erosion and compaction during winter fallow periods, we will utilize an existing cover crop experiment (Y1, 2) at Balruddery and sample throughout the growing season to explore how the physical structure of soil is affected by the decomposition and mechanical properties of roots of a range of over-winter cover crops that are purported to help alleviate soil compaction and densely rooted mixes that may enhance soil aggregation. Data generated here will inform experimental and modelling work in 1.1.2 and 1.1.4 (Y 3-5).

O6: What influences the release and retention of organic phosphorus in Scottish soils?

The objective will focus on a range of semi-natural /non-agricultural organic soils (common field sites on Uist and Orkney with 1.3.1), extensive grassland

(Glensaugh, 1.1.2, 1.4.3) with contrasting arable soil at Balruddery (2.3.4) acting as an experimental comparator. In addition, ^{31}P NMR will be used to assess the P composition of bulky organic fertilisers (BOFs) (seaweeds and composts) as knowledge of their P speciation will allow informed interpretation of plant growth data, selection of plant genotypes and risks of P leaching. BOF's will be analysed by X-ray diffraction to identify crystalline inorganic phosphate phases and by ICP-MS and XRF to measure the concentration of micronutrients and other elements. Soil will be extracted with a solution of NaOH/EDTA. The extract will be analysed by ICP to determine the total P content, and by ^{31}P NMR to determine P species present (monoesters, diesters, phosphonate, and polyphosphates) and their amounts. The conditions for proper quantification will be determined by inversion/recovery experiments to determine the appropriate pulse angle and relaxation delay times. The NMR measurements will be made at Dundee University (or other) by subcontract. The P composition of bulky organic fertilisers will be made by NMR in the same way. Analysis of BOFs for micronutrients and other elements will be made by ICP-MS, and by portable XRF and total reflection XRF (as developed in 1.1.4).

Isotope ratio measurements of $^{16}O/^{18}O$ in phosphate will be taken to determine if P cycling in these soils is different from each other. The ratio of $^{16}O/^{18}O$ in phosphates is variable through the result of natural processes especially hydrolytic cleavage by phosphatases. Differing ratios can be indicative of different biological pathways or soil parent materials. This type of work involving $^{16}O/^{18}O$ in phosphate is in its infancy and few measurements of the ratios and factors responsible for change have been elucidated. Few studies have attempted to understand $\delta^{18}O$ variations in soils. For these isotopic measurements P will be extracted from the soils using ion exchange resins (anion alone or mixed anion/cation resins to enhance P release) or dilute HCl. The extracted phosphate will be quantitatively recovered as pure Ag_3PO_4 by procedures involving DAX-8 resin and intermediate precipitation of cerium phosphate, or other procedures involving insoluble salts. The composition of the purified Ag_3PO_4 will be assessed by total reflection XRF. The oxygen isotope ratio of the pure Ag_3PO_4 will be measured by mass spectrometry after conversion to CO by heating in a glassy carbon tube reactor. In Y3-5, this work will attempt to include the isolation of different organic P fractions in the soil by chromatographic methods and determination of the $^{16}O/^{18}O$ ratios in fractions such as esters, polyphosphate and phosphonates.

The research maps to the regulatory functions of soil, such as storing, filtering and transforming nutrients, substances and water but is also relevant to the production of biomass (agriculture and forestry) and soil biodiversity. This objective will therefore yield new information about the P status and biological turnover of organic P compounds in Scottish soils. Data generated here will inform experimental and modelling work in 1.1.2 and 1.1.4 (Y 3-5).

Key linkages, interdisciplinarity & collaboration: This RD will make linkages that will bring additional benefits including interdisciplinary, collaboration, draw in future funding, growth of new research areas and external uptake of research. The RD benefits from significant collaboration across a number of RDs and uses common experiments based in 1.1.2, 1.3.1, 1.4.8 and 2.3.4. We will host regular meetings to bring SRP researchers together on the regulation of soil function topic. This forum will be used to explore how sols systems understanding and modelling can be improved through collaboration and integration. We will explore how these can develop across the SRP, particularly from Y3, with common approaches and methods, shared sites, shared analyses and through adding value with new collaborative projects and students.

RD1.1.1 is the starting point of a data pipeline that flows through RD1.1.2 to

RD1.1.4. RD1.1.1 will provide data to RD1.1.2 for BBN modelling scenarios and inform the contribution of soil biota to GHG emissions (RD1.1.3). Functional soil data will be utilised in synthesis analyses and DSM studies (RD1.1.4). Research here on grasslands will inform the newly established Farmland Biodiversity Initiative (RD1.4.8). Characterization of fungal communities associated with peatland restoration and will inform the design of the climate change effect experiment proposed in years 3-5 (RD1.1.2). Understanding the effect of grazing and cover crops on soil stability and the intimate interactions of microbiota with roots will inform studies on resilience (RD1.1.2). The work here will support biodiversity studies in WP 1.3 and those investigating native genotypes (RD1.3.1), rhizosphere studies in RD2.1.7, comparative studies in agricultural soils (RD2.3.4) and impact of variable inputs (RD2.3.8). Soil structure and rooting studies will also inform RD2.1.7. Many of the soil functions and indicators tested in RD1.1.1 on extensively managed soils will also be applied to agricultural soils as a direct comparator and vice-versa (WP2.3). Specifically, an understanding on soil and crop management on the C and N cycle will inform understanding of GHG emissions and link directly to RD2.3.6. Understanding the impacts of management on soil quality and function and management interventions for mitigating threats to soil quality, will resonate with studies in RD2.3.4 and RD2.3.8. Work on buffering and filtration of soils has strong links with the freshwater and terrestrial ecology work in WP1.3 and between the soil water and erosion research within WP1.2.

Wider RESAS Programme (CREW, Underpinning Capacity): Work on soil shear strength and aggregation proposed here links to issues regarding accumulation of suspended solids in rivers reducing both their carrying capacity and reduce interstitial flow in gravel beds, critical for other ecological services such as salmonid reproduction (relevant to CREW). The proposed work will help CREW inform Scottish Government policy teams in addressing issues around erosion and particulate movement in water flow. The RD will also make extensive use of some of the facilities provided by RESAS underpinning capacity, including plant genetic populations (1.3.1), field platforms including Balruddery and Glensaugh and the National Soils Inventory for Scotland.

Other Funding Bodies: The primary aims of WP1.1, and in particular RD1.1.1, are aligned with the priorities of many funders e.g. RCUK (e.g. BBSRC, NERC), EU H2020, New Zealand MBIE Catalyst. Also, several ongoing PhD studentships are relevant to this RD and we anticipate that additional PhD studentship opportunities (e.g. STARS) will be generated that will train the next generation of soil scientists. Research outcomes from 1.1.1 will leave the group well placed to leverage further funds to consolidate the findings here and provide a strong basis on which to collaborate with national and international peers.

Added Scientific Value: Research proposed will have impact on areas of research priority for SNH and SEPA, and RCUK and indirectly to levy boards thus allowing this research to leverage funds from a wide range of sources. This RD has particular resonance with the aims of the NERC Soil Security Programme. We will work to develop further collaboration with this initiative e.g. regular communications via the Soil Security Advisory Group (Hutton staff as a member), invitations to the NERC team to meet the RD/WP team and through MRP staff active within the NERC projects. Beyond the UK, research in 1.1.1 will integrate well with projects and project partner priorities across Europe, funded through Horizon 2020 calls. The research is complementary to that which occurs at a number of UK institutions where we have existing collaborative projects including: Rothamsted Research, Universities of Aberdeen, Cranfield, Dundee, Highlands and Islands, Hull, Lancaster, London, Nottingham, Royal Holloway, and Sheffield. This offers

significant opportunities for continued collaboration and leverage of research funding sourced from outwith Scotland, e.g. New Zealand.

KE: Our core KE will be delivered with the CKEI. This RD will integrate its KE with Theme level annual stakeholder events, providing input to the Royal Highland Show, Scottish Parliament science events, CECHR public events, LEAF Open Farm Sunday and industry stakeholder fora. RD representatives will support the Soil Stakeholder Group. With RD1.1.3 we will seek to organise a workshop showcasing our research at the Edinburgh Centre for Carbon Innovation. We also propose (2019/2020) a cross-SRP conference focussed on "Scotland's soils" that will help shape policy and content in the ITGF (2021-26) and context for the World Soil Congress in Glasgow, 2022. We will maintain the online Soil Phosphorus Forum that provides direct KE opportunities with a range of audiences. Targeted KE messages will use press briefings and popular/industry articles, e.g. Scotsman, Scottish Farmer and MRP /CKEI social media outlets. At EU level, we will continue to integrate and interact with European Innovation Partnerships. Members of the RD participate in the Global Soil Partnership and the Global Soil Biodiversity Initiative.

Audience: Greater scientific understanding of soil functionality will help underpin confidence in policy measures for land managers. Proposed work is of the highest scientific quality and will contribute to global agendas on soils, contextualised by UN SDGs. Scientists will continue to publish in appropriate high impact journals with a number of peer reviewed scientific publications already identified. Presentations will be given at relevant national and international scientific conferences. PIs will endeavour to inform the soils research and policy arenas with membership of influential national and international committees e.g. EU EIP, Royal Society, RCUK.

Impact: The fundamental nature of this RD will yield data underpinning significant advances in scientific understanding of soil function and the complex role of soil and its constituent components in contributing to a range of ecosystem services and their maintenance. The RD has a key role in enabling other RDs, by providing data for downstream analysis and modelling. The RD will raise awareness of stakeholders of knowledge gaps regarding Scottish soils, and will support the SSG. RD outputs would inform relevant policies e.g. SRDP (O2, O4, O5, O6), GAEC (O3, O4, O6), cross compliance (O2, O3, O5) and CAP (O5, O6), inform and advise implementation of the EU Habitats Directive, Land Use Strategy 2, Scottish Soil Monitoring Action Plan, Scottish Biodiversity Strategy and National Peatland Plan/Peatland Action, and internationally with Machair designated an EU priority habitat. Results will be channelled through direct contact with SNH, SEPA and SG, using policy briefs tailored for specific SG policy units, and delivery to SEweb, SSW. The international quality of the science has potential to leverage significant competitive funding from a range of sources.

RESEARCH DELIVERABLE NUMBER: 1.1.1

Work planning and timetable for Year 1

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Stakeholder meeting. Regular meetings with stakeholders e.g. Soils Stakeholder Group, SG, SNH and SEPA representatives to ensure work flow aligns with policy requirements	**KE**											
SRP Soil research and Data pipeline meeting. Meetings to develop research links and data flows between WP1.1, Theme and Theme 2, 6 monthly.			**KE**						**KE**			
D1.1: Sampling to test whether predictions regarding the trajectory of vegetation and below-ground community recovery are accurate and link to collected GHG emissions data. Prepare collected samples for analyses Links to M1.1 Resample peatland chronosequence, samples prepared for downstream analyses												**D1.1**
D2.1: Discuss yearly findings with key stakeholders and engage and interlink with other research platforms throughout the UK Links to M2.1 **-** Develop soil microcosm system to assess plant–soil–microbiota interactions, with optimization and validation of the system												D2.1
D3.1: Synthesize existing data to determine the impact of rotational (grasslands, fallow and arable) management in Machair soils on soil nematode. Output – Peer reviewed publication								**D3.1**				
D3.2: Establishment of soil mesocosms using soil derived from common experiments and commence measurements across the reporting year and into year 2 . Links to M3.2 - Evaluate indicators for quantification of C and N cycling in grassland and contrasting low-input and intensive arable soils from common experiments, testing standardized methods												**Cont d Year 2**
D4.1: Facilitates selection of genotypes for subsequent glasshouse experiment Links to M4.1 - Sampling of grassland sites within Farmland Biodiversity Initiative at Glensaugh										**D4.1**		

D5.1i: Develop tool applicable to grasslands, tested and refined in-field and linked to work in 1.1.2 in woodlands **D5.1ii: In-field testing and validation of the tool developed in D5.1i** Links to M5.1 - Develop *in situ* shear resistance measurement tool for grassland systems					**D5.1i**							**D5.1ii**
KE event. LEAF Technical event			**KE1**									
KE event. Attendance and presentation at International Soil Bio and Eco-engineering conference, a key international meeting of researchers investigating soil stabilisation (practitioners, farmers, industry)				**KE2**								
D5.3: Synthesis of existing data on the impact of soil erosion due to winter rainfall events on fallow fields and concomitant effect on soil function through changing biotic communities Output – Peer reviewed publication								**D5.3**				
D6.1i: Characterisation of P in soils by ^{31}P NMR and micronutrients soil by sequential extraction to identify the phosphorus species in organic soils of Scotland (publication) and **D6.1ii: Presentation at International Organic P conference** Outputs – Peer reviewed publication and conference presentation									**D6.1ii**			**D6.1ii**
KE events. Presentations at Royal Highland Show (KE3), possible Glensaugh Open Day (KE4), article on soil P forum (KE5)			**KE3**		**KE4**				**KE5**			
End of year reporting to RESAS (ALL OBJECTIVES)												**R1**

Work planning and timetable for Year 2

Year 1: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
Stakeholder meeting. Regular meetings with stakeholders e.g. Soils Stakeholder Group, SG, SNH and SEPA representatives to ensure work flow aligns with policy requirements	**KE**						**KE**					

Data pipeline meeting. Regular 6 monthly meetings with representatives from Soils Theme 1 and Theme 2			**KE**						**KE**			
D1.2: Ensure robustness of metagenomics approaches to undertake metagenomics analysis of fungal communities for subsequent data provision to RD1.1.2 **D1.3: Completion of metagenomics experiment** Links to M1.2 - Metagenomic analysis to assess shifts in fungal community under the restoration chronosequence. Data generated pipelined to 1.1.2 for analysis and modelling in years 3-5.								**D1.2**				**D1.3**
D2.2: Optimisation and validation of tools. Together with outputs from D2.1, this work will deliver a research platform for studying root-soil-microbiota pertinent to a range of habitats e.g. grasslands Links to M2.2 - Develop quantitative imaging tools for microcosm systems							**D2.2**					
D2.3: Analyse and collate image data Links to M2.3 – Optimising and validating the developed imaging tool generated in D2.2 with data flows for modelling												**D2.3**
D2.4i: Initial testing of model assumptions Links to M2.4 - Conduct preliminary modelling interactions between roots and soil microbiota												**D2.4i**
D3.1ii: Synthesize existing data to determine the impact of rotational (grasslands, fallow and arable) management in Machair soils on AM fungal communities **D3.1iii: Identify drivers of change on soil communities in Machair soils** Outputs – Peer reviewed publications				**D3.1iii**								**D3.1iii**
D3.2i: Ascertaining standardized methods for evaluating indicators to quantify C and N cycling in soils **D3.2ii: Validating data generated in D3.2i against soil process measurements**						**D3.2i**						**D3.2ii**

Links to M3.2 - Evaluate indicators of C and N cycling in grassland, low-input and intensive arable soils from common experiments												
D4.2: Temporal monitoring to ascertain the impact of nutrients, host plant and host plant genotype on AM fungi and associated soil factors Output – Peer reviewed publication												**D4.2**
D5.1iii: Temporal assessment of soil stability in contrasting grazing systems Links to M5.1 Application of tool developed in D5.1i												**D5.1iii**
KE event Activity at Royal Highland Show			**KE6**									
KE event LEAF Open Farm Sunday				**KE7**								
D5.4: Preliminary guidance available for land owners and policymakers Links to M5.4 - Assess soil compaction and erosion in over-wintering crops to develop preliminary guidance on soil management												**D5.4**
D6.2i: Informing decision for further measures of $^{16}O/^{18}O$ in other soil fractions **D6.2ii: Isotope ratios ($^{16}O/^{18}O$) of phosphate in organic soils of Scotland.** Links to M6.2 - Characterisation of 16O/18O in HCl extracts of soils. Output (D6.2ii) – Peer reviewed publication			**D6.2i**								**D6.2ii**	
End of year reporting to RESAS (all objectives)												**R2**

Name of RD: 1.1.2 Soil Resilience to Change

Research aim and key drivers: Understanding and manipulating soil resilience is essential to avoid exceeding several planetary boundaries and underpins sustainable soil management in compliance with Good Agricultural and Environmental Conditions (GAEC) and Statutory Management Requirements. The research in this RD aims to develop empirical models of the relationships among disturbance factors, soil properties, processes and soil functions for a range of important Scottish semi-natural ecosystems. This will enable assessments of the resilience of soil functions to scenarios of climate, environmental and socio-economic change to be made. The work will contribute towards the understanding of ecosystem and ecosystem service resilience identified in the 2020 Challenge for Scotland's Biodiversity. It will also support the research priorities identified in the Scottish Soils Monitoring and Action Plan and the National Peatland Plan.

The Soils Monitoring Action Plan (2012) identified a range of soil functions, many of which can be affected by global change drivers (e.g. climate change, pollutant deposition) and policy-related changes in land management (e.g. SRDP measures, targets for ecological restoration (2020 Challenge for Scotland's Biodiversity), land use targets (Land Use Strategy for Scotland) and habitat specific policies (Forestry Strategy, National Peatland Plan). Soil resilience to disturbance is a crucial factor in determining soil sensitivity and response to threats, yet it remains poorly understood. Sustainable management of the soil resource requires an improved understanding of the relationship between external drivers, soil properties and processes and soil function. The focus for this RD is on understanding the ability of soil to resist, recover from or adapt to disturbance and predicting the resilience of soil functions.

Who has been consulted in developing this proposal: A summary of 1.1 was circulated to relevant stakeholders prior to the first submission. Specific feedback was received from RSPB, SEPA and SNH. This revision has been made with further extensive consultation with Scottish Government and CAMERAS organisations.

Summary of the proposal: This RD will produce novel empirical models of key soil ecosystems for the major, semi-natural habitats in Scotland (alpine, moorland, peatland, forest, grasslands, low input arable ([The work in O2.3 will include low input arable soil systems and links closely with that done in intensive arable habitats covered by Theme 2, enhancing understanding across the whole range of arable soils], Fig. 1) to explore how changes in land-use (e.g. SRDP measures) and threats to soils (e.g. climate, pollution) may affect the soil and the functions it provides (Fig. 1). The definition of functions provided by soils in this RD is that used by the Soils Monitoring Action Plan (2012), many of these functions are considered ecosystem services in other policy documents and within other RDs within the ITGF; for consistency with the relevant soil policy documents we refer to them as soil functions throughout this RD.

Soil functions rely on a number of soil processes/properties including soil structure maintenance, organic matter and nutrient cycling and soil biodiversity. These functions are also viewed as "*intermediate and supporting services"* (sensu UK NEA); see RD1.1.1 Fig 1. The sensitivity of each of these to a perturbation will determine the overall response of the soil function – its resilience - and responses will vary among soil types. The challenge for this RD is to provide evidence of changes in soil function under different threats, assess the relative impact of threats within and between different habitats, identify the rate at which soil functions change in response to threats and the management that may increase the resilience of soil functions to these threats.

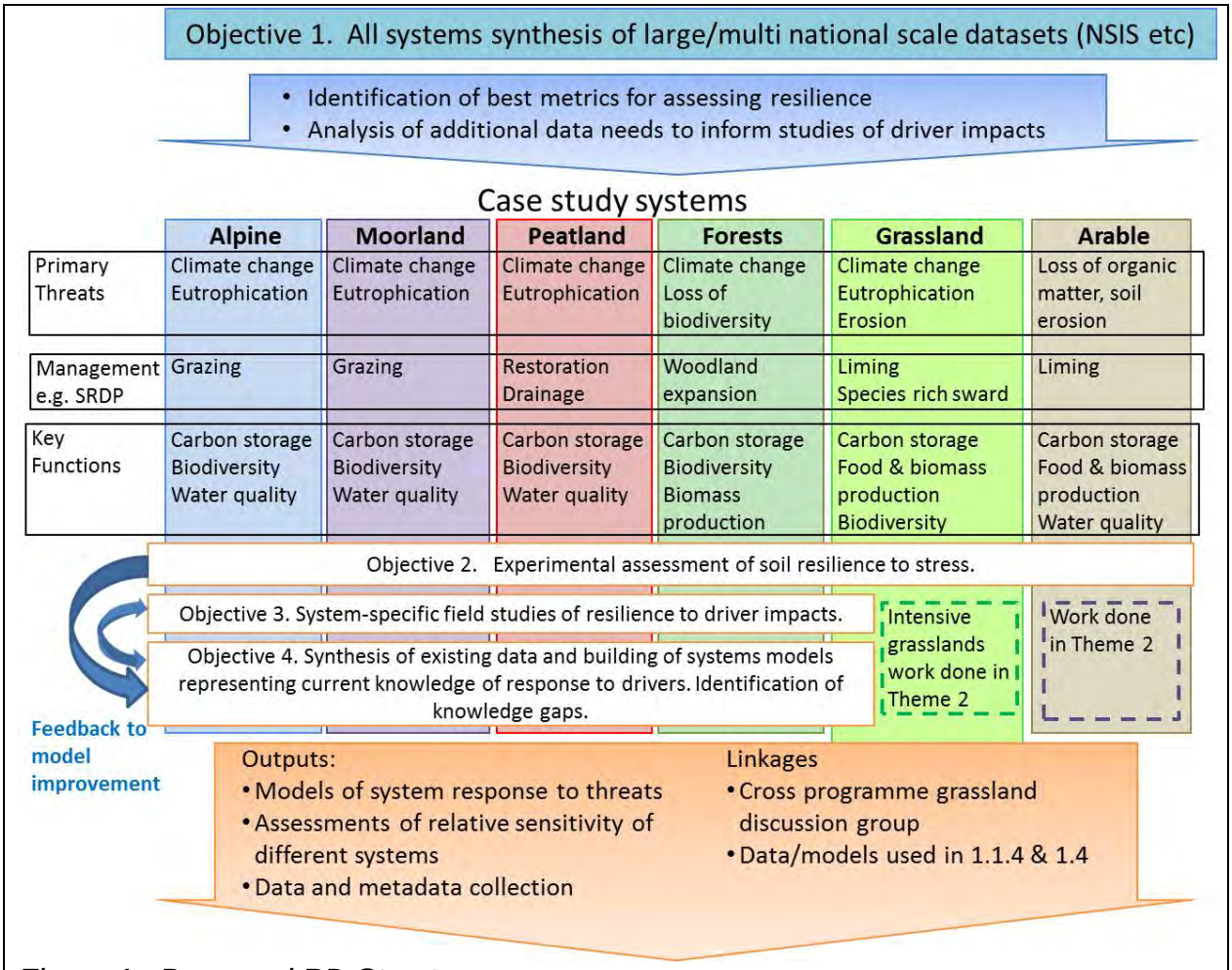
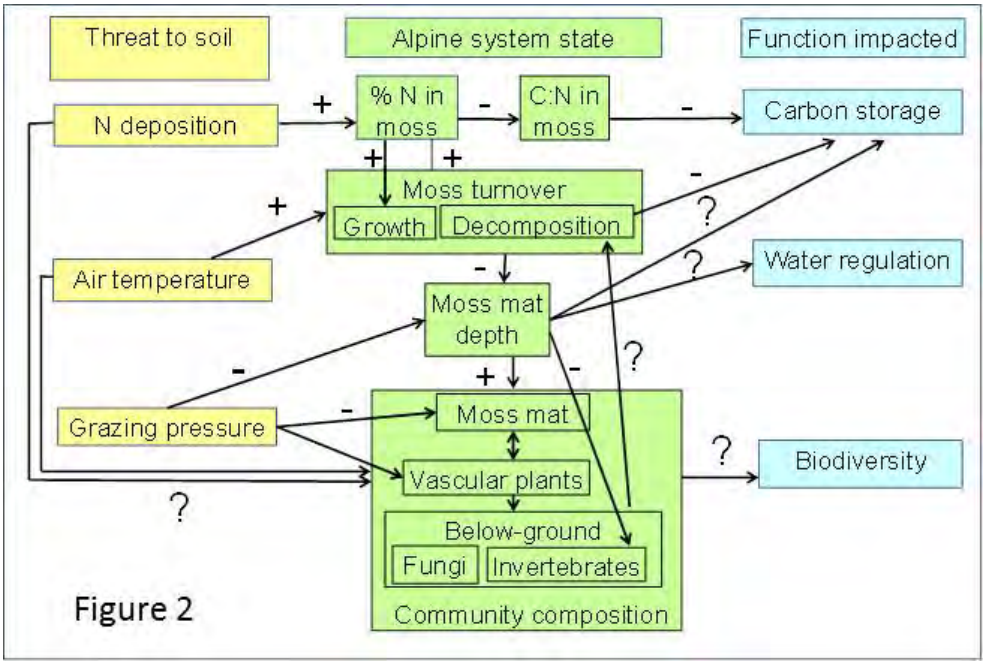


Figure 1. Proposed RD Structure



The ultimate aim of this RD is to produce simple system models (O4) that will show how perturbations drive changes in delivery of soil functions (Fig. 2) in the major, semi-natural habitat types in Scotland (Fig. 1). Current process-based models for soils such as ECOSSE, DNDC, INVEST (see RDs 1.1.3 & 1.3.3) are detailed, data hungry, soil-specific models. Few, if any, of these models can accommodate variation between ecosystems due to differences in the nature and timescales of threats, processing

rates and starting conditions. The modelling approach proposed here will improve understanding of the whole system rather than provide a detailed, mechanistic soil model. In order to achieve this we need to collate existing data, identify knowledge gaps and fulfil new experimental work (Objectives 1-3) which will all feed into Objective 4. Having established the relationships between threats and soil functions, the deliverables from this RD will feed into 1.1.4 to enable impacts of threats to be mapped at different scales under different scenarios.

Figure 2 shows an example of the type of empirical system model that will be built for each case study habitat. This example (focused on above ground components – in the RD we will focus below ground) shows the impact of three drivers (N pollution, air temperature and grazing pressure) on an alpine system and consequences for three ecosystem services. Known positive (+) and negative (-) relationships are shown together with unknown relationships (?). Identification and quantification of these relationships will be the focus of new experimental work in the RD.

Detailed work plan: (Objectives (O), milestones (M) and deliverables (D))

O1: Identification of key soil properties/processes for the assessment of soil function resilience to disturbance at the national scale.

Using existing national-scale databases (NSIS, Scottish Soils Database, CS, Natural England long-term soils monitoring network) covering all habitat types, we will determine (1) how sets of soil properties define soil types, (2) the relationships between soil properties and soil functions, and (3) the variability in soil properties and function in relation to disturbance factors. This objective will also identify systems that are data deficient for assessing response to disturbance factors.

O1.1. Collation and assessment of data sets to identify sets of properties defining soil types (**D1.1i** Year 1) and gap analysis of data deficient systems (**D.1.1ii**. Year 1). Report on 'Suitability of large scale data holdings for analysis of driver impacts on soil properties' for discussion and dissemination with key stakeholders **(KE.** Year 2).

O1.2. Analysis of national-scale soil property data, determining relationships between soil properties, soil functions and disturbance factors (**D1.2i**. Year 2). Submission of paper on soil properties and soil resilience to disturbance factors (Output – scientific paper, **D1.2ii.**, Year 2).

O2: Comparative assessment of the resilience of soil physical and biological properties to disturbance.

O2.1. Understanding the effects of management changes on soil resilience. **D2.1i.** (Years 1 &2) Contemporary chemical versus traditional fertilisation approaches in Machair systems. **D2.1ii.** (Years 1 & 2) The effects of muirburn on soil resilience. Publication on Machair management and muirburn impacts on soil resilience. **D2.1iii & D2.1iv.** (Years 3-5) Two other characteristic management changes selected after 18 months, depending on results in this and other WPs. **D2.1v.** Publication on overall assessment of management changes on soil resilience.

O2.2. Understanding soil resilience appropriate for modelling approaches. **D2.2i.** (Years 1&2) A comparison of carbon and nitrogen cycling in mineral soils with characteristic physico-chemical characteristics. **D2.2ii.** (Years 1&2) The interplay between initial soil conditions and the resultant resilience of mineral soils to perturbation. Scientific publication. **D2.2iii.** (Years 3-5) The effects of repeated and additional perturbations on soil resilience. **D2.2iv.** (Years 3-5) Development of a modelling framework to predict soil resilience.

O2.3. Complete analyses of existing water-stable aggregate samples for a range of low input arable and grassland topsoils and add to existing NSIS dataset and compile

dataset of IR spectral data and correlations with aggregate stability and other key soil properties to establish methods for rapid assessment of topsoil aggregate stability. **D2.3i.** (Year 1) Compile a dataset of water stable aggregation for soils with a range of land uses, textures and carbon concentrations. Identify gaps in data. **D2.3ii.** (Year 1) Complete analysis of existing aggregate samples using IR spectroscopy. **D2.3iii.** (Year 2) Develop calibrations between spectral and aggregate data. Scientific publication of relationships between water stable aggregates and land use. **D2.3iv.** (Year 3) Results to be used to enhance erosion risk assessment by BBN in RD1.1.4.

O2.4. Determination of the importance of root properties in the stability of soils and landslide resistance. **D2.4i.** (Year 1) Data collection from controlled environment study on root decomposition and biomechanical properties. **D2.4ii.** (Year 1) Tool developed for the in situ measurement of woody root contributions to soil shear strength. **D2.4iii.** (Year 2) Field testing of tool developed for quantification of roots to soil stability. **D2.4iv.** (Year 2) Submission of paper on the tool developed for *in situ* measurement of root contributions to soil shear strength. **D2.4v.** (Years 3-5) Long term data collection of root decomposition in the field. **D2.4vi.** (Years 3-5) Paper submitted on in field assessment of root contributions to soil shear resistance.

O3: Determination of soil system resilience to disturbance in selected key ecosystems under field conditions.

This objective will utilise existing long-term field sites and new experiments where necessary to supply empirical data on the response of key soil properties and processes to the most significant disturbance factors in each system in order to inform Objective 4.

O3.1. Alpine systems – improved understanding of soil resilience: Characterisation of microbial communities in Racomitrium heath. **D3.1i.** Extraction of DNA from existing samples (Year 1) **D3.1ii. & D3.1iii** (Year 2). Molecular quantification and community characterisation of nitrifiers, denitrifiers, N-fixing bacteria. **D3.1iv**. Scientific paper on N-cycling microbial communities across N-dep gradient. **KE** (year 2). One-day workshop on the state of UK alpine ecosystems. **D3.1v.** (Year 2) Scientific publication on resilience in alpine soils. **D3.1vi**. Field sampling for closing gap in data (years 3-5, if required).

O3.2. Moorland/woodland - Improved understanding of soil resilience. **D3.2i.** (Yearly 1-5) Manipulation of litter and ground flora to assess resilience of moorland soils under woodland expansion. **D3.2ii.** (Years 3-5) Assessment of moorland soil resilience using tree age/size to identify of rates of change. **D3.2iii.** (Year 4) Scientific publication on the impact of woodland expansion on moorland soils.

O3.3i & ii. Peatlands - Improved understanding of soil resilience. **D3.3i.** (Year 1) Establishment of drought roof study at Forsinard to assess the resilience of vegetation composition and soil C and N cycling functions in restored peatlands. **D3.3ii.** (Year 2) Analysis of soil properties in relation to drought/restoration age. **KE.** Report for discussion and dissemination with key stakeholders 'Impact of peatland restoration on ecosystem service delivery'. **D3.3iii & D3.3iv.** (Year 2) Analysis and publication of suitability of 7 soil indicators of N pollution. **D3.3v.** (Year 4) Scientific publication on effects of 3 years of drought condition on the success of vegetation recovery in restored peatlands. **D3.3vi.** (Year 5): Scientific publication on effect of 3 years of drought condition on the stability of soil functions in restored peatlands. **D3.3vii.** Assessing scaling up of soil indicators using national data sets (Year 5).

O3.4: Grasslands – Understanding the mechanisms of resistance and resilience to management changes in extensive grasslands. **D3.4i**. Establish large-scale management change (liming) experiments (year 1). **D3.4ii**. Complete two-year analysis on how grassland systems resist, recover and adapt to liming. **D3.4iii**.

Publication of liming impacts. Years 3-5 – identify the proximate and ultimate mechanisms of how grassland systems resist, recover and adapt to liming (year 3). Identify key soil indicators of resistance and resilience. Synthesize experimental data for dissemination to key stakeholders, and integration into process-based and stakeholder-relevant mathematical models (Year 4). Scientific publications on resistance and resilience of grasslands to land-use change (Years 3 and 5).

O4: Development of systems models for key ecosystems

(Synthesis of lab-, plot- and national-scale data, including Objectives 1-3) to explore soil property and process response to disturbance factors and implications for resilience of soil functions.

O4.1i & ii: Collation of existing data from literature and field experiments and development of initial empirical system models to relate disturbance factors, soil properties and soil functions to resilience. **KE** (Year 1) Workshop with PIs and stakeholders to discuss the different approaches to studying resilience. **D4.1i.** (Year 1) Alpine heathland model. **D4.1ii.** (Year 2) *Racomitrium* heath model. **D4.1iii.** (Year 2) Moorland model. **D4.1iv.** (Year 2) Peatland model. **D4.1v.** (Year 3) Workshop on 'Soil resilience to change for policy makers' (presenting systems models for completed case studies). **D4.1vi.** (Year 3) Woodland model. **D4.1vii.** (Year 3) Grassland model.

O4.2. Revised systems models updated with data collected during current programme.

D4.2i. (Year4 & 5) Updated models for all systems.

Research already undertaken in this area, track record of researchers:

The PIs in RD1.1.2 have a very strong track record of working in a range of habitats and of identifying induced changes in community composition/ecosystem processes due to a range of drivers. Whereas many studies provide snapshots in time, the novel work of this RD will synthesise existing and new data to create integrated models allowing assessment of potential changes in ES delivery over time and resilience of soil properties and functions. A number of the PIs bring expertise in translating ecological data into process-based modelling of soil functions and our collaboration with BioSS will provide expertise in Bayesian statistics, graphical modelling and systems modelling approaches relevant to the extension of Bayesian Belief Networks (BBNs) and unification with Structural Equation Models (SEMs).

Technical approach:

O1: Identification of key soil properties/processes for the assessment of soil function resilience to disturbance at the national scale.

This objective will involve large scale analysis of existing information on soil chemical and biological characteristics across all ecosystem types. This will include novel use of IR spectroscopic data as an overall chemical profile of soil. These analyses will explore variability in soil parameters across habitats, aiming to identify sets of soil properties that are the most indicative of each soil type and which can be used as indicators of change in soil functions in response to threats in our case study systems model. A gap analysis will identify priority systems/areas/soil properties/functions for which, if any, additional, new data are required to make these assessments. Statistical approaches will examine spatial distribution of the combined large-scale soil data sets in relation to key drivers, to ascertain if there is sufficient coverage of driver gradients to be able to investigate soil property or function response. This gap analysis will inform data collection for Objective 3.

O2: Comparative assessment of the resilience of soil physical and biological properties to disturbance.

Two sets of lab-based studies using standardised disturbance regimes (e.g. Zhang et al 2010, Griffiths et al. 2015) will compare the resilience of the biological and physical properties of soils. Measured parameters will include microbial activity and community dynamics. Soil characterisation will include measurement of soil bulk density, volumetric water content at field capacity, macroporosity (pores>60µm), soil penetration resistance, water stable aggregates, IR spectroscopic and rheological measurements of soil physical resilience to stress. The first set of experiments will run over all years of the programme with a different soil type/management combination tested each year. The first (**O2.1**) will target effects of chemical vs traditional fertilisation on Machair, contrasting effects with organic soils of the Northern Isles. In the second year, focus will shift to moorland systems (muirburn as driver), and other ecosystems will be examined in later years. The second set of experiments (**O2.2.**) will explore the interactions between soil physics, chemistry and biology that underpin soil resilience. This approach will utilise more severe experimental impacts to yield a greater understanding of the effects observed in the first set of experiments. This second set of experiments will also run for the duration of the programme, with the first two years focussing on how different soils with characterised physical, chemical and biological properties vary in their resilience of functions relevant to ecosystem services (carbon cycling, nitrogen mineralisation) or in terms of processes that affect ecosystem service delivery (compaction, soil stability, erosion). Discussions with the PIs developing the models within this WP, O4 and RD1.1.3 will determine how to include the relationships established in this objective into both the new and existing models such as ECOSSE, DNDC etc. and further inclusion in digital soil assessments in RD1.1.4. This objective builds on an existing collaboration between TJD and BSG by using two contrasting systems (Machir versus muirburn) to test the utility of the resilience assay (biological and physical properties of soils) which will be complemented by exploring other systems in later years matching model systems in the deliverable.

O2.3. Water stable aggregates. The resilience of soil aggregates to breakdown is a key property that affects the susceptibility of topsoils to erosion. We will assess the stability of soil aggregates from a range of land uses (low input arable and grassland) in year 1 and incorporate the information into a BBN to assess erosion risk in RD1.1.4 and threats to soil functions. We will also assess the potential to utilise IR spectroscopy to rapidly assess aggregate stability and hence erosion susceptibility at a range of sites including Balruddery Research Platform (year 2).

O2.4. Roots and soil stability. The importance of root properties in soil stability and landslide resistance will be assessed using new experiments that will improve predictions of the impact of vegetation removal on the dynamics of slope reinforcement by woody roots. Biomechanical properties of the root systems will be studied in relation to root decomposition and thermal time in a range of controlled (year 1) and *in situ* environments (year 2). A mechanical 'ground anchor' tool will be developed to quantify soil resistance to shear (years 1 and 2), allowing *in situ* temporal and seasonal variability to be assessed (year 3-5). Further work will be performed to investigate gaps in our understanding highlighted through results in years 1 and 2 in later years of funding. .

O3: Determination of soil system resilience to disturbance in selected key ecosystems under field conditions

We will conduct field scale experimental work that assesses the impact of threats on soil functions along the current or predicted future range of the primary threats for each case study system (Fig. 1). The gap analysis in Objective 1 and the initial development of the systems models (Objective 4) will help in identifying the

knowledge gaps to be addressed in this experimental work. The results from this work will refine the models in Objective 4 in year 5. Each of the four objectives will aim to improve understanding of soil resilience in the studied system.

O3.1. *Alpine ecosystems:* Years 1-2 will concentrate on developing empirical models for both *Calluna* and *Racomitrium* heaths (Objective 4) with small elements of additional analysis (on existing samples) undertaken to complete datasets on key elements of the soil microbial communities associated with nitrogen transformations in *Racomitrium* heath (year 1). Identification of remaining key knowledge gaps from both a scientific and policy perspective (gap analysis in Objective 1 (years 1-2) and stakeholder consultation/KE event year 2) will guide years 3-5, additional studies may be required to supplement knowledge gaps. If this later work is required, we envisage retaining a focus on N deposition and climate change, which have already been identified as key drivers of change in the alpine zone and will utilise a UK scale gradient study, as a cost effective means of generating the required data.

O3.2. *Moorland and woodland ecosystems:* A number of land use options may influence resilience in moorland ecosystems. Years 1-2 will focus on developing systems models for the SRDP measure of woodland expansion. Previous work has shown that woodland expansion onto moorland drives changes in soil chemistry, processes and carbon storage, the rate at which changes occur and the resilience of the moorland system is unknown. Recent work in the current programme that aimed to accelerate impacts of woodland expansion (MOORCO), showed that nine years of tree litter addition and removal of ground flora had limited effect on soil microbial communities (i.e. high resilience). This work will continue in order to measure soil resilience focusing on changes in decomposition rates, carbon and nutrient storage (Years 1-5). Years 3-5 will assess rates at which moorland soils change in relation to tree growth (age and size), with the aim to identify which soil functions are least resilient and can serve as indicators of change.

O3.3. *Peatland ecosystems:* Ongoing experimentation in the current RESAS programme at the RSPB Forsinard restoration chronosequence (from afforested peatland to blanket bog) will be extended to include a drought experiment (year 1). This approach is supported by SNH as it is unknown whether the current restoration methods are equally effective in areas that experience significantly lower rainfall. We will test the effects of drought/restoration management over time on commonly utilised proxies for net GHG emissions - the water table, soil moisture, spatial patterning and stability of vegetation and active below-ground communities and produce operational definitions of resistance/resilience. Analysis of below ground biodiversity as a metric of resistance/resilience will be limited (due to cost of repeated sampling). Measurements and data collection will be only in years 3-5 and will be informed by the results gathered in RD1.1.1. We will aim to test the hypothesis that drought-inflicted changes in soil functions limit the ability of peatlands to support appropriate above-ground biodiversity. Data from ongoing activities (RD1.1.3) will be used to select the most divergent net GHG emissions and the most extreme events will be covered by sampling seasonally. However, plot scale measurements of direct impact of drought treatment will still be required. The effects of N deposition on peatland functioning will be explored further using synthesis of existing datasets from the CEH Whim Moss experimental NPK addition plot experiments. Specifically, existing data will be used to assess the potential of seven indicators (soil pH; soil carbon to nitrogen ratio; base cation to aluminium ratio; solution ammonium/nitrate; fungal to bacterial ratio (PLFA); fungal molecular markers (sequence analysis and TRFLP), and phosphomonoesterase as indicators of N pollution. Issues of variability within the soil and sample size will be explored. This will allow the least resilient -most sensitive-

indicators to N pollution to be identified (data analysis years 1 and 2). The work will then be scaled up by linking with O1 above (during years 3-5), to assess these indicators at a national level by using existing large scale datasets (NSIS, Scottish Soils Database, CS, LTMN, new Digital Soil Map for Scotland).

O3.4. *Extensive grassland ecosystems:* Work will be closely coupled to a new field-scale liming experiment established at the Glensaugh and Hartwood farm platforms, integrating above-below ground interactions and complementing similar experimental manipulations in intensive grasslands (Theme 2). Expertise at the Rowett Institute (RINH/UoA) (Lead: David Johnson) will test soil systems resilience to liming and closely align to on-going RCUK funded research 'Soil Security' and SARISA programmes. Data on GHG emissions from the field trials will be provided by eddy-flux measurements in RD1.1.3. This will quantify other key processes related to carbon and nitrogen cycling including production of major greenhouse gases (CO_2, N_2O), and transfer of recent plant photosynthate carbon to soil microorganisms (using stable isotope tracer and probing techniques). These measurements will complement descriptors of key soil biodiversity groups (free-living and symbiotic microorganisms, soil invertebrates, plants, herbivores). We will use mesocosm and laboratory experiments to disentangle the drivers by which liming impacts on soil system multifunctionality, for example by manipulating plant species and soil food web composition, thus enabling us to gain a mechanistic understanding of how liming affects ecosystem processes. In addition, these data will feed into statistical modelling activities undertaken in O4, and in development of policy-relevant soil function models in 1.1.4.

O4: Development of systems models for key ecosystems

We will use empirical models (e.g. Bayesian Belief Networks (BBNs), Structural Equation Models (SEMs) or Kohonen Self-organising Maps) to identify the relative impacts of different threats and land-management on delivery of soil functions (Fig. 2). The most suitable type of empirical model will be identified in collaboration with BioSS (Underpinning Capacity Function 7) and the Rowett. Initial development of models in years 1 & 2 will utilize previous research including RESAS funded work on alpine *Calluna* and *Racomitrium* heath, MOORCO (moorland and forest systems), Muirburn experiments (moorland systems), RSPB Forsinard restoration chronosequence (restoration from afforested peatland to blanket bog) and Whim Bog N deposition experiment (peatland systems). This work will allow data to be synthesised and the identification of gaps in knowledge which will be addressed by experimental work (Objective 3, Fig. 1). In year 5, data from Objectives 1-3 and 1.3.3 for woodlands will be used to refine models and fill knowledge gaps. Models will be designed to inform development of risk- or scenario-based models of soil function delivery (link to RD1.1.4), to support policy advice and to assist with identifying knowledge gaps to inform future research.

Expertise: *Hutton*: Analysis of the effects of climate change, N pollution, land use change on soil; impacts of restoration techniques on soil carbon stocks and GHG emissions; resilience assessments in soil ecosystems; assessment of soil erosion potential; root biomechanics and soil stability; impact of soil loss and degradation of soil function, and IR spectroscopic analysis of soil. *SRUC*: Resilience assessments of populations and processes in soil ecosystems. *BioSS and Rowett*: Bayesian statistics and graphical modelling, relevant to BBNs and unification with SEMs.

Key linkages, interdisciplinarity & collaboration:

Objective 2: There is a clear opportunity to assess commonalities between above (RDs 1.3.1 and 1.3.3) and belowground drivers (this RD). Work on soil stability links to RDs 2.1.7 and 1.1.1 and will be integrated with work from Geotechnical Engineers and

Foresters using existing links with the Division of Civil Engineering at the University of Dundee, the School of Engineering at University of Southampton, and Forest Research. The experimental work on assessing soil disturbance will also link strongly to experiments in RD1.1.1 and RD1.1.3 in relation to habitats selection and with projects in WP2.3 where agricultural soil work is situated.

Objective 3: The alpine case study will deliver data relevant to the requirements of RD1.1.1 and on ES delivery to RD1.1.4 and WP1.4. A linked SNH funded PhD studentship (with UoA and Edinburgh University) on interactions between P, C and N cycling in upland/alpine systems and impacts on ES supply started in Sept 2015. Collaboration is developed with CEH Lancaster on C cycling in alpine systems. The moorland case study has links to RDs 1.1.1, and RD1.3.2 (woodland expansion work). The peatland restoration experiment is a direct follow up (in time) of the work in RD1.1.1.and further links with work in RD1.1.3 as this is co-ordinated across the same experimental platform with data used to provide validation for remote sensing-based models of peatland condition and soil moisture (RDs 1.1.4. and 1.3.3) and to further development of the WISE Peatlands decision support tool (CxC-Peatlands). In addition, there are linkages to socio-economic work in RD1.1.4 and 1.3.2.

Added scientific value: Even though resilience is a key concept in many government and conservation agency policies, few studies have made the link that this RD aims to do between changes in soil properties or processes and measures of resilience and this link urgently needs to be established. A large body of work already exists at the Hutton (funded by RESAS and others) and other institutes (CEH) which will be utilised for reviews, synthesis and model development. Previous RESAS funded work will provide baseline data for changes in soil communities/properties /functions in the five case-study habitats. CEH also has data on impacts of different drivers on soils e.g. Whim Bog N deposition experiment and Countryside Survey data, both of which we have access to and will utilise in this RD. The Defra "Review and initial assessment of what makes some soils more resilient to change and how this resilience can be conferred to other soils." (produced as "Sub-project D of Defra Project SP1605: Studies to support future Soil Policy") provides a summary of the properties of soil that enhance resilience in England and Wales. We can build on this work and develop it in greater detail for specific habitats within Scotland. This added value will allow us to identify many of the relationships between drivers, land cover, management and soil processes, by collating them together into one system model for each habitat. Where data are likely to be lacking is in the quantification of relationships and measures of resilience; this is the novel element of this work and it is these knowledge gaps that the experimental work within this RD aims to fill.

KE, audiences and impact:

KE: Research in this RD aims to develop empirical models of the relationships among disturbance factors, soil properties, processes and soil functions for a range of important Scottish semi-natural ecosystems. This will provide the immediate RD end users (SG and CAMERAS) with tools to promote implementation and provide guidance on sustainable soil use and management – both of which are underpinned by soil resilience. In order to maximise the integration of resilience into policy and guidance, multiple pathways to impact need to be explored and clarified for this research to meet its ultimate aim. Resilience of systems is a topical subject and interactions with ongoing projects are important.

Audience: From April 2016, the RD coordinator will sit in on SNH's "Contingency planning" project which relates directly to 1.1.2 and we will liaise closely with this project. RD1.1.2 will work closely with the CKEI, Soils Stakeholder Group and the Peatlands Research and Monitoring group to ensure that outputs and systems models are of direct relevance to end user organisations. At least one meeting per year is

planned with these groups. A key component of 1.1.2 are the workshops, with the one in the first year enabling PIs and stakeholders to work together to develop our thinking on resilience, what it means and how to measure it, prior to model development. A second workshop will present outputs of systems models in year 3.
We will engage with the wider national and international scientific community to learn from the latest science in this rapidly developing area and to present our work. We plan to hold a session on soil resilience at one international conference during years 4-5 (e.g. Ecosystems Services Partnership, Ecological Society of America). The RD will contribute to Theme level discussions with relevant RCUK projects and Theme level public KE events.
Impact: Along with other RDs in this WP, we will work with the Soils Stakeholder Group to evaluate previous pathways to impact. This work will identify what stakeholders see as successful impact, types of previous successful pathways to impact and learn from these examples to develop a successful pathway to impact for this RD. Envisaged KE events to support impact are listed in the Gantt chart and project summary. These include workshops (3), report for discussion and dissemination with key stakeholders (at least 3), attendance at public events such as the Royal Highland Show, LEAF Open Farm Sunday, Edinburgh Science Festival, presentations of research at inter- and national conferences and numerous scientific papers. The scope and content of the reports, any briefing notes required and workshops will be discussed with the Soils Stakeholder Group and SG prior to delivery.

RESEARCH DELIVERABLE NUMBER: 1.1.2

Gantt chart. (D = Deliverable (in blue), M= Milestone; KE= KE output (in yellow); R= reporting to RESAS (in red)).

Note that KE activities that are a direct result of a deliverable are listed within each deliverable but shaded yellow, KE activities relevant to the whole RD are listed at the end.

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 Collation of national-scale soil property datasets and assessment of coverage in relation to habitats and disturbance factors. D1.1i. Collation and assessment of data sets. D1.1ii Gap analysis of data deficient systems									D1.1 i			D1.1 ii
O2.1 Determine the effects of management changes on soil resilience. D2.1i. Investigation of impacts of contemporary versus traditional fertilisation approaches in Machair systems.							D2. 1i					
O2.2. Understanding soil resilience appropriate for modelling approaches. D2.2i. A comparison of carbon and nitrogen cycling in mineral soils with characteristic physico-chemical characteristics.												D2.2 i
O2.3. Complete analyses of existing water stable aggregate samples for a range of cultivated topsoils; add to NSIS dataset; compile dataset of IR spectral data and correlations with aggregate stability and other key soil properties to establish methods for rapid assessment of topsoil aggregate stability. D2.3i. Compile dataset of water stable aggregation for soils and identify gaps in data. D2.3ii. Complete analysis of existing aggregate samples using IR spectroscopy									D2.3 i			D2.3 ii
O2.4. Roots and soil stability D2.4i. Data collection on woody root decomposition in a controlled environment. D2.4ii. Development of *in situ* tool for testing woody root contribution to soil shear strength								D2.4 i				D2.4 ii
O3.1. Alpine systems -Improved understanding of soil resilience: Characterisation of N- cycling microbial communities in *Racomitrium* heath. D3.1i. DNA of extraction from existing samples. D3.1ii. Molecular quantification of nitrifiers, denitrifiers, N-fixing bacteria. M3.1a Completion of quantification of N-cycling microbes				D3. 1i								D3.1 ii M3. 1a
O3.2. Moorland/woodland - Improved understanding of soil resilience. D3.2i. Manipulation of litter and ground flora to assess resilience of moorland soils to woodland expansion									D3.2 i			
O3.3. Peatlands - Improved understanding of soil resilience. D3.3i.							D3.					

Establishment of drought roof study at Forsinard to assess the resilience of vegetation composition and soil C and N cycling functions in restored peatlands							3i					
O3.4. Grasslands – improved understanding of soil resilience. D3.4i. Establish large scale management change experiments					D3.4i							
O 4.1i Development of a framework for systems models to relate disturbance factors, soil functions and resilience. KE. Workshop with PIs and stakeholders to discuss the different approaches to studying resilience.			KE									
O4.2ii Collation of existing data from literature and field experiments and development of initial empirical system models to relate disturbance factors, soil properties and soil functions to resilience. D4.2i. Alpine heathland model. M4.1 completion of draft model for alpine system												D4.2 i M4. 1
KE Events												
KE Events: contribute during the year to Soils Stakeholder Group, Peatlands Research Group and SNH contingency planning project group meetings to ensure knowledge exchange between ongoing projects.			**KE**			**KE**			**KE**			KE
KE Events: RD contribution to Theme level KE event on World Soils Day (5th Dec)									KE			
Engagement with annual Theme 1/Theme 2 soils event								**KE**				
Report on new materials provided to Scotland soils website SEweb, UKSO												KE
Annual Report (Year 1)												R1

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 Collation of national-scale soil property datasets and assessment of coverage in relation to habitats and disturbance factors. M1.1 – Completion of data collation and analysis of data coverage/gaps. KE: Report on 'Suitability of large scale data holdings for analysis of driver impacts on soil properties' for discussion and dissemination with key stakeholders	M1. 1	KE1. 1										
O1.2. Analysis of national-scale soil property data – relationships between soil properties, soil functions and disturbance factors. D1.2i. D1.2ii Scientific paper on soil properties and functional types. M1.2 Completion of analyses of relationships among soil properties, soil										D1. 2i		D1.2 ii M1. 2

functions and resilience from large data sets.												
O2.1. Effects of land use change on soil resilience. D2.1ii. Analysis of the effects of muirburn on soil resilience, using additional relevant perturbations of dry-wet cycles. Publication on Machair and muirburn impacts on soil resilience. M2.1 Impact of management on soil resilience										D2.1ii M2.1		
O2.2. Understanding soil resilience appropriate for modelling approaches. D2.2ii. Investigation of the interplay between initial soil conditions and the resultant resilience of mineral soils to perturbation. Scientific publication. M2.2 Completion of appropriate modelling approaches												D2.2ii M2.2
O2.3. Complete analyses of existing water stable aggregate samples for a range of cultivated topsoils and add to existing NSIS dataset and compile dataset of IR spectral data and correlations with aggregate stability and other key soil properties to establish methods for rapid assessment of topsoil aggregate stability. D2.3iii. Develop calibrations between spectral and aggregate data. Publication. M2.3 Completion of investigation into stable water soluble aggregates										D2.3iii M2.3		
O2.4. Roots and soil stability. D2.4iii. Field testing of tool developed for quantification of woody roots to soil stability aggregate data. D2.4iv. Submission of paper on the tool developed for *in situ* measurement of root contributions to soil shear strength. M2.4 Completion of analysis of roots and soil stability								D2.4iii				D2.4iv M2.4
O3.1i Alpine systems -Improved understanding of soil resilience: Characterisation N- cycling microbial communities in *Racomitrium* heath alpine gradient. D3.1iii. Community characterisation of nitrifiers, denitrifiers, N-fixing bacteria. D3.1iv. Scientific paper on N-cycling microbial communities across N-dep gradient. M3.1b Completion of community characterization of N cycling microbial communities									D3.1iii			D3.1iv M3.1b
O3.1ii Alpine systems -Improved understanding of soil resilience. KE. One-day workshop on the state of UK alpine ecosystems. D3.1v. Scientific publication on resilience in alpine soils.						KE						D3.1v
O3.2. Moorland/woodland - Improved understanding of soil resilience. D3.2i. Manipulation of litter and ground flora to assess resilience of moorland soils to woodland expansion. Publication. M3.2 Completion of 1st two years assessment of Moorland/woodland manipulation.												D3.2i M3.2
O3.3i Peatlands - Improved understanding of soil resilience. D3.3ii:									D3.3			KE

Analysis of soil properties in relation to drought/restoration age. KE. Report on 'Impact of peatland restoration on ecosystem service delivery'.									ii			
O3.3ii Peatlands - Improved understanding of soil resilience to N pollution. D3.3iii. Analysis of the suitability of 7 soil indicators to N pollution. D3.3iv. Scientific publication on suitability of 7 soil indicators to N pollution. M3.3 Final assessment of Peatlands work.											D3.3 iii	D3.3 iv M3. 3
O3.4. Grasslands – improved understanding of soil resilience. D3.4ii. Complete 2 year analysis on how grassland systems resist, recover and adapt to liming. D3.4iii. Publication of liming impacts. M3.4 Final assessment of Grasslands work.											D3.4 ii	D3.4 iii
O4.1i Collation of existing data from literature and field experiments and development of initial empirical system models to relate disturbance factors, soil properties and soil functions to resilience – *Racomitrium* heath. D4.1ii. Initial *Racomitrium* heath model. M4.2 completion of draft model for Racomitrium heath system											D4.1 ii M42	
O4.1ii Collation of existing data from literature and field experiments and development of initial empirical system models to relate disturbance factors, soil properties and soil functions to resilience – Moorland. D4.1iii: Initial moorlands model. M4.3 completion of draft model for Moorlands system											D4.1 iii M4. 3	
O4.1iii Collation of existing data from literature and field experiments and development of initial empirical system models to relate disturbance factors, soil properties and soil functions to resilience – Peatlands. D4.1iv: Peatland model. M4.4 complete draft model for peatland system											D4.1 iv M4. 4	
KE events												
KE Events: RD contribution to Theme level KE event on World Soils Day (5th Dec)									**KE**			
Engagement with annual Theme 1/Theme 2 soils event								**KE**				
KE Events: contribute during the year to soils stakeholder group, peatlands research group and SNH contingency planning project group meetings to ensure knowledge exchange between ongoing projects.			KE									
KE event: Attendance and presentation at International Soil Bio and Eco-engineering conference, a key international meeting of researchers investigating soil stabilisation (practitioners, farmers, industry) (linked to 1.1.1)				KE								
Report on new materials provided to Scotland soils website SEweb,												KE

UKSO												
Annual Report (Year 2)												R2

Name of RD: 1.1.3 Soil and net GHG emissions

Research aim and key drivers: A recent analysis of the Scottish doughnut showed that Scotland, even though it is only a small contributor to overall global GHG emissions, is one of the higher *per capita* emitters (Sayers *et al.*, 2014). Thus, the Scottish Government has accepted that it has a moral responsibility to demonstrate to the rest of the world that it can reduce its net emissions and move to a low-carbon economy in a sustainable way. As a result, it passed the Climate Change (Scotland) Act in 2009, committing the country to a target for reduction of GHG emissions of 42% by 2020 and 80% by 2050, targets that are amongst the highest in the world.

Since then, it has been developing policies and proposals within the major sectors to help it meet these targets, described in *"Low Carbon Scotland: Meeting the Emissions Reduction Targets 2010-2022. The Report on Proposals and Policies"* (referred to as the RPP1) published in 2011. The land-use sector has an important role to play in helping to reduce net GHG emissions by sequestering CO_2 into the soil and vegetation. Restoration of degraded peatlands, for example, has been recognised as a cost-effective way of reducing C losses and sequestering CO_2 from the atmosphere, and is in the process of being incorporated into national greenhouse gas (GHG) accounting methods to count towards achieving emission reduction targets. Similarly, targets for woodland expansion reflect an alternative policy mechanism to help store C in landscapes. The RPP1 was revised in 2013 to become RPP2 and specifically included peatland restoration as a proposal based on previous work carried out at Hutton. The RPP2 will be revised again in 2016 and will be succeeded by the RPP3.

Despite this, progress in achieving emission reduction targets in the land use sector has been slow. Peatland restoration is now included in national inventories and can count towards national emission reductions. As a result, the Government has committed £1.7M for peatland restoration in 2012, with a further £5M in 2014. Plans are being made as to how best to invest this support in sustainable restoration options. Targets have also been set to plant 10,000 ha of new trees per year to reach a target of 100,000 ha by 2020, but these rates have not been achieved, with only 7000 ha being planted in 2013. Clearly, there is a need for further research to understand why these targets are being missed, and also to identify other policies to help the Rural Land Use sector to contribute to emission reductions.

The work proposed in this RD will focus on the impacts of land use, including the agricultural intensification of extensive/upland soils and the management of semi-natural ecosystems such as peatlands and moorlands (wet and dry heathlands excluding areas of deep peat) on soil carbon stocks and greenhouse gas dynamics. This work will reduce the uncertainty in our estimates of GHG uptake and release from these systems and will enhance our understanding of the impacts of forest-to-bog peatland restoration and moorland management (e.g. prescribed burning) on long-term rates of C sequestration

The impact and outputs of the work have wide-reaching consequences; specifically it will contribute to the development of the Report on Policies and Procedures (RPP3 and RPP4) and the Scottish Climate Change Adaptation Programme 2 (SCCAP2).

Who has been consulted in developing this proposal? A number of key stakeholders have been consulted including SNH, FC, RSPB and SEPA. SEPA "welcome that this work package sets out to address gaps in information to enable ecosystem service assessments" and asked to be included in discussion on the collection of the data so that they can use it in their development of sensitivity mapping of ecosystems and their services and the CICES framework. RSPB have offered use of their reserves

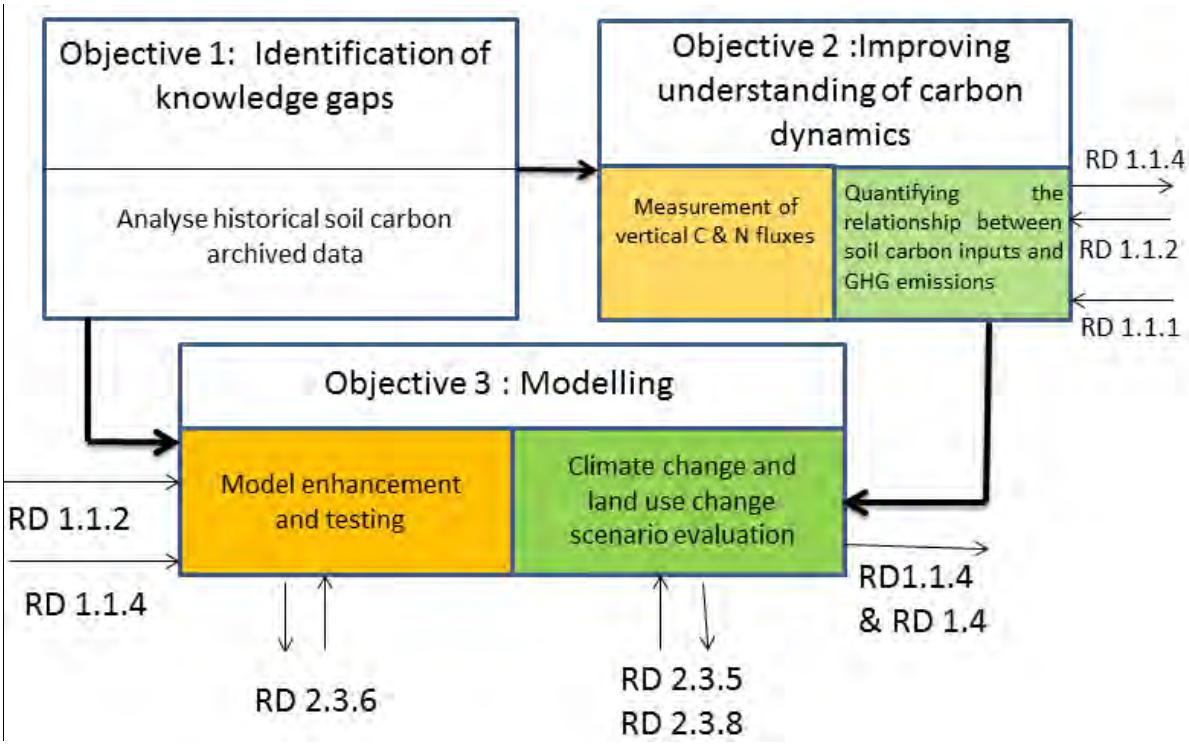
for some of the experimental work and provided advice on how the work links with their requirements.

Summary of the proposal:

Objectives and activities: The objectives of the work are to:

- O1. Analyse historical archived data for trends in soil properties, especially soil organic carbon, over 30 year period spanning increased agricultural intensification and other land use change trends.
- O2. Improve the quantification of greenhouse gas uptake and release in peatland and moorland ecosystems, and to enhance our process based understanding of carbon and nitrogen dynamics in these ecosystems.
- O3. Incorporate this enhanced understanding into existing simulation models, and use the models to identify hot-spots of GHG emissions and to evaluate the impacts of land use and climate change scenarios on these systems.

The structure of the RD is as follows:



Objective 1: Data analysis:

Work in the 2011-16 Programme has focused on collating and analysing data from a variety of sources, assessing soil carbon stocks, particularly changes in afforested soils. The analysis of this data has led to the development of pedotransfer functions, while analyses of 12,700 topsoil samples from cultivated land in Scotland showed no significant declines in carbon contents. Other work compared the IPCC approach of attributing agricultural contributions with a new approach adopted by Scottish Government, and showed that although the latter resulted in a larger emissions footprint being attributed to the agricultural sector, the large reduction in grassland to cropland conversion since 1990 meant that total agricultural emissions in Scotland have fallen 26.6% when calculated by the SG, compared to a drop of 19.1% using the IPCC method. A further set of historical archived (collected over period 1950-75) agricultural soil samples (~1000) together with the accompanying background sampling and original analytical data exist at the James Hutton Institute

and represent a change from lower input agricultural systems to more intensive agriculture. It is proposed to analyse these in the 2016-21 Programme. The rates that individual soil attributes change in response to the influences of management and climatic factors tend to overlap, be synergistic and show long-term time lags. By resampling a subset of fields and quantifying the current soil C and nutrient status, and linking this to an understanding of changing patterns of climate, land use and management, we can assess the impact on changes in soil carbon stocks over the past 60 years. The results will provide input into the soil process models predicting future change elsewhere in the RD. We will use a set of historical archived agricultural soil samples (~1000) collected over the period 1950-75 at Hutton together with the accompanying background sampling and original analytical data. **M1.1**: Archive and analyse collated soil carbon data. **D1i.** (Year 1) A soil database will be created by collecting key soil properties from a variety of sources. **D1ii.** A set of fresh soil samples from former experimental fields from North East Scotland will be collected for further analysis. **D1iii. Output; (**Year 2) Refereed journal article on the impacts of intensification and land use change since the 1950s on soil C stocks and associated characteristics.

Objective 2: Improved understanding of carbon dynamics:

2.1 Isotope work: To gain a better understanding of the processes that drive emissions, we have used stable isotope techniques to partition soil surface CO_2 efflux at a number of sites across Scotland, with the aim of quantifying the contribution of heterotrophic and autotrophic components to total emissions. The experimental sites have encompassed a diverse array of land-use types ranging from arable to bog/moorland (e.g. Ballogie, Glensaugh, Glen Tanar, and the NSIS sampling sites at Ardallie and Corse). NSIS data have been interrogated at a national level, producing $\delta^{13}C$ and $\delta^{15}N$ 'isoscapes' of topsoil, and the key drivers of the observed isotope patterns have been identified. Further work has been undertaken to examine in detail the distribution of $\delta^{13}C$ with depth in soil profiles, in an attempt to better understand the balance between labile and recalcitrant C, and link this to the partitioning of the soil surface efflux. Together these results form the basis of our proposed future plans. We hypothesize that (a) the pattern of $\delta^{13}C$ enrichment down soil profiles is indicative of the C mineralization potential, (b) C mineralization rates are in turn indicative of the relative labile vs. recalcitrant contents of C stocks, and (c) the relative labile C content of soil profiles will be reflected in respiration losses i.e. the respiration losses from profiles containing more labile C will contain relatively more heterotrophic compared with autotrophic respiration.

2.2 Soil carbon dynamics: Related work has quantitatively identified the important processes of microbial decomposition of soil organic matter (SOM) not accounted for by current models. This work showed that plant-derived inputs can significantly increase decomposition of existing SOM, reducing net C-accrual from increased inputs, as predicted by standard models. Applying the new assumptions to a global carbon model (Community Land Model) significantly altered the predicted global distribution of soil C-stocks and improved predictions of these distributions compared to C data held in a global database. Work is currently underway to incorporate these modifications into the models being used for Scotland, which will be extended into the 2016-2021 programme.

2.3 GHG fluxes measurements: During the 2011-16 Programme, eddy covariance equipment was installed on a restored peatland at Forsinard in the Flow Country and at Hartwood Research Farm. The specific focus of this work is to assess the impact of forest-to-bog restoration techniques on carbon and GHG dynamics. Through this work a collaborative programme of research has been

developed with the University of Highlands and Islands Environmental Research Institute, St. Andrews, Stirling, Aberdeen, CEH, SNH and the RSPB, where a network of towers and new/historic sites have been instrumented to capture the carbon and GHG dynamics associated with different land use types (pristine and afforested peatlands) and restoration sites of different ages. We will continue this long-term assessment to capture the influence of inter-annual climatic variability on C stocks and emissions providing a better process based understanding of the drivers of GHG dynamics in these systems and also facilitating model testing, development and upscaling exercises using remotely-sensed data. This work will be with a newly appointed Macaulay Development Trust Research fellow in remote sensing. It is also proposed that GHG measurements be extended to investigate the implications for GHG emissions following liming of extensively grazed semi-natural grasslands in new field-scale experiments established at the Glensaugh and Hartwood farm platforms managed by JHI within RD1.3.1. Our results will provide input into the analysis of ecosystem resilience and vulnerability of this field experiment undertaken in Objective 3 of RD1.1.2.

M2.1: Collect new data on soil δ13C values with depth and potential soil C mineralization rates and partitioned soil respiration fluxes. **D2.1i** Collection of soil down profiles at three sites contrasting in land use and additionally partition respiration at these sites. Collection of soil down profiles at three sites contrasting in land use and additionally partition respiration at these sites. **D2.1ii** Isotopic analysis of collected soil. **D2.1iii → output; (Year 2**) Refereed journal article on the relationships between the pattern of soil δ13C values with depth and potential soil C mineralization rates and partitioned soil respiration for six selected NSIS sites of contrasting land use.

M2.2: Collect process and analyse eddy covariance data collected from the Forsinard peatland restoration sites. **D2.2i** Establish site to collect CO_2 eddy covariance data from the Forsinard peatland restoration sites **D2.2ii** analyse and gap fill using different gap filling techniques to assess the carbon flux in the Forsinard peatland restoration sites **D2.2iii → output; (**Year 2) Refereed journal article on net GHG emissions measurements from restored peatlands based on the Forsinard peatland restoration sites.

M2.3: Establish and collect static chamber measurement setup for GHG emission measurement at Glensaugh and Hartwood **D2.3iv**. (Year 3) produce a refereed journal article on net GHG emissions measurements from peatland restoration. **D2.3v, Year 4&5** Establish EC tower in Hartwood site and collect CO_2 flux data from the field site.

Objective 3: Modelling approaches and scenario analysis: Modelling work has focused on further refinement of the ECOSSE model, which was used in the CXC-Woodlands project to quantify carbon stock changes and GHG emissions following conversion of different land use types into woodland to evaluate the implications of the Scottish Government's target of 100,000 ha of woodland expansion by 2022. Other work in progress is to incorporate the effects of soil priming on mineralisation rates into existing soil process models. A review of existing models describing C and N dynamics in peatlands is being carried out, as was an evaluation of the RESAS Carbon Calculator used in planning permissions for wind-farm developments. Work will also continue with the modelling of GHG emissions associated with current land use and management, to deliver a better process based understanding and the implications for future climatic variability. Mapping of peatlands and peatland carbon is an ongoing activity. Current work has mainly focused on the spatial location of peatlands, while ongoing work will link with the digital soil mapping exercise in

RD1.1.4 to improve the accuracy of spatial estimates of peatland ecosystems. Peat depth and related C stocks are still only partially understood, with large areas of the country still largely unexplored.

M3.1: Improve various model(s) by incorporating vegetation dynamics and soil C inputs in peatlands and moorland systems. (**D3.1i, Year 1**) Modification Holocene peat model and ECOSSE models to incorporate vegetation dynamics and soil C inputs in peatlands. (**D3.1ii, Year 2**) Calibrate and validate models on selected sites to optimize model performance (**D3.1iii → output. Year 2**) Improve long-term estimates of net Global Warming Potential (i.e. overall GHG emissions and C sequestration rates) from peatland restoration sites for inclusion in RPPs and produce a refereed journal article on this topic.

M3.2: Modelling analysis of carbon sequestration potential of upland soils (**D3.2i**. **Year 3**) produce a refereed journal article on the potential for upland soils to sequester more carbon based on climate, soil type, and current C stocks.

M3.3: Modelling analysis of impact of climate change (increased temperature, changed precipitation patterns) on carbon storage in peatlands and moorlands (**D3.3i. Year 4**) Refereed journal article on the likely impact of climate change on C storage in peatlands and moorlands

M3.4: Develop a prototype model of peat depth at the national scale (**D3.4iv. Year 5**) Produce a model of peat depth able to predict the depth of blanket peat across the country.

Technical approach

Objective 1: Data analysis We will use historical archived agricultural soil samples collected over the period 1950-75 at Hutton for this work. This period represents a change from lower input agricultural systems to more intensive agriculture. We will use this unique resource maintained by Underpinning Capacity to analyse trends in key soil properties (Loss on Ignition, soil C, extractable phosphorus and pH) and relate these to changes in intensification of land management activities. Appropriate statistical methods will be used following advice from BioSS. The results will allow us to improve processes in different models for predicting future changes in soil carbon elsewhere in the RD.

Objective 2: Improved understanding of carbon dynamics:

Isotope methodology: Differences in natural ^{13}C isotope can be used to characterise soil surface CO_2 efflux and partition this into autotrophic and heterotrophic components. A key strength of this approach is that it allows partitioning of the surface efflux with minimal disturbance. We will measure the soil surface efflux at selected field sites by deploying a specifically designed dynamic chamber system, followed by soil and root incubations to provide end points of a simple isotope mixing model. Longer term soil incubations will be used under controlled conditions will be used to assess labile C dynamics pools identified by their ^{13}C natural abundance.

Eddy covariance techniques: Eddy covariance is an established technique which allows C fluxes to be measured at an ecosystem level and provides an integrated measure of net C exchange. This technique relies on monitoring a range of environmental parameters, such as atmospheric CO_2, H_2O, CH_4 concentrations, wind speed and direction from an elevated position in a landscape above the standing vegetation. A new installation has recently been purchased by the James Hutton Institute, which conforms to the ICOS specifications and both complements and extends the existing infrastructure operated by CEH, St. Andrews and UHI at Forsinard, and also by SRUC at their Defra-funded Agricultural GHG platform at the Crichton Dairy Research Centre. The Forsinard system is tailored for remote,

unmanned operation, making use of solar panels, wind turbine and rechargeable batteries, data loggers and a satellite data-transfer link. Chamber based measurements of soil derived GHG emissions are also made which contribute to capturing the spatial variability of GHG emissions and also allow for an assessment of the contribution of different micro-topographical features or management treatments on GHG emissions. Measurement and modelling of GHG emissions from peatlands in various stages of restoration will focus on established plots in the Forsinard area. These techniques will be used in the newly established liming experiments at the Glensaugh and Hartwood farm sites. We have an existing field-scale liming experiment established at the Glensaugh and Hartwood farm platforms which cover limning impacts on extensively grazed semi-natural grassland systems (linking RD1.1.2). We will use these sites to measure GHG emissions from different managements. There is scope to carry out CO_2 measurements using Eddy Covariance measurement at Hartwood farm.

Objective 3: Modelling approaches and scenario analysis: Four process-based models, DNDC, ECOSSE, HPM, and PALM will be used. DNDC is a dynamic process-based model that has been developed to simulate GHG emissions (CO_2, CH_4 and N_2O) from agricultural soils. The model can also be scaled to provide national estimates of GHG emissions and test future climate and management scenarios. The ECOSSE model was developed expressly to deal with the highly organic soils common to Scotland from concepts originally derived for mineral soils in the RothC and SUNDIAL models. Following these established models; ECOSSE uses a pool type approach, describing soil organic matter (SOM) as pools of inert organic matter, humus, biomass, resistant plant material and decomposable plant material. All of the major processes of C and N turnover in the soil are included in the model, but each of the processes is simulated using only simple equations driven by readily available input variables, allowing it to be developed from a field based model to a national scale tool, without high loss of accuracy.

HPM is a carbon, water and vegetation simulation model incorporating peat decomposition and accumulation model. The model contains a vegetation sub-model which is based on the assumption that water table depth and peat depth are the two factors determining peatland vegetation and its productivity. Vegetation is categorised into 12 plant functional types for which net primary productivity is modelled, and the litter contributions from each plant type are tracked in the peat column. HPM models long time periods, over millennia, which allows outputs to be compared with peat core data. We would also explore the possibility of modelling blanket peat depth across Scotland using existing data and revisiting previously sampled sites to ground-truth model outputs and to explore the capabilities of the model to predict changes in peat depth.

PALM (People & Landscape) is a socio-ecological system model, integrating social, economic and biophysical processes. It employs an agent-based approach with a number of decision-making entities (e.g. farm households) located on a landscape made up of different land units, each of which contains routines to simulate, water, C and N dynamics. Decisions made by the household agents result in actions which may influence the dynamics of H_2O, C and N within the landscape. The model simulates above ground vegetation growth (crops, weeds, trees) and C inputs into the soil from these. The soil module contains a surface litter pool, plant roots, two fresh organic matter (FOM) pools, and three soil organic matter (SOM) pools with varying mineralization rates.

Detailed work plan

Objective 1: Data analysis: Year 1, collate database of key soil properties (Loss on Ignition, soil C, extractable phosphorus and pH) and contextual information such as latitude and longitude, land use and crop type from existing records held at the James Hutton Institute. Identify those sites where archival soil material still exists. Year 2, extract archived samples from the National Soils Archive for reanalysis. Collect fresh samples from a selection of former experimental sites in North-east Scotland. Undertake analyses of approximately 100 archive and 100 matching fresh samples soil samples. Year 3, assess trends in changes in key soil properties from 1950s to present due to intensification of agriculture and relate these to current low input systems to assess likely changes if agriculture is intensified.

Objective 2: Improved understanding of carbon dynamics:

Isotope work: Soil processes at depth are often overlooked but significant amounts of C can be stored here which are still vulnerable to loss. Enrichment of C isotopes are often observed going down soil profiles; concomitant with this soil C changes, from a mixture of labile and recalcitrant C at the surface to be dominated by recalcitrant material at the bottom of the profile. We plan to utilise existing Underpinning Capacity, namely the isotope data within the NSIS database, in a new innovative manner. We will revisit selected NSIS sites varying in pattern of soil $\delta^{13}C$ values with depth and establish relationships with potential soil C mineralization rates and partitioned respiration. A great advantage of using the NSIS data set in this manner is that it allows up-scaling, providing better confidence in our data and improving the basis on which policies can be developed to preserve and enhance soil C sequestration. We envisage that the process of up scaling will utilize existing data on soil series and ultimately provide a mechanism of mapping soil processes such as potential mineralization rates.

Eddy covariance measurements: Experimental work using eddy covariance and static chamber techniques currently undertaken at the Forsinard (peatland) and Hartwood (afforested peatland) sites will be extended in this programme to develop long term GHG emission data sets. Further collaborations with Forest Research, including a joint PhD studentship, will be developed at the Hartwood site where the afforested peatland is due to be felled and restored subsequent to the installation of on-shore wind turbines. The EC systems are operated continuously and regular site visits will be required to maintain the calibration sensitivity of the analysers; this work will be undertaken in conjunction with regular bi-monthly measurements of soil derived GHG emissions using static chamber techniques. Gas samples collected during the deployment of the static chambers will be stored in pre-evacuated vials and transported back to the laboratory where they will be analysed using gas chromatography techniques. All GHG and associated ancillary data will be collated in a central database that will be updated on a six monthly basis to provide a continuous, expanding data set for integration with the modelling and remote sensing work. Along with eddy covariance measurements dissolved organic carbon measurements will be carried at appropriate intervals to quantify carbon budget as a whole in each site.

Objective 3: Modelling and scenario analysis: Ongoing development of the ECOSSE model will proceed in collaboration with the University of Aberdeen. As with most models, the sizes of the C pools in ECOSSE are determined by optimisation to match observed values. Measurements of the size of the labile C pool using the ^{13}C approach described above and physico-chemical fractionation studies should help to quantify these pools with more accuracy. In addition, the methane subroutines of the

DNDC, ECOSSE, HPM and PALM models will be improved, particularly in relation to the dynamics occurring after the rewetting of peatland through restoration. The latter will then be used to explore scenarios of change, including the impacts of climate change using the UKCP09 climate scenarios, changes in land use, land management, particularly of peatlands (e.g. peat drainage/drain blocking). They will also inform the development of a simpler model to calculate the contribution of peatland restoration to national emission reduction targets, which although less precise at the site scale, will run on far fewer parameters and at the national scale.

Expertise: The James Hutton Institute provides expertise in the following areas relevant to this work package:

- Eddy flux correlation measurement and analysis to quantify vertical gaseous fluxes between surface vegetation/soils and atmosphere
- Isotope analysis using the National Soils Inventory of Scotland (NSIS) database
- Ecosystem modelling with special focus on soil C and N dynamics and GHG emissions
- GIS capability for processing and manipulating spatial data for the production of maps
- Linking land-surface GHG exchange with remotely sensed information to enhance up-scaling and mapping activities

The proposed work will further develop our capacity in eddy-flux correlation work, particularly in relation to analysing and interpreting the data, which has so far focused on data collection. The modelling work will further develop our expertise in carbon and nitrogen dynamics in the anaerobic peatland environment. Both of these areas of expertise will be enhanced through the linkages with remote sensing, a new area for Hutton in recent years.

Through links to Theme 2, Scotland's Rural College will provide expertise in the following areas to support activities in RD1.1.3:

- Measurement of GHG emissions using manual and automatic chambers and eddy flux correlation towers: GHG data generated from several land especially from grassland systems will be used in RD1.1.3 for model calibration.
- Soil science expertise for the analysis of historical soils data, land use and land management. This expertise in import in this RD epically model upscaling model results from site to regional scale.

Key linkages, interdisciplinary & collaboration: The main linkages will be with other RDs in WP1.1. In particular, the C dynamics and GHG emissions from peatlands will involve close linkages with the resilience of peatland soils and peatland restoration RD1.1.2); the same sites will be used. The results from the GHG/C eddy flux correlation and modelling work will provide information on one of the indicators of resilience, soil carbon. The model of peatland restoration able to predict future benefits at the national scale will be used as a tool to help assess best areas for restoration (RD1.1.2). The work on predictions of peat depth (and hence carbon stocks) across the country will link to Underpinning Capacity. Land use and spatial databases developed in RD1.1.4 and RD1.1.2 will be used for upscaling models from plot to regional scale. Digital soil map or part of the digital soil map can be used for this purpose if the resolution of the model and maps match.

There will also be strong linkages with the agricultural GHG work in RD2.3.5, RD2.3.6 and RD2.3.8. GHG data generated from grassland systems in RD2.3.6 will be available for calibrated and validating DNDC and other models in RD1.1.3. This activity also links with the modelling exercises in RD2.3.5 and RD2.3.8. Similarly, the work on the field-scale liming experiment established at Glensaugh and Hartwood farms in RD1.1.2, will quantify the GHG emissions and changes in carbon stocks

following the application of lime. These results will feed back into RD1.4 work for examining trade-offs and synergies with other ecosystem services, and for assessing the resilience of liming impacts on extensively grazed semi-natural grassland systems. As the NSIS isotopic dataset encompasses all of Scotland's main land uses, it will include agricultural sites, and as such will link to WP 2.3 Agricultural systems and land management.

Due to the focus on biophysical processes requested in the ITGF, i.e. GHG emissions and C sequestration, this RD has limited interdisciplinary in relation to the social and economic sciences. The only research area listed in the ITGF potentially involving socio-economic expertise, i.e. "Approaches to overcome barriers to uptake of sustainable soil carbon management practices on semi-natural and peatland/moorland habitats" is covered in **RD1.1.4.**

External collaboration will be largely with the University of Aberdeen in relation to ECOSSE model development and use, with Forest Research in relation to woodland management modelling (particularly on organic soils and soils with an organic surface horizon), and with CEH in relation to the contribution of the RD work to national inventories. Collaboration with the Forsinard Flow country research hub will also continue, which includes St. Andrews University, the UHI, Stirling University and the RSPB.

Added scientific value: The GHG work will contribute to the emission activity data required for the new Intergovernmental Panel on Climate Change (IPCC) wetlands guidelines, with links to the DECC Emission Factor project and the Land Use, Land Use Change and Forestry (LULUCF) Emission Inventory team at the Centre for Ecology and Hydrology (CEH). This work will also contribute to the Integrated Carbon Observation System (ICOS) network as an ancillary site, gaining international exposure for this work.

The modelling work will contribute via the Global Research Alliance Modelling Platform (GRAMP) project to the Global Research Alliance (GRA) work on reducing GHG emissions by identifying region specific mitigation options, particularly the Croplands and Peatlands sub-groups, and to the Modelling European Agriculture with Climate Change for Food Security (MACSUR) project of the Joint Programming Initiative on Agriculture, Food Security and Climate Change (JPI-FACCE).

KE, audiences and impact: Results will be delivered to appropriate audiences through conferences, workshops, exhibitions, stakeholder participation, peer-reviewed articles, policy briefs, and other forms of media.

Audience: Specifically in relation to RD1.1.3, we will communicate our work through regular meetings and email exchanges with the main users, the LULUCF GHG Inventory Group at CEH, the Agriculture GHG Inventory Group at North Wyke, the GHG emissions group at the Department for Energy and Climate Change (DECC), and Forest Research. Other links will be through four Defra-funded projects aimed at improving the UK GHG Inventories (ACO112, ACO114, ACO115, and ACO116), which involve staff from CEH, North Wyke, SRUC and Hutton. Close interaction with other RDs in Themes 1 and 2, particularly RD1.1.2, RD1.1.4, RD2.3.5 and RD2.3.6, will also help with synthesising and interpreting results. With all of these links, we will keep the respective projects informed of each other's work through appropriate attendance at respective meetings, exchange of workshop summaries, and explore joint working in the future.

RD1.1.3 will work closely with the CKEI, the Soils Stakeholder Group and the Peatlands Research and Monitoring group to ensure that outputs and systems models are of direct relevance to end-user organisations.

Of particular importance for dissemination of much of the work in this RD is the

ClimateXChange initiative established by the Scottish Government in 2011 as collaboration between the MRPs and universities to synthesise research results and make them available to its policy teams. The James Hutton Institute is a major contributor, providing information on peatland restoration, woodland expansion, agricultural mitigation and adaptation, risk to biodiversity, impacts on tourism, windfarms, domestic energy demand, carbon trading, targeting of mitigation measures in the SRDP, and indicators of climate change. Our membership of the Scottish Government's Agriculture and Climate Change Stakeholder Group (ACCSG) is another avenue for knowledge exchange with the appropriate Scottish Government policy teams and stakeholders.

Relevant findings of our work will be disseminated through scientific networks such as PeatNet, MethaneNet, ICOS, and the Global Research Alliance on Agricultural Greenhouse Gases (GRA). Within Europe, we will attend and present papers at conferences, as well as use our involvement in EU-funded projects (e.g. JPI-FACCE-MACSUR) to exchange knowledge with other researchers in the area of GHG emissions and C sequestration and participate in future joint funding proposals.

Impact*:* It is expected that the research outputs from RD1.1.3 will have impact at a range of scales. Hutton will use its status as an official UN Observer Organisation to take part in UNFCCC meetings and to showcase some of our work. Where appropriate, we will also contribute to future IPCC assessment reports. RD1.1.3 (particularly peatland restoration) will contribute at the Scottish Government and ultimately international level via the IPCC Wetlands supplement and the revisions of the Report on Policies and Proposals (RPP4) in which peatland restoration is a major focus. The National Peatland Plan will benefit from new information on peatland restoration from RD1.1.3 while, in combination with Theme 2, RD1.1.3 will significantly improve the knowledge base on GHG emissions from Scottish soils to inform a range of policy areas in Scottish Government in particular agriculture, environmental quality and climate change. We will work closely with the CKEI to deliver impact across these areas and elsewhere as required.

RESEARCH DELIVERABLE NUMBER: 1.1.3

Work planning and timetable for Year 2016/2017

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1i: Collating database for key soil properties from a variety of sources.												**D1i**
O1ii: Collect fresh soil samples from former experimental fields from North East Scotland												
O2.1i: Collect of soil down profiles and partition respiration at 3 contrasting land use sites								**D2.1 i**				
O2.1ii. Preparation and isotopic analysis of collected soil												
O2.2i. Establish site and collect eddy covariance data from the Forsinard peatland restoration sites												
O2.2ii. process and analyse eddy covariance data collected from the Forsinard peatland restoration sites												
O3.1i: Modify models to incorporate vegetation dynamics and soil C inputs in peatlands.												**D3.1i**
KE Events: contribute to SEPA, SNH, peatlands research groups to ensure KE between projects. ca 1 / quarter			**KE1**			**KE1**			**KE1**			**KE1**
KE events: Participate in RD1.1.2 workshop with PIs and stakeholders to discuss the different approaches in studying resilience.			**KE1**									
KE event: Present research outcomes at CxC and SSG meetings; discuss with stakeholders to match research outputs to their needs								**KE2**				
KE Events: RD contribution to Theme level KE event on World Soils Day (5th Dec)									**KE3**			
Engagement with annual Theme 1/Theme 2 soils event								**KE**				
End of year reporting to RESAS												**R1**

RESEARCH DELIVERABLE NUMBER: 1.1.3

Work planning and timetable for Year 2 (2017/2018)

Year 1: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1ii: Collect fresh soil samples from former experimental fields from North East Scotland						**D1ii**						
O1iii:Undertake analysis of soil samples										**D1iii**		
O1iv: Publication / report development : Journal article on land use change since the 1950s on soil C stocks.												**M1.1 D1iv**
O2ii. Preparation and isotopic analysis of collected soil							D2. 1ii					
O2iii: **Publication / report development** : (**M2.1**) Journal article on relationships between soil δ13C with depth, potential soil C mineralization and partitioned soil respiration across contrasting land uses.												**D2.1iii M2.1**
O2.2i. Establish site and collect eddy covariance data from the Forsinard peatland restoration sites												**D2.2i**
O2.2ii. process and analyse eddy covariance data collected from the Forsinard peatland restoration sites												**D2.2ii**
O2.2iii: Publication / report development : M2.2: Produce a refereed journal article on net GHG emissions from peatland restoration												**D2.2iii M2.2**
O3.1ii. Calibrate and validate models on selected sites to optimize model performance.								D3.1ii				
O3.1iii: Publication / report development : Produce a refereed journal article on overall GHG emissions and C sequestration rates from peatlands and moorland systems in Scotland												**M3.1 D3.1iii**
Presentation at European Geosciences Union – General Assembly 2017 international conference	D3.1i D2.2i											
Engagement with annual Theme 1/Theme 2 soils event								**KE**				
Conference presentation at America								D3.1i				

Geophysical Union meeting								D2.2i				
KE event: Present research outcomes in CxC annual meeting and discuss with various stakeholders on their research needs.								D3.1i D2.2i				
End of year reporting to RESAS												**R2**

Name of RD: 1.1.4 *Soil management*

Research aim and key drivers

To remain within safe limits of key variables (e.g. soil carbon, GHG emissions) and to avoid potential tipping points to undesirable states in the face of environmental change, it is essential that soil is managed sustainably. We aim to support the sustainable use and management of Scotland's soil resource by providing new and improved tools to predict how soil functions respond to land use, management and environmental pressures. These decision support tools will enable users to address a wide range of policies and decision-making across scales from field to national.

Many current soil function tools have past climate conditions embedded within them or have limited opportunity to alter basic soil parameters. We will refine existing models to reflect contemporary conditions and, with RINH/UoA, develop new models of soil functions utilizing existing data and output from RDs 1.1.1-1.1.3, Theme 2 and additional analyses of soil samples from suitable grassland sites e.g. samples from the proposed compulsory soil testing. The tools will allow the assessment of soil multifunctionality and the relationships between soils and water quality, climate change and agriculture and provide input particularly to WP1.2 and 1.4 (to inform the Natural Asset Register and improve SRDP targeting). The timing of delivery of these tools will be through discussion with the Soils Stakeholder Group and CAMERAS partners.

We will develop Digital Soil Maps (DSM) to improve the current national soil map giving a more refined spatial assessment of the key soil properties important for mapping soil functions at a range of scales from field to national. This DSM research will align Scotland to the FAO-supported Global Soil Partnership (endorsed by UK Government). Novel methods of soil analyses (e.g. rapid, in-field, spectral techniques to quantify indicators of change) will develop capacity for stakeholders to capture and use soil data to meet their needs as set out in to the Scottish Soil Monitoring Action and the National Peatland Plans. We will make use of existing and new platforms, including websites (SEweb, Scotland's soils, UKSO) and mobile apps to make tools and information freely accessible.

Both monetary and non-monetary values associated with soil and soil management influence land managers' decisions and a better understanding of these values can support and inform sustainable soil management policy and decision making. Peatland restoration will be used as an exemplar to investigate these values and to develop decision tools that are based on cost-effectiveness and cost-benefit to help achieve restoration targets in the NPPl and to identify barriers to sustainable peatland management for multiple benefits. SNH, SEPA and SG scientific advisors where consulted during the development of this RD but we propose continued consultation with Soils Stakeholder Group (SSG) to prioritise the function model development.

Development and revision of new and existing models will draw on (and feedback to) experimental work in other parts of the programme such as RDs1.1.1-1.1.3, Theme 2 (e.g. 2.3.7).

Summary of the proposal:

The resilience of a soil to continue to provide a range of functions varies spatially with soil type, land management and environmental drivers such as climate. Many of the existing soil function models currently in use do not have the ability to simulate change and often have embedded and out-dated climatic parameters. To provide suitable tools that can be used to assess the impact of

change on the ability of the soil to provide a range of functions, these models need to be refined and new models developed. However, these models should not be developed in isolation and we will engage with stakeholders via the SSG/CAMERAS partners to ensure appropriate soil functions are addressed. Initially, we will develop a Bayesian Belief Network (BBN) model that incorporates existing work to assess the loss of function and impact on water quality due to topsoil erosion as an exemplar.

To provide a sound basis for the mapping of soil functions, we will develop a digital soil map (DSM) of Scotland using legacy soils data and covariates (topography, climate, and land use). Initially we will derive soil property maps for those key in mapping soil functions and will align Scotland with current global scale initiatives (Global Soil Partnership). This will allow the disaggregation of soil map polygons that have contrasting soil types. We will also incorporate remote sensing techniques alongside spatial modelling of soil hydrological properties in support of the Natural Asset Register and improve SRDP targeting (WP1.4) in years 3-5 to assess their use in e.g. improving flood prediction, GHG (N_2O) emission (with 2.3.7) and crop production.

The predicted soil properties will form the input data for risk assessments of soil functions by spatial statistical methods and for national or regional scale mapping of soil functions. Although the use of non-contemporary legacy soil data in DSM can be criticised, it is a substantial and valuable body of data on the distribution of soils and their relationships with the covariates.

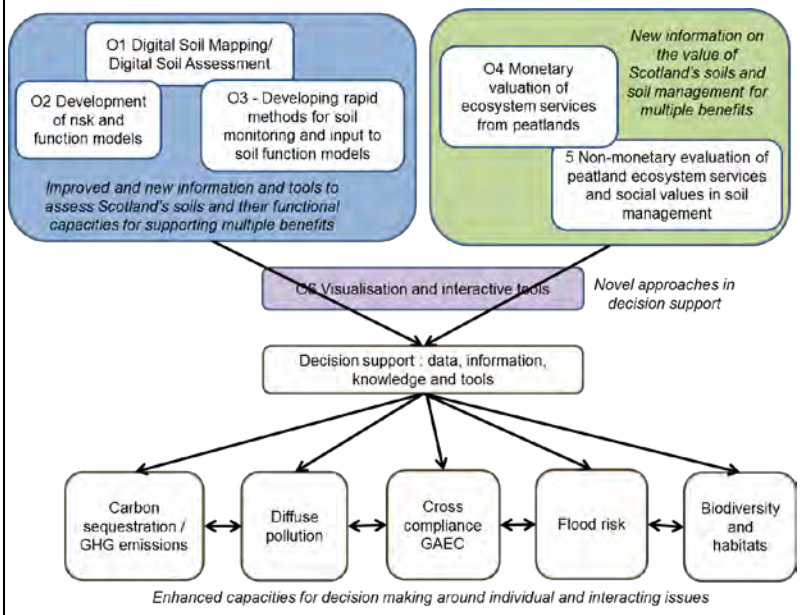
Monitoring soils requires high frequency sampling to capture the spatial variation so we will explore the potential of rapid, cost-effective, *in situ* and lab-based spectroscopy (IR and XRF) methods to detect changes in soil indicators such as carbon content, pH, (micro) nutrient status and biotic soil properties to help meet the needs of the Soil Monitoring Action Plan and generate data for inclusion within soil function models. In particular, we will develop methods to link above ground (remotely sensed) peat condition data with below ground (spectral data) to improve the assessment of the C sequestration potential of Scotland's peatlands (National Peatland Plan).

We will better understand the monetary and non-monetary (including cultural) values of ES and benefits related to soils by investigating the perceived benefits and dis-benefits (and hence the motivations and barriers) to peatland restoration including spatially explicit estimates of the non-market benefits associated with restoration, and an improved supply side assessment of associated opportunity costs and equity considerations.

Better understanding of how the benefits and dis-benefits relate to social and cultural factors such as access to peatlands and active engagement in the restoration process (in collaboration with Water@Leeds and building on existing LIFE+ projects) will help in the design of management strategies that take account of multiple benefits.

We will make data, tools and knowledge available to SG, agencies, NGOs, LAs, land managers and the public through the development of INSPIRE compliant web mapping services and apps Later, we will test the usefulness of information on erosion events collected through public observation (citizen science) submitted via a specifically designed app to validate the erosion risk models. We will develop 3D visualization techniques increase practitioner and public engagement by allowing them to view the impact of changes relative to their local surroundings (linking to flood risk estimation RD1.2.3).

Technical approach: RD1.1.4 has six main Objectives (O1-6). These are outlined in Figure 1 to illustrate their contribution to the overall aims of RD 1.1.4, WP1.1 and Theme 1.



O1 Digital Soil Mapping/Digital Soil Assessment: The current national scale map has polygons which comprise contrasting soil types. We will generate new maps by DSM techniques that utilise legacy and new soils data from the Scottish Soils and other databases along with covariates of topography, climate and land use. This will provide statistically robust estimates of soil physical, chemical and biological properties updating of the base data and allowing extrapolation of new data, information and knowledge from RDs 1.1.1/2/3. Moving from DSM to Digital Soil Assessment (DSA) of soil functions and risk mapping will be key aims and will be used for ES modelling of, for example, nutrient and sediment retention, soil hydrology (using new remotely sensed soil moisture data) and updating of the native woodland model (RD1.4.2). Other models will be developed in years 3-5 following consultation with the SSG/CAMERAS partners.

We will test different DSM approaches using a standardized set of covariates and soil data. Geostatistical techniques with spatially explicit covariates, remote sensing (RS) data and soil morphological features, have been shown to improve the level of detail and improve accuracy. We will then develop regionalised, quantified models for physiographic units based on the SCORPAN conceptual model and predict a range of soil properties for mapping soil functions. These methods are applicable to many parts of the world and will input information and data to global scale initiatives such as FAO-UN GSP and a GB-wide harmonized digital dataset through collaboration with Cranfield University. We will further develop and test new methods of integrating spectroscopy and other remotely sensed data into DSM and (years 3-5) quantify the uncertainty associated with fine scale DSM.

Spatial Bayesian approaches will be used to deliver maps of the risk (probability) and uncertainty of peat degradation, erosion, emissions, loss of soil functions occurring. These will use statistical models, expert knowledge and data generated by DSM to assess direct and indirect impacts of climate change and land use on the risk (links to RD1.4.2). In years 3-5 we will further map these impacts utilizing local and plot-based work (RDs 1.1.1 and 1.1.2 Objective 1, in particular) to assess impacts on soil biodiversity.

The new digital soil and function maps and risk models will be made available via SEweb, Scotland's Soils website, UKSO, through both Android and iOS apps and 3D visualization techniques and add to the Natural Asset Register being developed in RD1.4.1 and the mapping in RD1.2.3.

O2 Development of risk and function models: Bayesian Belief Networks (BBNs) are useful where there is insufficient 'hard' data but a considerable amount of knowledge and understanding. BBNs are probabilistic and show conditional relationships graphically as nodes and linkages, making them useful to explain concepts, are easily revised as new data and knowledge becomes available and can be used to establish what changes are required to reach mitigation targets. We will use BBN to create a unified risk assessment of erosion for all Scotland to assess likely losses of topsoil, carbon and soil functions by incorporating an existing BBN for assessing peat erosion with existing output from the PESERA model for mineral soils and direct assessments of soil aggregate strength for a range of soils and land uses (RD1.1.2). The BBN will be used to identify mitigation measures to reduce erosion (Soil Monitoring Action Plan and the SSF -SO2). Incidences of soil erosion from SEPA staff's 'catchment walks' and later from citizens (through a specifically developed app) will be used to validate the risk model and provide evidence to update the State of Scotland's Soils report. We will investigate if this model can be used to enhance the assessment of peat erosion in the WISE Decision Support Tool. Later (years 3-5) will investigate the relationships between areas of high erosion risk and soil/land use combinations that are potential sources of sediment to water courses by comparing the results of risk maps with the results of sediment tracer analyses (RD1.2.1).

In collaboration with RINH/UoA, we will develop summary process models to assess the risk to, or resilience of, soil functions such as water, GHG gas and nutrient regulation, carbon sequestration and nitrate leaching following changes in soil properties in response to environmental drivers. The models will be informed by RDs 1.1.1-1.1.3 and 2.3.7 (GHG) specifically and build on previous work. The calculations will be in a spreadsheet format to allow users to manipulate inputs but later (years 3-5) after validation, they will be packaged for use by policy makers whist retaining transparency in key aspects. Cross validation with data intensive process-based models (e.g. 2.3.7) will allow the examination of the robustness of these models. The potential impact of liming on multiple soil functions will be explored by simulating pH change in a number of soil function models. Samples obtained from suitable grasslands sites e.g. from the SG proposed compulsory soil testing scheme, will be used to validate modelling and to evaluate the likely effects of pH changes on soil functions based on current field conditions. Spatial extrapolation will be carried out using DSM mapping and feeds into RD1.4.1 (Natural Asset Register).

We will explore the potential of newly launched European Space Agency satellites that give high temporal and spatial resolution of soil moisture contents over different wave bands (Visible/IR/Thermal/Radar) to monitor changes in soil moisture content and improve estimates of water regulatory functions (RD1.2.1) as well as estimates of GHG emissions. We will review the algorithms to convert the spectral signatures to soil moisture and validate for Scottish conditions using existing data sets (ECN, COSMOS) for use in risk-based approaches.

O3 Developing rapid methods for soil monitoring and input to soil function models: We will explore the potential to use NIR/FTIR and XRF spectroscopy as rapid *in situ* methods for soil monitoring (Soil Monitoring Action Plan) and to

provide input into modelling of soil regulatory functions. Spectroscopy has the potential to give accurate predictions of many soil parameters from a single scan of a soil sample, and therefore provide a time saving and cost effective means of soil monitoring. Building on previous work (NSIS) we will extend the range of calibrations between the FTIR spectra and soil properties using fresh soil, archived NSIS soils and then *in situ* at Balruddery farm (linking to RD2.3.9). Alternative statistical methods of multivariate calibration will be investigated in collaboration with BioSS (funded by UC Function 7). As Portable XRF (PXRF) use in the field is limited by surface roughness, soil moisture, carbon, silica and aluminium, different calibrations are required for organic and mineral soil horizons. We will investigate protocols for soil surface preparation and design a device to support the instrument both horizontally and vertically for use in the field. When combined with FTIR, PXRF can provide cost effective and rapid methods for soil analysis. The method will also be tested in relation to RD1.1.2 (aggregate stability), RD 2.1.7 and 2.3.4 (tools for sustainable soil management and soil changes due to application of bulky organic wastes).

Methods to monitor soil carbon stocks in peatlands will be developed building on related SEPA-funded work. Additional data will be collated from windfarm sites, SNH's Peatland Action, remote sensing of soil moisture (to model bulk density values) and modelling of peat depth (RD1.1.3). Citizen science collection of peat depths is becoming available for Scottish peatlands and we will incorporate these data into future analyses. We will analyse the sampling methods tested during the NSIS resampling to establish which, if any, are the most appropriate for monitoring in specific soil types.

O4 Monetary valuation of ecosystem services from peatlands: Research into monetary valuation will address challenges of non-market valuation using survey-based stated preference methods. It will consider that benefits are spatially explicit, either through spatially heterogeneous provision or because marginal benefits differ across space. The impact of treating uncertainty regarding restoration and the business as usual scenarios will be tested. The valuation exercise may reveal a number of respondents unfamiliar with peatlands and methods to account for this will be developed.

Cost assessments in years 1-2 will involve identifying, through meta-analysis of restoration cost databases linked to characteristics of Scottish and UK peatlands (links to CxC research programme), suites of suitable restoration measures for specific peatland locations and their implementation costs. Different ways of eliciting information on opportunity costs of restoration will be explored. The aim is to prepare for cost-effectiveness analysis of restoration as well as to collate information for a spatially explicit cost benefit analysis that allows targeting of restoration activities on efficiency grounds (refined and completed in years 3-5).

O5 Non-monetary evaluation of peatland ecosystem services and social values in soil management: Non-monetary ES research will focus on novel ways to capture and characterise cultural and other ES from peatlands through a mix of quantitative and qualitative research. Qualitative work will include participant observation, interviews, focus groups and participatory methods with land managers, local people in areas with degraded or restored peatlands, and with volunteers involved in peatland activities. Quantitative work will apply attitudinal surveys such as Q-methodology, Best Worst Scaling or questions along the stated preference survey. The research will explore experienced

benefits and dis-benefits from existing peatland restoration projects and how factors such as access to restoration sites, the history and context of existing and previous uses, and restoration set-up influence these. The research will look at perceptions of trade-offs and conflicts between different uses and benefits in order to identify opportunities as well as barriers to managing peatlands for multiple benefits.

We will further clarify the relationships between social norms, social values and soil/land management decisions focusing on peatland restoration with other soils considered in RD1.4.1 to aid in the design of policies. Qualitative methods such as focus groups and interviews will be used to explore the influence of land managers and local people's social values and norms in relation to peatland use and restoration.

In addition, we will use the stated preference data generated through surveys in O4 to investigate whether the distribution of benefits across society is progressive, regressive or proportional with income. Furthermore, distribution of peatlands by land ownership will be analysed and how this may relate to peatland restoration which will help guide qualitative research in year 3-5. By bringing social values and norms together with economic values, this research will provide a better understanding of the incentives and barriers to peatland restoration and sustainable soil management.

O6 Visualisation and interactive tools: A mobile augmented reality application for smartphones will be developed where landscape data can be overlaid on to the users screen and updated as the field of view changes. In addition, an online model is planned to display the 3D environment integrated with DSM and other soil data to allow users/stakeholders to interact with points of interest relative to the impact of soil management on e.g. flood risk (RD1.2.3) and the effects of future land use and climate change. A citizen science approach to soil erosion monitoring/assessment will be investigated by producing an app for mobile devices to record any erosion events in years 3-5.

Detailed work plan – Milestone (M) and Deliverables (D); month (m)

O1 Digital soil mapping and assessment –The production of DSM of key soil properties (O1.1i) including the identification of covariates and of homogeneous physiographic units (M1.1i, m3), assessing existing 2/3D models and methods (M1.1ii, m6) and modelling soil properties for a test area (M1.1iii, m12) and then comparing with traditional soil mapping (O1.2i) to assess accuracy of the predictions (M1.2i, m21). New maps of soil hydrological properties (O1.3) following identification of suitable covariates (M1.3i, m16) and modelling of soil hydrological properties at landscape scale will be done in year 3 for input to WP1.4. Years 3-5: Expand the test areas for disaggregation of soil polygon maps, assess impacts of climate change and land use changes on specified soil functions. Remotely sensed soil moisture data will be obtained by m24 (M1.4i) and validated in year 3 using data from current monitoring networks (including ECN and COSMOS) as input to ES mapping (WP1.4)

O2 - Development of soil risk and function models: Development of a BBN to assess soil erosion risk (O2.1) by identifying the key variables and processes influencing erosion for organic and cultivated, mineral soils (M2.1i, m6); The BBN conceptual framework will be developed (M2.1ii, m6) and populated (M2.1iii, m8) to derive the conditional probabilities table (M2.1iv, m12) to produce a draft model (D2.1v). New experimental data (from RD 1.1.2) will be incorporated. The BBN will be tested at a workshop with relevant stakeholders and users (e.g. SEPA,

farmers groups, SSG) (KE2.1vii) to explore uncertainties, sensitivities and future scenarios (D2.2vii). Data from the compulsory soil testing will be used to model the impacts of liming on grassland soil functionality (O2.2i) over a 4 year period that samples will be available. Model selection will occur by m12 (M2.2i) with a workshop to disseminate interim results in m24 (KE2.2iv). Soil function models (O2.3i) will be developed to assess the resilience of a range of soil functions and implemented within a spreadsheet using equations for the key processes of C sequestration, nitrate leaching, water and air regulation and crop production (Mii-viii) in m4-24. Years 3-5: Validate erosion risk models against observational data from SEPA's catchment walks and reported incidences of soil erosion from citizens. Incorporate remotely sensed soil moisture data into ES mapping. Develop additional models of soil functioning in consultation with the Soils Stakeholder Group and CAMERAS partners.

O3 - Developing rapid methods for soil monitoring and input to soil function models: In years 1-2 the work using IR spectroscopy will include developing FTIR calibrations to extend the existing dataset (O3.1i, M3.1i m9) and develop calibrations for soil properties (D3.1ii, m18) followed by calibrations for *in situ* FTIR analysis of soils (M3.1iii, m23) and document (D3.1iv, m24).This will be built on in O3.2 where spectroscopy will be combined with remote sensing to study the properties of peats and highly organic soils (M3.2i-M3.2iii, m4,9,24). New methods for assessing peatland carbon stocks and modelling peatland function will be developed (O3.3i) using legacy peatland data i.e. peat depth (M3.3i, m6) carbon contents (M3.3ii, m9) and bulk density (M3.3iii, m18) with a report (D3.3ii, m21. Methods for using PXRF in the field (O3.4i) will be developed (D3.4i, m6) and comparison of fresh soil elemental concentration with lab-based analyses will be done (M3.4i m12) followed by field testing and application (M3.4iii, m17) and methods for *in situ* use documented (D3.4iv, m17) and paper written (D3.4v, m24). In years 3-5 we will develop protocols for the use of FTIR and PXRF methods in the field along with calibration equations to predict soil properties *in situ*. Identify areas where data are insufficient to estimate carbon stocks and implement a field campaign to collect additional data in these areas.

O4- Quantification of monetary benefits associated with peatland restoration. A stated preference survey for determining non-market benefits of peatland restoration (O4.1i) will be developed (M4.1i, m6) piloted (M4.1ii, m7) and implemented (M4.1iii, m9).The results will be analysed and a conference (D&KE4.1iii) and journal paper written (D4.1iv, m12) to assess the non-market benefits of peatland restoration. A report (D4.2ii, m24) on a preliminary opportunity cost assessment of peatland restoration (O4.2i) based on meta-analysis of implementation costs using Bayesian statistics and probabilistic models (M4.2i, m21) will be produced.

O5- Non-monetary evaluation of peatland ecosystem services and social values. In order to quantify benefits and dis-benefits from existing peatland restorations (O5.1i) projects will be identified in collaboration with SNH (M5.1i, m2), followed by development of guideline for participants (D5.1ii, m2). Volunteers will be observed and interviewed (M5.1iii, m19) followed by analysis by m24 (M5.1iv). To determine the benefits/dis-benefits to land managers, volunteers and the local population from peatland restoration (O5.2i). Interview guidelines (D5.2i, m2) will be developed and data will be obtained from workshops and focus groups (M5.2ii) over the period m3-17. The data will be analysed (M5.2iv, m22) to assess on benefits/dis-benefits of peatland restoration with interim reports at m12

(D5.2iii), final report (D5.2v, m24) and conference presentation (KE5.2.vi, m24).

O6 – Visualisation and interactive tools: A 3D virtual landscape display will be developed (O6.1i) with soil data overlaid on a test area (D6.1i, m6) and implemented for web browsers (D6.1ii, m12). It will then be use to investigate how people interact with the landscape (M6.1iv, m24) and presented at a conference (KE6.1iii, m12). In year 3 onwards we will develop and implement an interactive tool (mobile device application) for reporting soil erosion and develop an online survey for a prototype 3D landscape model of Augmented Reality.

Expertise: Recent peer reviewed work has developed and implemented both traditional and statistical approaches to calculate soil C stocks such as 3D Geostatistical General Additive Model. Staff have considerable experience in utilising and interpreting soil data and have produced a range of soil function and ES maps. The team has expertise in BBN, modelling erosion and process-based modelling of soil functions, spectroscopic techniques and multivariate calibrations. The team also has experience in applied non-market valuation and policy assessment in relation to soils and in relation to water, cultural ecosystem services, local perceptions of environmental changes and citizen involvement in science. The team was perviosuly involved in web-based delivery of soils information, development of apps for mobile phone and tablet platforms and expertise in soil monitoring and stakeholder engagement.

Key linkages, interdisciplinarity & collaboration

This RD synthesises and spatially extrapolates results from the other RDs in WP1.1 and have links with RD1.4.1 (natural asset inventory), RD 1.2.3 for valuation and mapping. The development of DSM places Scotland at the heart of the Global Soil Map and Global Soil Partnership communities and builds on legacy data (Underpinning Capacity). We will also collaborate with Cranfield University through a joint PhD in DSM. The development of new models of soil functions will be done in collaboration with University of Aberdeen.

There is a need for the development of rapid cost-effective, “dry” methods for soil analysis e.g. XRF/IR methods and potential collaboration with Bangor University with researchers at the World Agroforestry Centre, Nairobi and University of Adelaide to share expertise and contribute Scottish data to international libraries.

Monetary and non-monetary assessments of ecosystem services and peatland restoration will draw on research on ecosystem health and resilience (RD1.1.1/2), and databases developed of SRDP spending on peatlands via CxC. It draws on output from RD 1.3.2 (ecosystem service provision) and RD 1.3.4 (biodiversity management and off-setting) and has links to RD 1.4.1 on natural capital accounts and valuation. Assessment of peat condition relative to restoration is of value to SNH and the development of protocols for soil monitoring will input into work by CAMERAS partners.

Added Scientific Value

The Digital Soil Mapping work will provide more detailed soil maps with improved spatial resolution allowing (1) more precise land management decision making in Scotland; (2) more accurate assessment of landscape character and ES provision by soils; (3) improved information for policymakers. It will provide baseline data for innovative scientific work, including scenario modelling of the impacts of climate change and catchment dynamics.

Agronomists and soil scientists will gain access to a novel, rapid method for measuring soil parameters. Field-based spectroscopy, if sufficiently accurate, provides the triple benefits of cost reduction (reduced laboratory work), faster

response and more realistic evaluation of soils *in situ*. The sensor/calibration methods developed will be relevant not only to a wide range of soils under different land cover types (e.g. forestry, moorland, urban environments) but also to agricultural. Precision agriculturalists and scientific instrument manufacturers have shown commercial interest in this area of research and other applications of the technology might include forensic assessment of soil at crime scenes.

Information on cost-benefits of peatland restoration, especially aiming at spatial targeting based on cost-benefit or cost-effectiveness is limited within the UK and internationally, hence there is a need for primary valuation of peatland restoration and improved knowledge on spatial variation in costs taking into account both scientific uncertainties and value uncertainty related to the measurement of benefits and costs, to support the delivery of ambitious targets for peatland restoration laid out in the National Peatland Plan. Currently, no information is available on non-monetary values and social norms relating to the use and status of peatlands in the UK. As these influence public support and barriers to restoration better knowledge on these is key to the success of the National Peatland Plan.

KE, Audiences and Impact:

Impact: The WP1.1 vision is to support an increase in the area of Scotland under sustainable soil management and restoration. Our KE will be targeted at raising the awareness of land managers and other decision makers of the opportunities to expand existing, and initiate new, management/restorations. Soils are multi-functional and soil management is a key component of the environment including water quality, climate change and biodiversity. We will work closely with colleagues in these sectors to ensure that the impact of our work extends beyond the soils community (policy, regulation and research).

Policy teams, practitioners, and members of the public will benefit from the revised and updated soil property and soil function maps and models. These will allow SG policy teams, those in the associated agencies, and land managers to assess the implications of management measures on soil functions and sustainability. The maps will allow spatial targeting of SRDP measures and help to inform the public of the importance and vulnerability of soil in their area. Much of the impact of this RD will be through the assessments of multiple-benefits and trade-off analyses in WP1.4 and will contribute to the National Assets Register. We will measure our impact through the uptake of data, information and models by SG Policy and CAMERAS organisations, uptake and use of our research findings elsewhere in the Programme, especially WP1.4 which has a key role in assimilating and using soils information and by the use of information made available via websites and apps.

Policy engagement:

National**:** Our partnership in the Soils Stakeholder Group (SSG) will be an invaluable KE audience as it will bring together key stakeholders to whom we can showcase our research findings and discuss the utility of information, maps and other tools for specific circumstances. We expect to be presenting and discussing research findings regularly at SSG events. We will support the Soil Monitoring Action Plan in Scotland, e.g. providing and demonstrating methods for the rapid assessment of soil health indicators using handheld spectrometers that can be used to target sampling thus reducing the need for extensive and expensive sampling and analyses by wet chemistry techniques.

International: Soils are a key element in a number of the UN's Sustainable Development Goals, e.g. 1, 2, 6, 13 and 15. Our research will contribute to meeting these goals in Scotland and we will work closely with CKEI and policy

colleagues in reporting progress. We will continue our engagement within the Global & European Soil Partnerships contributing to the guidance and information being generated, contributing Scottish soils data and knowledge to the global community and contributing to the development and coordinating activities that promote Scottish science.

Making soils information and research findings widely accessible:

We will continue to engage with Scotland's Soils Website to make soils data accessible e.g. researchers investigating relationships between soils and other environmental parameters and land managers wanting information though mobile phone apps. In improving scientific understanding and demonstrating excellence of RESAS funded science, we will publish in leading international scientific journals. Such peer reviewed papers give RESAS confidence in the quality of related KE output and policy briefs. We will take part in farmer's events such as LEAF and Potatoes in Practice demonstrating the tools developed use of the *in situ* spectroscopy methods and apps in relation to farm management. The information and techniques such as the erosion estimation will be of interest to regulatory bodies such as SEPA in the control of diffuse pollution.

We will hold meetings with key contacts in SNH to exchange knowledge in relation to the work on peat restoration and with SEPA in relation to novel erosion risk models to help mitigate diffuse pollution. We will seek to engage with organisations such as RSPB, land manager groups and water managers on the value of peatland restoration to support the National Peatland Plan.

RESEARCH DELIVERABLE NUMBER: 1.1.4 Soil Management

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	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i: Produce a digital soil map of key soil properties for Scotland Identification of suitable covariates (M1.1i); assess existing 2/3D models and methods (M1.1ii); run models for test areas (M1.1iii)			M1.1.i			M1.1.ii						M1.1.iii
O1.2i: Comparison and integration of DSM products with products derived from traditional soil maps (M1.2i) year2												
O2.1: – Develop a BBN to assess soil erosion risk in Scottish soils and threat to loss of topsoils and key functions Synthesise existing data and modelling to identify key variables and processes influencing erosion risk and vulnerability for organic and cultivated/mineral soils (M2.1i)						M2.1.i						
O2.1ii: Produce a conceptual BBN and summary report including data linkages and conditional probabilities (D2.1ii).						D2.1.ii						
O2.1iii: Collect data/information for populating the BBN, with particular emphasis on variable/data linkages, and identify and fill data gaps (M2.1iii).								M2.1.iii				
O2.1iv: Build the conditional probability tables (CPTs) by incorporating the data and information into the BBN (M2.1iv).												M2.1.iv
O2.2i: Assessment of impacts of liming on grassland soil functionality Assess models linking liming rates with models of soil parameters and processes (M2.2i)												M2.2i
O2.2ii: Modelling of long-term changes to soil parameters and functions over time, based on potential liming rates. M2.2ii (year 2)												
O2.3i: Development of risk to, and resilience of, soil functions based on summary process-based models Identify key soil functions for which to develop summary process-based assessments (M2.3i)			M2.3.i									
O2.3ii: Develop equations for C sequestration (M2.3ii); for Nitrate leaching (M2.3iii); for Greenhouse gas emissions (M2.3iv)						M2.3.ii			M2.3.iii			M2.3.iv
O3.1i: Development of FTIR calibrations to predict soil									M3.1			

properties and extend the existing dataset Acquire additional FTIR spectra for NSIS and new samples (M3.1i); Develop calibrations to predict soil properties (D3.1ii) year2									.i			
O3.2i Develop a methodological approach to use spectroscopy and remote sensing data to predict key attributes and properties highly organic soils Select, characterise and model FTIR for a pilot peatland (M3.2i);									M3.2 .i			
O3.2ii: Development of FTIR calibrations to characterise peat condition (year2)												
O3.3i: Improve methods to estimate and monitor peatland C stocks Assess legacy peatland data to develop methods to estimate peat depth (M3.3i); to estimate peat carbon content (M3.3ii): to estimate peat bulk density (M3.3iii) year 2						M3.3 .i			M3.3 .ii			
O3.4i: Development and refinement of PXRF methodologies for soil monitoring and input to soil function models Construct device to support PXRF instrument in field (D3.4i); compare elements determined by PXRF with total measured by HF digestion and ICP (M3.4i)					D3.4. i							M3.4i
O3.4ii: Report comparing PXRF, HF digestion and ICP results (D3.4ii)												D3. 4ii
O3.4ii: Report comparing PXRF, HF digestion and ICP results KE 3.4ii)												KE3. 4ii
O4.1i: Quantify monetary and non-monetary benefits associated with peatland restoration Development of stated preference survey and application for ethics approval (M4.1i)						M4.1 .i						
O4.1ii: Pilot of stated preference survey (M4.1ii) followed by implementation of stated preference survey (M4.1iii)							M4.1 .ii		M4.1i ii			
O4.1iii: Conference presentation on methodological advances in valuing non-market benefits of peatland restoration												D4.1. iii KE4. 1.iii
O4.1iv: Analysis of the non-market benefits of peatland restoration compared to 'average' costs at a national level and paper (D4.1iv)												D4.1i v
O5.1i: Quantify benefits and dis-benefits from existing		M5.										

peatland restoration projects Select study sites in collaboration with SNH (M5.1i)		1i										
O5.1ii: Develop guidelines for participant observation and apply for ethics approval		D5. 1ii										
O5.1iii: Carry out participant observation in peatland restoration activities (M5.1iii) year 2												
O5.2i: Assess benefits/dis-benefits of peatland restoration from a variety of stakeholders Develop interview, workshop and focus group guidelines and apply for ethics approval (D5.2i)		D5. 2.i										
O5.2ii: Conduct Interviews and workshops/focus groups with land managers, local people and volunteers in peatland restoration areas and non-restoration areas (M5.2ii) year 2												
O5.2iii: Interview and workshop interim report for selected focus group (D5.2iii)												D5.2. iii
O6.1i: Develop a 3D visualisation tool to test how people interact with and value soils in the landscape Develop 3D virtual landscape display with soil data (D6.1i)						D6.1. i						
O6.1ii: Implement interactive 3D model for web to display the 3D environment integrated with soil data and DSM to capture user/stakeholder comments that they associate with soil features.												D6.1. ii
O6.1iii: Presentation at workshop on landscape visualisation, GIS Research (D6.1iii)												D6.1. iii
O6.1iii: International conference on landscape visualisation, GIS Research (KE 6.1iii)												KE6. 1iii
Local stakeholder engagement: Presentation of research outcomes at CxC and SSG meetings; discuss with stakeholders to match research outputs to their needs. Work with WP1.4 to support SSG.	**KE**			**KE**			**KE**			KE		
Hold KE event for World Soil Day (KE1)									KE1			
Contribute to the implementation of the Soil MAP through participation in events, support to the soil MAP working group and contributions to reporting.	**KE**			**KE**			**KE**			KE		
Participate in RD1.1.2 workshop with PIs and stakeholders to discuss the different approaches to studying resilience. KE2		KE2										

Farmer engagement at Potatoes in Practice and LEAF open farm events and Global workshop for Soil Proximal Sensing		D3.1 KE 3.1	D3.1.iv KE3.1.iii		D3.1.iv KE3.1.iiii							
Engagement with annual Theme 1/Theme 2 soils event								**KE**				
End of year reporting to RESAS (ALL OBJECTIVES)												**R1**

RESEARCH DELIVERABLE NUMBER: 1.1.4 Soil Management

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	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i: Produce maps of the most appropriate soil properties for mapping soil functions in Scotland (D1.1i)									D1.1i			
O1.1ii: Report/paper on digital soil mapping (D1.1ii)												D1.1 .ii
O1.2i: Comparison and integration of DSM products with products derived from traditional soil maps (M1.2i)									M.1.2i			
O1.3i: Development of new maps of soil hydrological types: Identification of suitable covariates (M1.3i); modelling and mapping of secondary soil hydrological properties at landscape scale (M1.3ii) year 3 for integration into soil function mapping (WP1.4)				M1. 3i								*Yr3* →
***O1.4i: Preparation of temporal soil moisture data for integration into soil function and risk models*:** Collection and processing of remotely sensed soil moisture data and ground based measurement data from current sensor networks (M1.4i)												M1. 4.i
O1.4ii: Validation of soil moisture products with relevant data (M1.4ii) year 3												*Yr3* →
***O2.1v – Develop a BBN to assess soil erosion risk in Scottish soils and threat to loss of topsoils and key functions*.:** Draft model and summary report including data linkages and conditional probabilities (D2.1v); incorporate data from RD112 (M2.1v)				D2. 1.v								
***O2.1*vi:** Use developed BBN to explore uncertainties and key sensitivities in the erosion risk assessment (M2.1vi)										M2.1. vi		
O2.1vii: Host workshop with relevant stakeholders and users (e.g. SEPA, farmers groups, SSG) to							KE2.					

present, discuss and get feedback on the BBN (KE2.1vii). Modifications to the BBN will be made where relevant based on the output from the uncertainty exploration and the workshop, the BBN.							1vii					
O2.1viii: Use developed BBN to carry out 'what if' scenarios in consultation with SSG to assess e.g. how changing land use or climate affects erosion risk and to identify mitigation measures to reduce soil erosion (D2.1viii)												D2.1.viii
O2.1ix: First draft of peer reviewed paper describing the development of the BBN and the resulting assessment and mapping of soil erosion risk across Scotland (D2.1ix)												D2.1.ix
O2.2ii *Assessment of impacts of liming on grassland soil functionality*: Modelling of long-term changes to soil parameters and functions over time, based on potential liming rates.	Yr 1 ←											*Yr3* →
O2.2iii: Model testing and development of spatial dataset of grassland soil characteristics and liming rates.												*Yr3/4* →
O2.2iv: Workshops with stakeholders (farmers and policymakers, separately) to inform them about interim research outputs (KE2.2iv)												KE2.2.iv
O2.2v: Research publications on modelling work and datasets (D2.2v)												D2.2.v
O2.3ii Development of risk to, and resilience of, soil functions based on summary process-based models: Develop equations for supply of water (M2.3v); supply of nutrients (M2.3vi); for erosion (compare output with BBN) (M2.3vii) and crop production (M2.3viii)			m2.3.v			M2.3vi			M2.3.vii			M2.3.viii
***O3.1ii Development of FTIR calibrations to predict soil properties and extend the existing dataset*:** Develop calibrations to predict soil properties (D3.1ii)						D3.1ii						
O3.1iii: Develop methodology and multivariate											M3.1.	

calibrations (with BioSS) for in situ FTIR analysis of fresh soil for rapid soil monitoring (M3.1iii)											iii	
O3.1iv: Document methodology for use of in situ FTIR analysis of soils (D3.1iv)												D3.1.iv
O3.1v: Presentation at Global workshop for Soil Proximal Soil Sensing (KE 3.1v a); Farmer engagement at LEAF open farm events (KE 3.1v b) and Potatoes in Practice (KE 3.1v c)		KE 3.1va	KE3.1.v b		KE3.1v c							
O3.2ii Develop a methodological approach to use spectroscopy and remote sensing data to predict key attributes and properties highly organic soils: Develop FTIR calibrations to characterise peat condition (D3.2ii)			D3.2ii									
O3.2iii: Establish modelling relationships (calibration, validation, relationships with vegetation, peat properties and remote sensing) (M3.2iii)												M3.2iii
O3.2iv: Report on the use of spectroscopy and remote sensing for predicting peat properties (D3.2iv)												D3.2.iv
O3.2v: Presentation of results at a scientific conference(KE3.2v)												KE3.v
***O3.3i: Improve methods to estimate and monitor peatland C stocks*:** Complete for peat bulk density (M3.3iii)	Yr 1 ←					M3.3iii						
O3.3ii produce a report on improved methods to estimate and monitor peatland C stocks (D3.3ii)									D3.3ii			
O3.4iii Development and refinement of PXRF methodologies for soil monitoring and input to soil function models: Test and apply methods for using PXRF in field conditions for vertical and horizontal soil surfaces (M3.4iii)					M3.4iii							
O3.4iv: Report on the use of PXRF in field conditions for vertical and horizontal soil surfaces (D&KE3.4iv)					D3.4iv KE3.4iv							
O3.4v: Peer reviewed paper providing methods for in situ XRF analysis of soil (D3.4v)												D3.4.v

O4.1iv Quantify monetary and non-monetary benefits associated with peatland restoration: Analysis of the non-market benefits of peatland restoration compared to 'average' costs at a national level and write paper/ report (M&D4.1iv)	Yr 1 ←		M.4.1iv	D4.1iv								
O4.1v: Paper on methodological advances in valuing non-market benefits of peatland restoration (D4.1v)				D4.1.v								
***O4.2i preliminary opportunity cost assessment of peatland restoration available*:** Meta-analysis of 'restoration cost databases' linked to peatland characteristics using Bayesian statistics and probabilistic models (M4.2i)									M.4.2i			
O4.2ii: Report on meta-analysis of implementation costs using Bayesian statistics and probabilistic models (D4.2ii & KE 4.2ii)												D4.2ii KE4.2ii
O5.1iii Quantify benefits and dis-benefits from existing peatland restoration projects Carry out participant observation in peatland restoration activities (M5.1iii)	Yr 1 ←						M5.1.iii					
***O5.1*iv:** Analysis of participant observations (M5.1iv)												M.5.1iv
***O5.2ii Assess benefits/dis-benefits of peatland restoration from a variety of stakeholders*:** Conduct Interviews and workshops/focus groups with land managers, local people and volunteers in peatland restoration areas and non-restoration areas. Produce workshop reports (M5.2ii)	Yr 1 ←				M5.2.ii							
O5.2iv: Analysis of workshop and focus group data (M5.2iv)										M.5.2iv		
O5.2v: Report on workshops on benefits & dis-benefits from peatland restoration (D5.2v)												D5.2.v
O5.2vi: Conference presentation on benefits/dis-benefits of peatland restoration (KE5.2vi)												KE5.3vi

O6.1iv: Use 3D Model to investigate how people interact with the landscape We will use virtual reality labs with large screens (e.g. Virtual Landscape Theatre) or mobile devices to test audience perceptions and reactions (M6.1iv)												M.6. 1iv
Hold KE event for World Soil Day (KE1)									KE1			
Participate in RD1.1.2 workshop with PIs and stakeholders to discuss the different approaches to studying resilience. KE2		KE3										
Farmer engagement at Potatoes in Practice and LEAF open farm events			KE4		KE5							
Contribute to the implementation of the Soil MAP through participation in events, support to the soil MAP working group and contributions to reporting.	**KE**			**KE**			**KE**			KE		
Local stakeholder engagement: Presentation of research outcomes at CxC and SSG meetings; discuss with stakeholders to match research outputs to their needs. Work with WP1.4 to support SSG.	**KE**			**KE**			**KE**			KE		
Engagement with annual Theme 1/Theme 2 soils event								**KE**				
End of year reporting to RESAS (ALL OBJECTIVES)												**R2**

Name of WP: 1.2 Water resources and flood risk management

1. Work Package Overview

Vision: *By 2021 this WP will have consolidated the evidence base on functioning and targeting of measures to improve water quality and manage flows, including predicting ways to ensure that current good water management remains robust to future conditions. Through excellent scientific work on resilience of water resources we will enable wider options for water management so that traditional infrastructure approaches may be rationalised against whole ecosystem methods that unite objectives across waters, soils, habitat and development needs. We will therefore help increase Scotland's international reputation in water and natural resources management and ensure water resources enhance, not limit our economic growth.*

The WP (Fig. 1) comprises four Research Deliverables: RD1.2.1 evidence and process knowledge; RD1.2.2 modelling tools for assessing current and future impacts; RD1.2.3 a framework for evaluating risk, resilience and adaptation; and RD1.2.4 fundamental understanding and evidence to build on successful policy approaches to water management in Scotland. It is convenient to think of both the evidence base, modelling and management acting across issues of water quantity (with links to morphology) and quality (links to pollution).

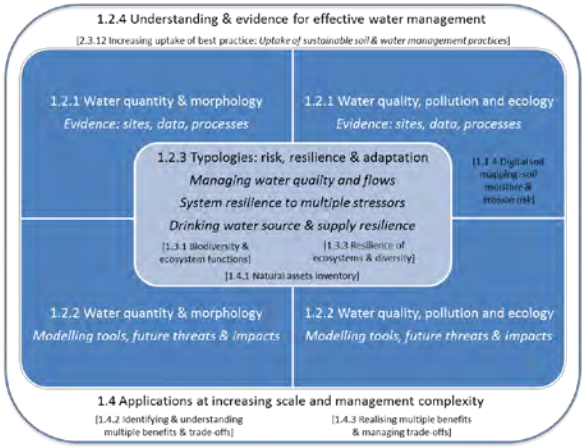


Figure 1. Overview of RD integration, intra- and inter- theme linkages.

The WP builds from the current program to improve the evidence base of observed and modelled data on water quantity (floods and droughts, morphology) and quality (sediments, nutrients, pathogens and emerging contaminants) currently and under projected scenarios of environmental change. This will quantify the concept of whether Scotland is living within or outside of its planetary boundaries with respect to the natural resource of water; examples being waters within safe limits or not of phosphorus pollution for ecological quality, or pathogens for drinking waters. We seek to unite scientific understanding of water systems and their current management with opportunities to utilise emerging ecosystem management principles that invest in ecosystem restoration to build appropriate resilience and bring wider natural asset benefits; examples being for Local Authorities (in the case of flood resilience) and water industry (for wastewater handling and drinking water protection). New emerging pollutants are considered alongside unsolved issues such as fine sediments, with new approaches bringing better evaluation of pollutant impacts through combining with physical stressors. Bigger, topical storylines cutting across these RDs gather knowledge on how water resources govern the boundaries of a sustainable society:

- managing water quality and flows that provide boundaries to societal development;
- ecosystem approaches to recognise how multiple stressors interact and help overcome how such boundaries limit economic growth and society benefits;
- drinking water source and supply resilience to improve health and society.

Our consultations show that these areas draw on major current challenges for science communities and environmental managers, regulators and policymakers. The issues are pertinent for the four priorities of Scottish Government's Economic Strategy in terms of *Investment* in natural capital and human health in terms of water and environmental quality aspects, *Innovation* and *Internationalisation* of how natural systems research enables growth especially in the water industry, maintains environmental compliance whilst enabling economic or infrastructure development, and *Inclusive growth* in building community access to good recreation, data and actions in, for example local flood mitigation.

WP1.2 focusses on three integrative storylines designed to feed into upcoming policy timelines and unite skills and resources to bring RD work areas together for higher impact collective outputs for stakeholder sectors (Fig. 2):

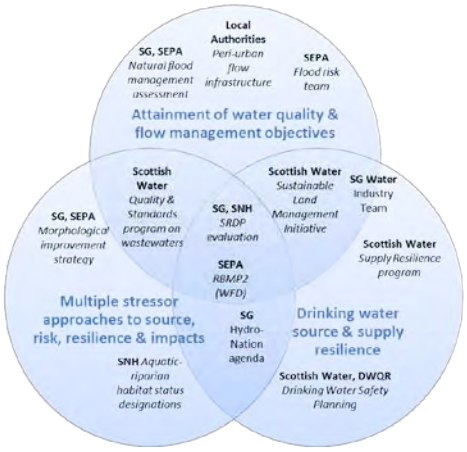


Figure 2. How the three integrative stories relate to major policy & industry requirements.

Evidence and understanding to attain water quality and flow management objectives: The aim is to make water quality and quantity management more efficient by looking for opportunities for multiple wins across quality, flow and habitat measures; gathering evidence (RD1.2.1), modelling (RD1.2.2) flow and contaminant impacts, giving recommendations (RDs 1.2.1, 1.22 and 1.2.4, respectively) for novel catchment green infrastructure (eco-engineered features e.g. bunds, buffers, rural SuDS to inform peri-urban development plans and SRDP) working across water quality and quantity (and associated biodiversity) benefits. In RD1.2.3 the resilience provided by natural flood management (NFM) measures will be compared with that in-built with traditional engineering approaches. Linking with RD1.4.2 informs managing trade-offs; together answering aspects of how natural assets can be better managed to improve functions, depending on required benefits, by who and where.

Multiple stressor approaches to sources, risk, resilience and ecological impacts: A framework for risk and resilience of water environments brings together empirical evidence and modelled scenarios of how multiple stressors (from RDs 1.2.1 and 1.2.2 e.g. extreme flows, pollution, light, temperature) interact with catchment attributes and their functions (e.g. from characteristics such as good riparian and morphological condition to catchment attributes such as inherent soil P leaching, runoff generation or erosion status). This contributes to Theme-level goals of understanding how resilient are Scotland's natural assets associated with the water environment (RQ2) and will promote better ecosystem management tools and help to explain effects of RBMP actions on classifications under WFD (RQ4); for example, where chemical status has improved but ecological condition less so, in explaining SEPA's Priority Catchment work). RD 1.2.3 provides specific process data from

experimentation on resilience to wastewater impacts (delivering to Scottish Water's Quality and Standards program and RBMP2 objectives). Catchment/waterbody attributes with explanatory power for risk and resilience to environmental pressures will inform the National Assets Register in 1.4.1 and communication tools (1.2.4).

Drinking water source and supply resilience: The condition of raw water sources, the supply network and ability to ensure safe, sustainable public and private supplies is critical to public health and economic development. Evidence on pathogen source, residence, infectivity, impacts and links with wider contaminants of concern in 1.2.1, model development and analysis of classifications for drinking water risk in 1.2.2 comes together in 1.2.3 to inform water safety planning, using spatial catchment typologies approaches informed by soil and water risk factors, then exploring catchment vs treatment methods to inform risk management interventions across a range of supply systems; 1.2.4 informs delivery of drinking water improvement actions with delivery and spatial targeting tools. The policy target is for Scottish Water's Resilience of Supplies initiative in collaboration with DWQR and SG Water Industry Team. This links to wider Dissolved Organic Carbon (DOC) work (PhDs, RESAS Innovation bid) and water treatability this will inform more sustainable water treatment options and practical case studies in 1.4.3.

2. Coordination and Management

2.1 Work package management and coordination within the Strategic Research Programme

Within WP working: This work package involves two MRPs: (1) James Hutton Institute staff (~90% of resource in years 1-2), (2) Moredun Research Institute (MRI; ~10% resource, years 1-2) and (3) HEI bid 8 involving CEH. The leadership structures comprise (i) objective leaders – for day to day administrative and scientific exchanges, (ii) RD leaders – for annual reporting, delivery and budget tracking and (iii) by WP coordinator (WPC) for overall management and issue resolution. The Moredun team are existing collaborators and a further benefit is that the senior MRI person is an expert on KE. For the CEH team the HEI funding will be tied to milestones/deliverables under CEH responsibility (timetabled for years 1-2; headline only for years 3-5) within RD objectives.

Driving integration across the WP: The WP management group (WPMG), charged with WP-level integration and interactions at inter- and intra-theme level, comprise the WPC, four RD leaders all based at Hutton, MRI lead and CEH lead, responsible for deliverables. The WPC will maintain 20% of time to management of WP1.2 and interaction with WP1.4. Directly below this level are the Objective leaders. The WPC and/or the RD leaders will be the points of contact for RESAS according to the need. The WPMG jointly share responsibility for the delivery of the projects within and between RDs, including staff supervision, reporting, delivery and quality. The WPMG will meet twice a year to evaluate integration and resolve issues, but will be in regular day to day contact on specific project issues. CEH staff will engage, where necessary, on steering groups at RD/objective level.

WP Change Management: Research leaders with coordination roles at WP, RD and project levels have extensive experience planning and implementing interdisciplinary research. The research direction will be reviewed constantly (by the WPMG) on intelligence from (i) stakeholder coordination groups; (ii) advisory groups/panels on which staff sit, (iii) engagement and projects through the Centre of Expertise for Waters (CREW) and (iv) wider networks. This will ensure 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. The latter will be done in consultation with the RESAS Scientific advisor (H. Jones).

Links within the SRP: The Theme Management Group will seek opportunities for a stronger collective voice across WP outputs and the flow of information mapped via the deliverables between the WPs. Key inter- and intra-theme integration areas are shown in Fig. 1. Research through MRI on farm pathogen impacts to humans and animals brings additional links with the Centre of Expertise for Animal Disease Outbreaks (EPIC) and RDs 1.3.1, 2.3.3 and 2.2.6.

Centre of Expertise for Waters (CREW): CREW and the SRP have a strong, reciprocal relationship, consolidated in the previous program and with a similar proposed model going forwards for whereby: The SRP provides essential capacity building foundations (evidence, knowledge, tools, frameworks and maintaining skilled staff resource) for delivery of projects to short term needs through CREW. In turn, CREW informs the strategic program in several ways;

- Conclusions of reports highlighting current gaps in knowledge/evidence,
- Improved understanding of stakeholder (regulatory/policy/industry) research needs via targeted research prioritisation.
- Knowledge exchange to key stakeholders then to policy user groups, via workshops, meetings and regular interactions

To facilitate this exchange, WP project leads sit on steering groups for RBMP, Flood Risk Management, Drinking Water and Sustainable Rural Communities themes and the WPC will sit on the CREW steering group (Stutter).

Managing the annual reporting cycle: The WPMG will ensure that all activities and outputs and impacts are reported on by RD leads and collated to ensure that impacts are being achieved. The annual reporting cycle provides the key opportunity to revise RD's based on assessment that includes feedback from direct stakeholders so thus serves both an internal and external facing role.

2.2 Mechanisms for networking and collaboration

For scientific network, exchange and collaboration, the WP will use the following structures, in which staff are closely involved:

- Participation in current (e.g. Water Monitoring Action Plan) and developing CAMERAS evidence plans.
- Multi-agency management groups – e.g. River Dee Catchment Partnership.
- Through scientific networks (RC-UK, Horizon 2020) and projects (Defra Demonstration Test Catchments, Defra Modelling initiative, BBSRC Organic P, NERC Resource Recovery from Wastes; Danish Research Foundation BufferTECH, DFID-SG Climate Action Fund water governance, EU FP7 AQUAVALENS).
- By memberships of committees; both in the UK (staff are directly involved in Innovate UK, reviewing for the EA, national Diffuse Pollution Management Advisory Group, DPMAG) and internationally (reviewing for Horizon 2020, CEN Strategic Advisory Board for Environment and technology platforms e.g. the EU Water Supply and Sanitation Technology Platform).
- By direct practitioner working through catchment and field site based activities (e.g. the Lunan farmer focus group (>7 years), Tweed Forum (4 years), MacRobert Estate (>20 years), Balruddery Centre for Sustainable Cropping including events at LEAF technical days and the Glenlivet Estate.

2.3 Interactions with Underpinning Capacity

The long term environmental datasets of the Environmental Change Network sites (Glensaugh, NE; Allt a'Mharchaidh, Cairngorms; Sourhope, Scottish Borders), provide fundamental log-term datasets of soils, streamwaters, climate, deposition chemistry and biodiversity, and are used extensively for model development and to inform baseline trends onto which management-related change is evaluated.

2.4 Enhancing additionality

The WP has a mix of highly experienced staff adding value to the SRP through UK to international linkages (with other academics e.g. UK University partners through CREW and RCUK, EU project partners; research overview organisations e.g. EU Waters Joint Program Initiative; governing bodies e.g. Scotland's DPMAG, international CEN Strategic Advisory Board for Environment; industry through UK Water Companies and environmental SME's e.g. Dryden Aqua, Biomatrix; Consultancies e.g. Jacobs, Envirocentre, EU industry bodies e.g. Water Supply and Sanitation Technology Platform; EU Water and Agri European Innovation Platforms). These linkages generate considerable knowledge, data and connections that underpin the WP research, generate new intelligence on refining research directions for Scotland in a global context and maximise pathways for impact. We have considerable ambition and track record in this WP to lever external funds to expand the scope and impact of the WP research. Research development has already been shown in the next few years' workplan of Horizon 2020 for managing water flows with green infrastructure and farming for drinking water management; our strategic science direction fits these opportunities well.

2.5 Work package risk management

We have identified a number of risks and how WPMG will respond in Table 1.

Table 2: Projected key risks for WP1.2, where the overall risk status (likelihood x occurrence) is indicated in terms of Amber or Green, for medium and low risks, respectively.

Risk descriptor	Risk assess-ment	Impact	Controls	Risk owner
Resourcing: there is strong support for the ambitions of the WP but concerns on adequacy of resourcing given the small team of water and water governance/socio-economic specialists within Hutton and MRI.	Mod-erate	Limitations on the depth and timeliness of delivery in affected expertise areas. Over-commitment of remaining staff.	Whilst the water expert team in Hutton is well established and proven it is small in number and with this increases the danger of over-commitment at key times where work deadlines stack up. Good project management principles will be used to ensure delivery within this tight team. Areas of difficulty in resourcing into the SRP have been discussed with RESAS and mechanisms put in place include incorporating CEH resource via the HEI bid.	Theme / WP Coord-inator
Excessive staff turnover	Mod-erate	Over-commitment of staff in recruiting period. Reduced rate of progress.	Loss of key WP staff can have a significant impact on the delivery of programme, particularly where there is limited breadth of staff with key skills. In the current programme there was moderate staff turnover that limited progress in some key areas and MRP senior management will be encouraged to expeditiously approve replacements in instances of staff turnover.	Theme Coord-inator
Reacting to policy requirements reduces ability to maintain strategic research that enables improved methods and capacity	Mod-erate	Reduced rate of progress on strategic science aims and impact.	Within the WP there will be both continued development of existing research themes and development of new areas of research. The RDs aim to bring new methods to our research and to develop existing specialisms within new contexts thereby ensuring scientific rigour and development of capacity in the Programme. CREW provides a benefit in directing shorter-term, less strategic work	Theme / WP Coord-inator

Risk descriptor	Risk assess-ment	Impact	Controls	Risk owner
			there and bringing in HEI resource to deliver it.	
Inappropriate phasing of activity to fit with policy or agency timetables.	Low	Reduction in impact and fit with policy requirements.	The ITGF has prioritised key policy areas and has a rolling 2 year time window that allows subsequent re-prioritisation. Effective structures of intelligence will be maintained through CREW, SRP and RD steering groups for co-construction of research aims and impact (see KE section).	WP Coord-inator / RD leaders
Lack of control on Deliverable reporting.	Low	Ineffective communication of outputs leading to lack of awareness and eventually affecting impact.	Formally report key results as they become available rather than to annual schedule (e.g. using electronic systems such as Research Fish/MRP internal systems. Adopt a variety of timely dissemination techniques in the KE plan using tried and tested structures (e.g. CREW).	Theme / WP Coord-inator

3. Impact and KE

3.1. A KE structure to enable impact

Our overall KE strategy is to (i) identify audiences, (ii), raise impact through simple and clear communication and translation of research activities and outputs, and (iii) foster genuine co-construction. To maximise use of existing, consolidated structures (CREW), new initiatives (CKEI) and collective WP- to theme- level outputs; the strategy uses a tiered approach (Fig. 3).

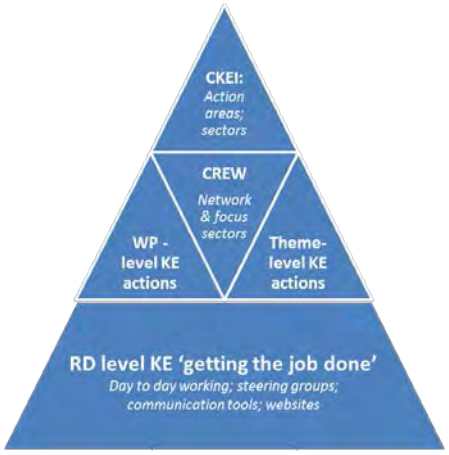


Figure 3. Overall KE structures for 1.2.

RD level KE: KE at the RD level forms the fundamental basis of the relationships; this is about familiarity and trust that enables getting the job done. The RD level KE is about clarity of our messages from the research and builds on the good working relationships of individuals to form a culture of closer day to day working across the lead organisations and RD teams. Three key RD-relevant subgroupings below the level of RBMP have already been identified with SEPA (Water quality, flows and morphology) and two staff identified for each who sit between day to day practical actions and 'developers' of these areas (i.e. targeting staff best for genuine two-way co-construction of both our research and SEPA's methods). Primary mechanisms include an ability to pick up the phone between individuals, to steering groups that enable project outcomes through data access and site sharing, and improve outcomes by tailoring outputs and timings (at the 1-2 year time range). This engagement will be shaped by how both sides best assimilate the knowledge; we have been told that face to face is best (we will time these meetings according to need), but that others favour IT tools to deliver short bulletins etc. Also at this level are numerous continuous KE interactions performed by the 'experts' in the projects of farmer focus groups, project seminars, scientific networks etc. *KE ACTIONS: (1) by month 6 we will have small steering groups established to facilitate close working with organisations at the level of the engaged individuals who then feed the knowledge back to their organisations at a variety of levels; (2) develop basic (by sign-up) email update systems for stakeholders engaged at (sub)RD levels; (3) continue regular project KE interactions led by researchers across disciplines.*

CoE-enabled KE: CREW is central to the RD-WP-Theme KE approach via informing the SRP longer-term goals on the basis of shorter-term R&D prioritisation across the four priority themes (Sustainable Rural Communities, River Basin Management Planning, Drinking Water, Flood Risk Management and Coastal Erosion), reviews and synthesis projects. This will cover wider than the water environment, across soil, biodiversity and community issues; bring Theme-integration benefits. The 2011-16 RESAS programme has shown, via numerous joint reporting narratives, that SRP supports, in return, CREW's ability for call down. The new proposal is to use CREW mediated dissemination (e.g. via web and access to policy user groups) as a 'shop window' for the SRP. This is efficient since SRP staff are involved in CREW research and across the four priority themes, meetings are taking place with key audiences and structures such as CREW's website and interactions with HEIs, Hydro-Nation scholars and the Hydro-Nation Agenda. CREW also gives valuable advice on clarity of message and approaches for different stakeholders. *KE Actions: (4) to work with the CREW team to develop opportunities and processes for raising stakeholder awareness of SRP messages, and connections between SRP and call-down abilities and dissemination via CREW priority theme meetings (aiming to attend one each priority area annually); also (5) increase interactions of SRP staff with CREW projects and stakeholders as part of training in good science communication (with the CKEI).* There is also potential to grow delivery to the CoE EPIC with the involvement of the MRI in the WP1.2..

WP to Theme KE: This seeks for stronger, clear messages across (i) RD outputs at WP level, and (ii) across Theme 1 where collective outputs have stronger messages for managing natural assets (see, for example, Fig. 1). There are a number of integrative aspects to this, including: combining messages at major meetings (e.g. SRuC-SEPA bi-annual conference) and coordinating practitioner/community engagement in research catchments. As part of clear messaging of 'what, why, for whom and when' from the WP the deliverables and milestones in this tender are specific and designed mostly for project management. Hence, we see a requirement for 'mapping' of a timeline of collective outputs across our three central storylines against the policy input timelines for our key stakeholders. Additionally, the change from the 2011-16 to 2016-21 RESAS programmes presents a step change in work from the stakeholders viewpoint. *KE Actions: We will (6) plan and host a new to old programme hand-over event for key policy leads and wider stakeholders by month 6; (7) for this provide a mapping of key integrated outputs across RDs against policy input timelines, and seek to keep this 'live' in a web format.*

CKEI: We will engage with the centralised KE resource's activities by:
Activity 2: *Branding, design, corporate identity,* here the WP will be making use of central KE services and ensuring that presentational standards are adhered to, particularly emphasising the key role of the SRP directly and in support.
Activity 4: Annual campaigns, the WP will utilise its intelligence gathering structures (e.g. CREW) to provide suggestions for high impact topical storylines.
Activity 5: Annual showcase event, as we have supported collective programme events before (e.g. SEPA-SAC bi-annual conference) we will strongly support these events with detailed and synthesis contributions.
Activity 6: We will contribute ideas and scientists into the *Think Tank approach*, transferring learning from CREW's Think Tank approaches.
Activity 7: Practitioner workshops, we are developing stronger ways of working with practitioners through our Catchment Partnership working (e.g. Dee Catchment

Partnership, Tweed Forum) and will bring these close connections to community, farmers, fisheries, land and estate sectors to CKEI workshops.
Activity 8: Staff KE development, we will identify key individuals for training and link to our proposal to use CREW to assist in WP staff becoming more effective scientific communicators (WP1.2 KE Action 5).
Activity 9: Secondments, work shadowing & placements, we will suggest staff who would benefit from the close engagement with agency or policy teams. Key targets will be Scottish Water or SEPA.
Activity 10: We will seek to make best opportunity of the proposed *Responsive Fund* by seeking to align this with topical issues and co-supporting funds.

3.2. Priorities, audiences and routes for impact

Policy and water industry: The WP's priority audiences are shown against our three integrative storylines in Fig. 2 and the policy timelines (Table 2). These can be mapped onto CREW's themes and user groups (River Basin Management, Flood Risk, Drinking Water, with Sustainable Rural Communities across many issues). Implementation of the WFD through the River Basin Management Plans process has been highlighted via our consultations as the leading focal point for actions on the effectiveness of rural diffuse pollution and measures, hydromorphological restoration, flows and abstraction pressures, and toxic substances in waters. The other key actions areas are flood modelling uncertainty and measure effectiveness in Flood Risk policy and Drinking Water Resilience and Water Safety Planning. There is considerable crossover in needs for Scottish Water, SEPA and SG Environmental Quality in terms of Catchment Management aspects of diffuse pollution from agriculture, septic tanks and wastewaters, covered by major initiatives (e.g. RBMP2 and Scottish Water's Sustainable Land Management initiative) and sub-components of pesticides regulations, and Nitrate and Habitat Directives. In addition to WFD driven goals we are pursuing new agendas of sediment and pathogen impacts, and mitigation effectiveness acting across flow (high and low) and pollution management. There are strong links to CREW work already underway, with the SRP providing the fundamental understanding and evidence. *Success will be improved understanding of how best to target actions according to their interaction with attributes of the catchment that explain effectiveness and govern benefits across multiple sectors of ecological status, flood management and drinking water quality (incorporating new topical pollution concerns and interactions such as with drinking water treatment chemicals). i.e. a better understanding of why and where ecological and other benefits occur as a result of actions, informed by catchment processes, efficient monitoring and modelling.* Ultimately, this will help achieve the requirements for Good Ecological Status in surface waters by 2027 by refining future RBMP cycles.

At Theme level (ie collectively across the WPs) a policy priority is the evaluation of the current SRDP programme (CAP Pillar 2), an enhanced use of greening space (CAP Pillar 1) and knowledge for planning of future SRDPs. In WP1.2 this is directly approached through spatial targeting of novel measures (e.g. rural SuDS and riparian management) via effectiveness assessment and landscape planning designed to feed into an expected 2018 review (for SG, SNH, SEPA). *Success will be a greater effectiveness of public expenditure on SRDP (possibly extended to similar benefits requirements from Environmental Focus Areas under Pillar 1) across multiple benefits for waters, soils and biodiversity by coordination of effective measures according to nested scales of landscape planning: from catchment coordination informed by local data and community participation to regional-national priorities.*We will align the impact to these agendas with secondary agenda around

resource efficiency (Circular Economy, Sustainable Water and Wastes aspects in Hydro-Nation) and climate adaptation.

Table 3: Summary policy prioritisation timeline for key stakeholders of WP1.2 and how we intend to interact (informing the KE Action 7, above).

Policy priorities	Impact routes	Audience	Timeline	RDs			
				1	2	3	4
WFD via River Basin Management Planning	Contribution to Nitrates Directive review via modelling	SEPA, SG (EQ)	2016 (and annually)	✓	✓		
	Report on 2nd cycle wastewater discharge actions to inform 3rd cycle plan	Scottish water, SG (WI Team)	Input to Q&S study 2018			✓	
	Input to evidence on outcomes of the Diffuse Pollution Priority Catchments	SEPA Water Quality, SG (EQ)	ASAP	✓	✓	✓	✓
	Input to evidence for the outcomes of morphological restoration (Pilot Catchments strategy)	SEPA Morphology, SG (EQ: Wat Env)	2016-17	✓			
	Development of wetted area approaches for regulating downstream of abstractions.	SEPA Water Resources, SNH, SG	2018-19		✓		✓
Bathing waters and shellfish objectives	Knowledge on coastal impacts of pathogens and emerging contaminants; catchment effectiveness in downgraded bathing water areas	SG (EQ), SEPA Water Quality	2016-17	✓	✓		
SRDP development and evaluation	Evaluation of current SRDP; maintain input to guidance on measures, management and targeting; contribute to ECAF development	SG (NatRes), SNH, SEPA	Expected 2018	✓	✓	✓	✓
Flood risk management	Incorporation of improved uncertainty methods into flood modelling (especially urbanisation) and NFM effectiveness to inform SEPA/LA's Confidence Framework	SEPA, SG (EQ), Local Authorities	2017-18	✓	✓	✓	✓
Drinking Water Source and Supply Resilience	Supporting Sustainable Land Management initiative for diffuse pollution and DOC	Sc Water, SEPA, DWQR	Ongoing	✓	✓	✓	✓
	Input to more sustainable (less chemical) approaches for drinking water treatment	Sc Water, DWQR	ASAP			✓	
	Contribution to assessment of current service resilience via drinking water safety planning	Sc Water, DWQR	Before 2021			✓	

With water-related SMEs to advance innovation in technology and its delivery/governance: We have sought to develop relationships with small scale technology providers (especially those developing green infrastructure, sustainable options for waters and wastewaters). These relationships will be utilised to deliver research into practice in the proposed SRP. Examples include collaboration with SDI at international trade shows (e.g. Aquatech Amsterdam 2015) and Scotland's Water Capability Statement, with enterprise agencies SE and HIE on supporting water innovation and water research commercialisation.

With consultancies: In delivering answers to environmental problems in partnerships with consultants such as JBA (Flood Management Handbook), Envirocentre (morphological survey work) directly utilising skills developed under the SRP.

Academia: Through CREW champions in HEIs, colleagues in researcher networks and project groups. This includes high profile programs of delivery via RCUK and EU Horizon 2020 and through our traditional methods of publication in the highest impact science journals, and the training and mentoring of students.

Public science engagement: With the CKEI the wider WP team will undertake ways of translating science to public audiences. This will include working with river volunteer groups, communities, schools groups (e.g. local schools hosting weather stations) and flagship events at the Royal Highland Show, Glasgow Science Festival, Edinburgh International Science Festival, etc. Examples of social media interactions

with the public are the iDee river monitoring app, provision of message triggering live river stage flood alerts, access to webcams (river level, flood extent) and model data. *Practitioners:* Through Catchment Partnerships (the Dee and Tweed) we will undertake practical working with communities, estates and river fisheries boards. *Steering groups, platforms and committees* – within the UK on the Diffuse Pollution Management Advisory Group, The Defra Demonstration Test Catchments, Innovate UK, and at EU/International on CEN Strategic Advisory Board for Environment, Water Supply and Technology Platform, National Water Retention Measures Group.

4. Quality assurance (QA)

The MRPs for WP1.2 will adhere to the quality assurance directives outlined at the Theme level, dedicated to achieving and maintaining high standards that meet the requirements of their work and the needs of their internal and external customers, to: (1) Comply with the BBSRC/Defra/FSA/NERC Joint Code of Practice for quality assurance and the BBSRC Statement on Safeguarding Good Scientific Practice, and (2) Operate an ISO 9001:2008 Quality Management System to: Comply with the requirements of customers and official bodies; Plan and develop standard work processes by means of Standard Operating Procedures, where required; Monitor quality performance through internal and external auditing relating to the pertaining ISO standard; Outline specific quality objectives and targets; Allocate sufficient resources to achieve its quality objectives and targets within budgetary constraints; Obtain and act upon feedback from stakeholders and Scottish Government; Appoint competent personnel to co-ordinate, implement and review quality management directives; Develop competency of all staff through the provision of tailored training and the clear communication of quality assurance requirements.

5. Ethical and regulatory issues: There are no foreseeable ethical and regulatory issues in terms of use of animals, humans, human tissue(s), genetically modified organisms and/or any dangerous material or other sensitive issues which the Scottish Government needs to be aware of.

6. Contribution to the 3R's (reduction, refinement and replacement): There is no use of animals in this research.

7. Sustainable development: The MRPs for WP 1.2 have Environmental Policy Statements which affirm that they are committed to preventing pollution, adopting and promoting environmental best practice to: Regularly assess and review our environmental aspects and impacts**;** Implement operational control procedures and monitor environmental performance by management reviews, meetings and audits**;** Comply with all relevant environmental legislation and other requirements**;** Operate an environmental management system which is systematically maintained, reviewed and revised to ensure continuous improvement. Some institutes currently operate to the ISO 14001 standard**;** Set environmental objectives and target, including CO_2 emissions reduction**;** Allocate sufficient resources to achieve environmental objectives within budgetary constraints**;** Senior management within the MRPs receive advice from Environment Committees or their equivalent**;** Ensure competency through provision of training and communication.

Name of RD: 1.2.1 Water and its ecosystem functions

Research aim and key drivers: River basins support nature, human life and economies in many ways, however, problems arising from agricultural and urban land use and, increasingly, climate change pose a range of management challenges. Pressures on our catchments include organic and inorganic pollution, flow and morphology alteration, flood risk, surface and groundwater abstraction, land use change, climate variability and change, invasive species and pathogens. There is a need to understand how these pressures affect the biophysical and ecological processes within our catchments. This RD will focus on understanding how the biophysical and ecological processes within water bodies operate and contribute to the delivery of ecosystem function and health. The core of this work will provide information and knowledge that is needed to address RQ1 and the issues of change, adaptation and management which are covered in RD1.2.2 to 4.

The Water Framework Directive (WFD) requires targeted measures to improve ecological status whilst the Habitats Directive requires that SACs attain and maintain Favourable Condition. There is an ongoing need for SEPA's monitoring strategy for WFD/RBMP and strategic research to be underpinned by effective statistical methods and associated sampling and instrumentation. Coupled with this, the EU Floods Directive (FD) requires governments to adopt, where possible, a sustainable approach to flood risk management. Natural flood management (NFM) is a sustainable approach to flood risk management being adopted in the Scotland, however, there is not enough evidence for the effectiveness of the various measures to allow it to be fully utilised by practitioners. RD 1.2.1. will contribute to a number of key research areas identified by SEPA, Scottish Government and the Environment Agency and driven by legislation pertaining to the WFD, Nitrates Directive (ND), Drinking Water Directive (DWD), FD and Habitats Directive (HD). In developing this proposal we have consulted with stakeholders from the Scottish Government, SEPA, SNH, Forestry Commission, RSPB, Scottish Water and NFU Scotland and aimed to address some of their issues.

Summary of the proposal: The work proposed will address the questions (a) to what degree do nature based solutions (NBS reduce flood peaks, improve morphology, improve water quality and deliver ecological benefits locally and at the catchment scale?, and (b) can we detect change in our catchments using novel multiscale experiments? We propose two research Objectives to address these research questions. The work will develop new and innovative experiments to explore links between processes combined with existing field experiments and platforms. The insight, technology and intellectual property generated will be disseminated to the appropriate stakeholders by a package of innovative KE activities.

O1: Evidence base for catchment processes: understanding the impact of Nature Based Solutions WHY? To provide empirical evidence on the effectiveness of measures for reducing flood risk and reducing diffuse pollution. Also, there is little evidence for the ecological benefits of river restoration projects, yet a significant investment in restoration work and monitoring has been made by the Scottish Government who requires the evidence for benefit to be established. This will help to give practitioners confidence in implementing measures related to the WFD and FD. There remains one major scientific and political question: to what degree do these measures work at the catchment scale? The area of research around nature based solutions is limited: so much so that the European Commission have identified this as a key area of research in their Horizon 2020 initiative. Therefore this Objective will put Scotland and the forefront of pioneering research in Europe. This research will support the Scottish Government/SEPA-led Pilot Catchments initiative (2015-2027) by providing a detailed assessment of the ecological effects of morphological restoration, a key goal of WFD-led River Basin Management Plans.

O1.1: Establishing an evidence base for NFM and rural SuDs (including Green Infrastructure): This work will monitor and analyse water quantity and quality data relating to natural flood management and rural SuDs measures installed at contrasting scales (assessing the multiple benefits). For example, we will perform field experiments to demonstrate the utility of designer riparian buffer strips and gather evidence around the functioning of catchment based measures in the Dee and Lunan catchments. As a new work area, we will also investigate the impacts of development of the peri-urban interface around Aberdeen on the hydrological cycle (focus on diffuse pollution and green infrastructure for managing flood risk). Extending work from the current and past programmes is essential in order to sustain our long term datasets that are vital for identifying hydrological change.

O1.2: Effects of altered and restored river morphology on aquatic physical habitat and ecology: This research will support the Scottish Government/SEPA-led Pilot Catchments initiative (2015-27) by providing a detailed assessment of the ecological effects of morphological restoration, a key goal of WFD-led River Basin Management Plans. We will use existing long-term monitoring data (O1a) combined with targeted ecological studies to investigate the influence of catchment scale factors on the success of morphological restoration projects in achieving ecological improvements. This will enable measures to be targeted and combined more efficiently and effectively. We will address the following questions: What are the impacts of altered river morphology and flow states on biodiversity across channel-riparian-catchment areas? What are the most effective scales at which to approach restoration? How effective is channel restoration for improving morphology and river/riparian ecology? What are the most effective scales at which to approach restoration?

O2: Contaminants of Concern: Sediment, pathogens & emerging contaminants

WHY? Fine sediment is thought to be affecting the integrity of Scottish SACs. There is no readily available monitoring technique or standard threshold. The ability to identify critical source areas will inform RBM planning and the prioritisation of measures to meet WFD standards. This work complements work being undertaken by DEFRA in the DTCs in England and will add to the evidence base and the potential for the development of new and existing tools for monitoring both sediment sources and their ecological impacts. Pathogens are frequently associated with sediment and current knowledge of pathogens in water and the risk they pose for drinking and recreational water is limited in Scotland and Europe. This is an area of growing concern and significant impact due to high costs incurred during outbreaks with Cryptosporidium and zoonotic bacterial pathogens. The knowledge obtained in this objective is a requisite for water catchment risk analyses. Current lack of knowledge can be attributed to difficulties in detection and tracking of pathogens in catchments and water itself and to limited understanding of the correlations between sources, indicator organisms and actual pathogens.

O2.1. Fine sediments: sources, impacts and management: The fine sediment research in this RD aims to deliver evidence to SEPA on the potential sources of fine sediments and associated contaminants. The work has three work activities. a) Sediment sources. Fine sediment in streams has many sources (e.g. river banks, arable fields or forestry) and its composition of fine sediment depends on both the soil erosion, flow routing and in stream processes. This means that the composition of fine sediments in a stream may not necessarily reflect the areas identified as being at a high risk of soil erosion. This project aims to link in-stream suspended sediment to potential source areas based on its chemical characteristics. We will, compare the sources detected in stream sediments with the areas that are expected to lose top soil (based on the erosion BBN being developed in RD1.1.4) in order to build an understanding of the importance of flow routing, sediment export and bank erosion to

fine sediment dynamics within catchments. This project has synergies with O2b in that it will focus on the potential of combined microbial, mitochondrial, organic, soluble and mineral matter tracers to identify source areas and comparison with model outputs, to refine source area and flow routing understanding; incorporate findings in model development in RD1.2.2. b) Impacts. Suspended sediment affects ecology directly through visual clarity of rivers and standing waters, and leads to transportation and release of nutrient and other contaminants, impacting on downstream river and standing water ecology. Fine sediment deposition affects the ecological status of rivers and the integrity of SACs by clogging riverbed habitats; of of fine sediments in a stream may not necessarily reflect the areas identified as being at a high risk of soil erosion. This project aims to link in-stream suspended sediment to potential source areas based on its chemical characteristics. We will, compare the sources detected in stream sediments with the areas that are expected to lose top soil (based on the erosion BBN being developed in RD1.1.4) in order to build an understanding of the importance of flow routing, sediment export and bank erosion to fine sediment dynamics within catchments. This project has synergies with O2b in that it will focus on the potential of combined microbial, mitochondrial, organic, soluble and mineral matter tracers to identify source areas and comparison with model outputs, to refine source area and flow routing understanding; incorporate findings in model development in RD1.2.2. b) Impacts. Suspended sediment affects ecology directly through visual clarity of rivers and standing waters, and leads to transportation and release of nutrient and other contaminants, impacting on downstream river and standing water ecology. Fine sediment deposition affects the ecological status of rivers and the integrity of SACs by clogging riverbed habitats; this is a live issue in major Salmon rivers where *Ranunculus* beds are promoting sedimentation, affecting the integrity of the SAC and fishery. We will investigate the ecological consequences of fine sediment infiltration using a national SNH dataset on sediment condition to test a range of approaches, including a new tool (redox potential as a proxy for reduced infiltration of the riverbed). c) Management. We will advise on where to prioritise measures for reducing erosion, methods for monitoring suspended and deposited fine sediment, and contribute to the development of standards. The fine sediment research in this RD aims to deliver evidence to SEPA on the potential sources of fine sediments and associated contaminants.

O2.2. Detection of the pathogen sources, mitigation and KE demonstration. Risk analysis and classifications, including link to future risk: The overarching aim of this activity is to develop our understanding of how sources of faecal pollution, methods for source tracking and pathogen behaviour relate to each other and the regulatory context of FIO measurements. Methods will be developed to enable the recovery and concentration of protozoan parasites from water samples and faecal samples derived from livestock and wildlife. The (oo)cysts cannot be amplified *in vitro* and therefore enough have to be derived from the environmental samples to enable downstream molecular analysis. Molecular techniques will be developed and applied to enable detection, speciation and genotyping of zoonotic waterborne protozoa from environmental samples. This information will enable source apportionment of pathogens in water. These techniques will also be applied to samples obtained from marine mammals to determine the impact of pollution involving waterborne protozoa from catchments upon coastal waters. The information gained will be used alongside characterisation of FIOs to inform regulators of the risk pathogens pose in contaminating drinking waters and to inform pathogen risk assessments. Combining source apportionment and tracking studies with characterisation of FIO communities in water vs. sediment allows us to better interpret regulatory monitoring data and to understand how and where source apportionment tools can be utilised to understand

risk and identify unresolved sources of faecal pollution, linking to risk models for the drinking water and coastal water protection.

O2.3: Understanding of environmental behaviour and effect of emerging contaminants by use of passive sampling and bioassay techniques: This project aims to develop, optimise and apply novel monitoring techniques (passive sampling methods such as Polar Organic Chemical Integrative Samplers (POCIS)) providing time weighted average (TWA) concentrations, to understand the occurrence, transport and behaviour of emerging contaminants (e.g. pesticides, PPCPs and EDCs) from catchments (e.g. pesticides land application and WWTPs effluent) upon coastal waters. By developing and use of highly sensitive bioassay techniques (e.g. E-SCREEN and YES), to evaluate the oestrogenic activity of present chemicals and assess their associated risks to the aquatic environment. This project closely delivers to SEPA's chemical monitoring priorities for the period of 2015-2021 (second cycle of RBMP) to better understand the scale of the problem (e.g. risk and impact) for the new WFD's priority substances (2013/39/EU) and increase consideration of emerging contaminants in the 'watch list ' of the directive (2015/495/EU).

Key deliverables and milestones: (format: D: Deliverables/output; **M: Milestones**; KE: KE event/session; m: month. Note: first number relates to sub-objective area and roman numeral relates to activity).

Objective 1:

- D1.1i: Yearly update reports and data analysis (m12, 24, 36, 48 and 60). D1.1ii: Publication on practical recommendations and potential impact of NFM (m12). KE1.1iii: Stakeholder meetings (m12, 24, 36, 48 and 60). D1.1iv: Publication and policy advice on a NFM monitoring case study with flood data (m60)‖**M1.1v: Experiment established (m6).** D1.1vi: Publication on understanding the impact of manipulating the plant species found in a riparian buffer zone (m12). D1.1.vii: Publication on Riparian buffer strips.‖KE1.1viii: Conference presentation [peri-urban] (m13 and 36). D1.1ix: Data report on peri-urban change (m24 and 48). D1.1x: Recommendations paper on Green Infrastructure placement in peri-urban catchments (m42). D1.1xi: Assessment of impact of urbanisation in case study catchment (briefing/paper) (m60).
- KE1.2i: Stakeholder meetings. **M1.2ii(a,c,e,g,i): Years 1(a),2(c),3(e),4(g),5(i) ecological sampling at Tarland complete. M1.2ii(b,d,f,h,j): ID and analysis of Years 1(b),2(d),3(f),4(h),5(j) monitoring samples complete**. D1.2iii: Report on 'gold standard' RR monitoring methodology (m6, with CEH). D1.2iv: Publication on 'gold standard' RR monitoring methodology (m12, with CEH). D1.2v: Publication on hydraulic habitat preferences of freshwater pearl mussels and impacts of altered morphology on habitat (m12). D1.2vi: Publication summarising 6 years of geomorphic monitoring on the Logie Burn. (m24). D1.2vii: Publication reporting hydromorphology, habitat and ecology findings from the Mar Lodge monitoring project (m48). D2.1viii: Report on morphological restoration on ecology (m54). D1.2ix: Publication on initial monitoring findings from a Pilot Catchment site (m60).
- KE1i and KE1ii Organisation of, or contribution to, international conference session (m12 and 24). KE1iii contribution to Scottish flooding event (m23). KE1iv: Input to farmer events (m18).

Objective 2:

- **M2.1i: Design and meeting complete (m6). M2.1ii Complete sediment source sampling (m18).** D2.1ii: Conference paper on sediment tracing methodology (m24). **M2.1iii: Complete analysis catchment 1 (m30).** D2.1iv: Analysis report on catchment 2 (m54). D2.1v: Synthesis and recommendations report on use as a monitoring tool (m60) ‖ **M2.1vi: Developed methodology for analysis of turbidity time series (m9);** D2.1vii: Conference paper on turbidity method (m24). **M2.1viii: Data analysis**

on impact of measures on turbidity-visual clarity complete (m48). D2.1ix: Report on impact of measures on turbidity-visual clarity (m54). KE2.1x: Meeting with main stakeholders SEPA, SNH (m6). **M2.1xi: Analysis complete (m12).** D2.1xii: Report reviewing techniques for monitoring fine sediment (m12). **M2.1xiii Sites agreed (m12). M2.1ixv: Sampling undertaken and completed (m24).** D2.1xv: Report on of effects of macrophytes on fine sediment and native range for Ranunculus (with CEH) (m24). D2.1xvi: Report on sampling techniques for deposited fine sediment (m36). D2.1xvii: Paper on effects of FS on FPM populations (m48). D2.1xviii: Report on fine sediment standards (m54).

- D2.2i: Report on identification of current best practice in microbial source tracking and other source tracking methodology (m9). **M2.2ii: sampling plan complete (m12)** D2.2ii: Microbial source tracking on NWIS DNA completed & interpretation in context of land use and FIOs (m24). **M2.2iii(a) Quantification methodology established for protozoan parasites. M2.2iii (b) Established recovery & concentration methods for protozoan parasites from water.** D2.2iii: Optimised methodologies to enable the recovery, concentration, quantification and genotyping of protozoan parasites from water and faecal samples derived from livestock and wildlife (m24). D2.2iv: A qPCR assay to quantify zoonotic Cryptosporidium (m24). KE2.2v: On-farm engagement meetings to discuss minimising environmental contamination with zoonotic pathogens (m21). D2.2vi: Application of molecular typing tools to identify zoonotic protozoan parasites in faecal and environmental samples within different study catchment areas (m36). D2.2vii: Analysis of molecular epidemiology and source tracking and pathogen quantification data to contribute towards risk assessment plans for water quality and safety in key catchment areas (m48). D2.2viii: Develop strategies to mitigate against contamination of the environment and water supplies with zoonotic protozoan pathogens (m60). D2.2ix: Briefing on impact of naturalised and sediment E. coli/Fio pollutants on interpretation of regulatory sampling (m60).
- **M2.3i: Optimisation complete (m12).** D2.3i: Optimise extraction, chromatography and mass spectrometry method for emerging contaminants determination (m12). D2.3ii: Develop an effective sampling technique (passive sampler) for a set of emerging contaminants (m24). D2.3iii: Apply method in catchment monitoring and samples/data analysis (m48). D2.3iv: Conference paper on instrumental analysis of emerging contaminants (m24). D2.3v: Conference paper on passive sampling technique (m36). D2.3vi: Publication on assessment of emerging contaminants pollution, pathway and their impact on water quality (m60).

Technical approach:

O1: Evidence base for catchment processes: understanding the impact of Nature Based Solutions

O1.1: Establishing an evidence base for NFM and rural SuDs (including Green Infrastructure): There is a need to gather long term datasets from catchments undergoing mitigation in order to assess the impacts at the catchment scale. This research will, 1) build on existing (and where appropriate develop new) catchment research platforms and projects in the River Dee, Aberdeenshire (specifically the Tarland Burn, Logie Burn and the River Dee at Mar Lodge), Lunan Water, Angus and local scale measures in the Bowmont Water, Scottish Borders; 2) investigate the interactions of rural and urban hydrology (including the changing peri-urban landscape surrounding Aberdeen (in a focus research catchment), and; 3) monitor the effectiveness of existing and new novel measures at our research farms. The technical approaches specifically linked to these research sites are as follows: **Sub-activity a:** This project sets out to provide data at the local and catchment scales to investigate the role of NFM in mitigating flood risk and rural SuDs in mitigating diffuse pollution within a Scottish context. This builds upon research in the current programme

therefore developing novel long term dataset. This project will build upon three established catchment based studies in which baseline and post-intervention dataset have been collected and a range of NFM and Rural SuDs measures have been or are planned to be installed. Specific examples of the types of monitoring will include distributed measurements of water levels, flows and rainfall. At sites such as Tarland and Lunan, water quality will be addressed. The sites will act as focal points for demonstration of opportunities, barriers and benefits to land managers and policy staff in agencies, authorities and related land businesses The focus of the work will be to evaluate and establish both small and larger scale interventions that potentially result in reduced flood risk and improved water quality at the catchment scale and are advantageous to the farmer and individual enterprises. The platforms will engage and interlink with other research platforms throughout the UK (e.g. Belford, Eddleston, DTC's) and internationally (e.g. Buffertech Denmark, AgReseach, NZ). This work will provide evidence for RDs such as RD1.2.4. **Sub-activity b:** We will assess the functioning of novel measures at our research farms. Two aspects of designed/engineered riparian buffer strips will be established and evaluated at the Balruddery Centre for Sustainable Cropping (CSC) experiment. Harvest treatments will consist of material being cut at different time intervals and the biomass either being left on the site or removed. Engineered buffers with a ditch parallel to the stream will be evaluated for benefits associated with the ditch and a tree zone in terms of biomass generation, riparian habitat and the action of the root bioactive zone in mitigating nutrient runoff. We will also examine multiple benefits e.g. buffers as an NFM measure and assess the role buffers play in mitigating storm runoff and reducing flood peaks. **Sub-activity c:** We will investigate the changing peri-urban landscape surrounding Aberdeen. Aberdeen is rapidly expanding, like many cities world-wide. Many surrounding peri-urban streams are failing WFD targets owing to rural/point source diffuse pollution and morphology. Therefore we will test the hypothesis, could new modern development coupled with Green Infrastructure improve waterbody WFD status during the rural to peri-urban land change? We will monitor and analyse the spatio-temporal water quantity (which can be intrinsically linked to flood generation) and quality of urbanising catchments at contrasting scales (from a few hectares up to 10 km^2) and stages of urbanisation to characterise the integrated impacts of urbanisation and GIs on flow pathways (nature and length with respect to flood generation) and associated water quality (e.g. conductivity, pH, temperature, suspended sediment, N, P, and DOC). Furthermore, at contrasting times throughout the year (e.g. low summer and high winter flows) detailed short term monitoring will include wider water quality assessments. These data will provide information on natural catchment processes, specific GIs, and the integrated effects of these at the catchment scale. The project will develop a new hydrological system change dataset during urbanisation to enable future research on peri-urban land use change.

O1.2: Impacts of altered and restored morphology on the physical habitat and ecology: Chemical status improvements alone have often resulted in a surprising lack of ecological recovery and therefore this work investigates how status improvements depend on physical and chemical improvements combined. We will test the hypothesis: 'Improvements in habitat (channel-riparian physical heterogeneity) following river restoration can improve ecological function (and hence WFD ecological status) over 3-5 year timescales. We will make optimum use of existing (Logie Burn; River Dee at Mar Lodge) and new opportunities (Pilot Catchments or PiP restoration site) for monitoring hydromorphological change. We will study how physical habitat, morphology and ecology recover following channel restoration, by monitoring key indicators of repaired function (feeding into 1.2.3 resilience work). Potential sites include: A) the Dee Catchment Partnership restoration site at Mar Lodge, where a

section of artificial embankment was lowered to reconnect the floodplain in October 2015 and represents a rare example at this scale of river in a UK context. Macroinvertebrate, terrestrial floodplain flora and RSPB bird data will be evaluated alongside a detailed hydrological and morphological study. B) A PiP river restoration site (croy removal) on the River Dee at Banchory which already has good hydromorphic (field sediment and hydraulic measurements and reach scale 2D hydraulic model data) and ecological (pre-restoration pearl mussel distribution and habitat) data available (as part of a joint EnviroCentre/Hutton consultancy project) and - subject to permission from SNH – would form a basis for a journal paper that would explore hydraulic controls on pearl mussel habitat and the impacts of morphology pressures on habitat availability. This work will not duplicate monitoring work already being undertaken by RAFTS and SNH to evaluate the ecological response to the restoration work undertaken in August 2015. C) A new restoration site for improved morphological status and NFM benefit where, using a field-based BACI (before, after, control, impact) design we will undertake detailed geomorphic and ecological monitoring to explore the effectiveness of proposed measures. We aim to work at Tarland, a physically degraded river system which is a priority for actions to satisfy the aims of the WFD where we have a long term monitoring programme established.

Objective 2: Contaminants of Concern: sediment, pathogens and emerging contaminants

O2.1: Fine sediments: sources, impacts and management: Sources. The project will use a combination of organic tracers (concentrations and carbon isotopic signatures of n-alkanes, strontium isotopes and neutral lipids) which provide land use markers from vegetation (developed in the seedcorn project on sediment tracing) combined with FTIR and ICPMS which provide an overall chemical profile of the sediment and therefore characterises both the organic and mineral matter. The aim is to improve the identification of areas that are at high risk of being sources of sediment into the water courses (Stutter et al., 2007). Strontium analysis will also be carried out on the water samples in order to determine the mixing of waters through the river system. The data analysis will include the development of statistical methods for interpreting the spatio-temporal data obtained from the tracer experiments in collaboration with BioSS (Brewer et al., 2005) and how these data might be used to help interpret suspended sediment and turbidity data. The project will also explore the relationship between source tracking methods and the prevalence of key human and animal pathogens (e.g. VTEC E. coli, Campylobacter, MAP and Clostridium) and antimicrobial resistance (AMR) genes in raw and drinking waters across Scotland. Development of mitochondrial source tracking methodology will be validated and applied (see O2b). Impacts. Work on sediment impacts and management will included a review and assessment of existing techniques for fine sediment monitoring, including redox potential, SS, turbidity, visual clarity, sediment sampling, and sediment trapping. We will develop methods with SEPA to assess change in turbidity on a Before-After-Control-Intervention design across several sub-catchments/typologies in priority catchments where new (e.g. SRDP) measures will take place. Statistical trend analysis will use for example, Hidden Markov, Singular Spectrum Analysis, and Advanced Neural Network techniques to characterise turbidity-water quality quantity-discharge relationships to seek to identify impact of measures, alongside other drivers. We will assess with SNH datasets on sediment redox as a driver of FWPM and salmon red habitat quality in River Dee complemented by field experiments to text measurement techniques and ecological interactions e.g. with macrophytes. Management: We will advise on how to use techniques for monitoring fine sediments, working with SEPA to identify monitoring standards.

O2.2: Detection of the pathogen sources, mitigation and KE demonstration. Risk

analysis and classifications, including link to future risk: A mitochondrial DNA tracking approach developed at Hutton during the current RESAS programme will be applied to raw (and a small subset of drinking) waters across Scotland, utilising the national waters inventory DNA archive developed during the current programme alongside fresh water samples from Tarland and Kirkton. The prevalence of key human and animal pathogens including (VTEC E. coli, Campylobacter, MAP and Clostridium) and Antimicrobial resistance genes (AMR) will also be determined and relationships between source tracking methodology, existing FIO data and the above microbial contaminants will be explored. A second molecular source tracking approach will be developed by MRI based on detection, speciation and genotyping methods for zoonotic waterborne protozoa from environmental samples. To facilitate this, methods will first be developed to enable the recovery and concentration of protozoan parasites from water samples and faecal samples derived from livestock and wildlife. The (oo)cysts cannot be amplified in vitro and therefore enough have to be derived from the environmental samples to enable downstream molecular analysis. Both methods, along with the best currently available source tracking method (e.g. Bacteroidales) and FIO analyses will be applied to common test catchments (Tarland and Kirkton) to facilitate comparison of methods and also to samples from marine mammals to determine the impact of pollution involving waterborne protozoa from catchments upon coastal waters. Methods will also be applied to sediment samples from project O2a for comparison with non-biological sediment tracers. E. coli, considered the primary faecal indicator organism, can become naturalised in the environment and therefore regulatory sampling may not reflect solely faecally derived E. coli. Further, sediment provides a reservoir for FIOs and pathogens, and observation of sediment E. coli dynamics is likely to provide different pattern of abundance/persistence compared with standard water column samples. Using physiological and genetic methods to characterise E. coli isolates and source tracking approaches to identify sources of faecal material, we will evaluate the role of naturalised vs. faecal E. coli in FIO tests and the relationship between sediment associated indicators and their water column counterparts. This work will have impact in identifying alternative land management opportunities, providing indicators for monitoring soil quality and in developing sustainable farm management practices.

O2.3: Understanding of environmental behaviour and effect of emerging contaminants by use of passive sampling and bioassay techniques (Zulin Zhang [Hutton]): The experimental work within this Objective will be carried out in the existing Tarland monitoring sites (O1a) to Dee River and the sea at Aberdeen to look the environmental occurrence, pathway and impact of emerging contaminants from catchment upon coastal waters. Also this study will consider the other established monitoring platforms in the Ugie catchment, to the Inverugie and north coast at Peterhead. Emerging contaminants (e.g. PPCPs such as diclofenac and antibiotics; pesticides: metaldehyde and chlortoluron; EDCs: 17β-estradiol (E2), estrone (E1), 17α-ethinylestradiol (EE2)) will be chosen as target emerging contaminants and instrumentations such as GC-MS and LC-MS/MS will be employed and optimised to measure ECs in this work. Also environmental parameters (e.g. water DOC, salinity, POM, pH, temperature and DO etc.) will be measured accordingly for understanding their impact on the emerging contaminants behaviour from catchment upon coast. Passive sampler (POCIS) performance will be determined and optimised for their sampling rate (e.g. by using performance reference compounds (PRC)) and their selectivity for target compounds by choosing selective sorbent (e.g. Molecularly imprinted polymer (MIP)). The bioassay methods (E-SCREEN and YES) are developed by hydro-nation PhD student, which will be used in this study.

Key linkages, interdisciplinarity & collaboration: *All other RD's within WP1.2:* This RD is vital to the success of WP1.2: As stated in the tender document, RD1.2.1. *"will provide the fundamental evidence to support the following RD's in WP1.2".* As examples, the RD will provide data to modelling tools in RD1.2.2, (e.g. morphological data utilised in hydraulic modelling approaches and fine sediment data will be captured in new modelling tools). The work here will support RD1.2.3. by giving baseline information to the work on resilience. Importantly, RD1.2.4. will use the gathered evidence around measures to support new guidance tools and therefore report on the effectiveness of measures. *Theme 1 Natural Assets:* Much of the evidence collected in this RD will be utilized by other WPs in theme 1. There are strong links with the freshwater and terrestrial ecology in WP1.3 (e.g. the riparian buffers work in O1.1 and RD1.3.3/4) and between the soil water and erosion work proposed here and the work within WP1.1 (e.g. the tracer work in O2.1. linking with work in RD1.1.4, O2), in particular the work on development of a BBN for erosion risk. Overall, the evidence gathered here will be utilized by WP1.4 (for example RD1.4.1) and it is the work within WP1.4 that will connect the research across theme 1. *Wider RESAS Programme (CREW, Underpinning Capacity):* The research proposed here will link with CREW (especially with KE outputs) to help it inform Scottish Government policy teams in addressing issues around all CREW thematic areas. The RD will also make extensive use of some of the facilities provided by RESAS underpinning capacity, including plant genetic populations, field platforms including Balruddery and ECN archive and database. O2b work links with RD 3.1.3 and 2.2.6/7. There are also important linkages for the pathogens work with 2.2.6 and 3.1.3 where there is work on antimicrobial resistance (AMR) which is also included here. *Other funding bodies:* (e.g. RCUK, TSB, EU H2020, Leverhulme, Hydronation, AHDB). The RD is complementary to a number of funded projects held by the key researchers in this RD. This will bring added value through complementary and synergistic activities between the projects. For example, there are strong links with the Environment Agency work area on Working with Natural Processes and contracts with SEPA e.g. the Natural Flood Management Handbook. We will make links to the Eddleston and Belford projects.

Added scientific value: The research proposed in this RD fits the research priorities of RESAS which are aligned with those of a range of National and International funding bodies and government departments at a Scottish, UK, European and Global level. The research is complementary and well interfaced with research that occurs at a number of UK universities and institutions where we have collaborative projects. These include: CEH (China based work and COSMOS-UK), Newcastle University (e.g. work on NFM, Rural SuDs and the Demonstration test catchments programme) and University of Aberdeen (links with Peri-urban work). O2b links with Aquavalens project consortium (EU) and with St Andrews University for sediment/pathogens work. Beyond the UK, research in RD1.2.1 will integrate well with EU projects and partners through Horizon 2020. For example, a thematic area suggested in the 2016/17 H2020 calls is on NBS. Therefore project 1 aims to align itself around that thematic area (and also the EC work on NWRM). Members of the group delivering to RD1.2.1 have identified close working areas with partners in China (through RCUK based work), New Zealand (AgResearch) and India (through the flow partnership) to name a few examples. Research outcomes will provide leverage for further funds to collaborate with National and International peers.

KE, audiences and impact: KE - RD KE will integrate with Theme annual stakeholder events, assisted by the CKEI e.g. Royal Highland Show, Scottish Parliament science event evenings, Sniffer flood risk event and local catchment based events across Scotland and internationally (e.g. SNH Good Practice). Links with the

‘Flow Partnership’ ensure global outreach and to keep abreast of new concepts in catchment based approaches. Value at an international level will accrue via integration and interaction with the European Innovation Partnerships [EIPs], Natural Water Retention Measures Network (NWRM), NW Europe Diffuse pollution policy group and links will Chinese catchment management networks. KE will include press briefings and popular articles, e.g. in popular press (Scotsman, BBC) and via a YouTube channel and Twitter updates. In conjunction with RD1.2.4, a workshop on the evidence gathered will be held alongside input to specialist UK and international events. O1.1. will input to LEAF technical days and O2.2. On-farm meetings will be held to engage the livestock farming community on the management of zoonotic protozoan pathogens and minimising resultant environmental contamination. **Audience:** This work has relevance to scientific, policy, regulatory, practitioner and land management audiences. Evidence collected will enable policy and practitioners to make informed decisions on catchment management. It will help land manager confidence in measures owing to greater scientific understanding. As the work is cognate with SG policy in the areas of Climate Change and Water Management government policy teams in flood risk, diffuse pollution and ecology will also have an interest in this work. The proposed work is of high scientific quality and will contribute to global agendas on flood risk and diffuse pollution management. Promotion of SG investment in research in this area will exploit papers published in the most appropriate high impact journals, and national/international events on catchment management. Presentations will be given at relevant events: O1.1 will organise a session at a European Conference and contribute to the Scottish SAIFF NFM policy group. Scientists involved with this work will contribute to over-arching SRP KE plans and public debates (e.g. EGU), short videos, etc. In O2, joint meetings will be held with the SEPA monitoring team and input into DPMAG. **Impact:** Catchment based measures are embedded in the FD and WFD. However, many practitioners and engineers are cautious over their implementation at the catchment scale owing to the lack of evidence of effectiveness. O1 will strengthen the evidence base through catchment based monitoring and assessments, enabling Scotland to be at the forefront of this pioneering research area. We will make use of our links with catchment-based groups across Scotland, UK and internationally, Locally, meetings with e.g. the Tweed Forum and Dee Catchment partnership will be held about the outcomes from the data. We will host visits to catchment demonstration projects in conjunction with other visits. The work will give advice to the SAIFF S&F group on NFM, DPMAG and flood LAG’s. Close links will be established to the EA’s Working with Natural Processes agenda. The main policy and legislative drivers for the proposed work include WFD, Floods Directive, Land Use Strategy (2011).

RESEARCH DELIVERABLE NUMBER: 1.2.1

Work planning and timetable for Year 1 (M= Milestone; D= Deliverable; KE= KE output; R= reporting to RESAS).

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i Data analysis and site update reports Continuation of a long term evidence database for the effectiveness of measures, yearly update reports and analysis on data gathered from Hutton catchment management research platforms (Links to O1.2 covering hydrology and morphology). Note: Strong links to all activities in O1.1.												D1.1i (yr1)
O1.1ii: Publication / report development Practical recommendations and potential impact of NFM at the catchment scale (publication).										D1.1ii		
O1.1iii Stakeholder engagement/advice meeting Discuss yearly findings with key stakeholders and engage and interlink with other research platforms throughout the UK.												KE1.1iii (yr1)
O1.1v: Establishment and instrumentation of engineered buffer strips at Balruddery. ***M1.1iv. Experiment established***						M1.1v						
O1.1vi: Publication / report development Understanding the impact of manipulating the plant species found in a riparian buffer zone on the storage and movement of nutrients (N and P) to water and atmosphere (publication).												D1.1vi
O1.1vii: Publication / report development Riparian buffer strips and biodiversity: costs, benefits and future monitoring (publication).												D1.1vii
O1.2i: Stakeholder meetings. Establish links to SEPA pilots programme and stakeholder aims and expectations for RR monitoring		KE1.2i										
O1.2ii: Ecological and morphological monitoring at research sites. *M1.2ii(a): Year 1 ecological sampling at Tarland complete. M1.2ii(b): ID and analysis of Year 1 monitoring samples complete.*									M1.2iI (a)			M1.2ii (b)
O1.2iii: Development of 'gold standard' River restoration (RR) monitoring methodology, inc. review of work in other countries (with CEH).					D1.2iii							
O1.2iv: Publication / report development 'Gold standard' RR monitoring methodology, inc. review of work in other countries (with CEH) (publication)												D1.2iv
O1.2v: Publication / report development Summarising hydraulic habitat preferences of freshwater pearl mussels and impacts of altered morphology on habitat (publication).												D1.2v
O1.2x: Stakeholder meeting Annual SEPA meeting on RR monitoring progress.												KE1.2x
KE (O1.1/2) Event: "Catchment Science and Management: Nature-Based Solutions for rural and urban environments" session at European Geosciences Union General Assembly	KE1i											

2016. Agenda setting event to mark the end of the old programme and start of new. Engagement with European Science and Policy – links to similar research.												
O2.1i: Experimental design Design nested sediment tracer experiment in consultation with SEPA in a selected catchment. ***M2.1i: Design and meeting complete***						M1.2i						
O2.1x: Stakeholder meeting Meeting with main stakeholders SEPA, SNH to establish key questions re ecological impacts and monitoring of fine sediment. ***M2.1x: Meeting complete***						KE2.1 x						
O2.1vi: Develop methodology for analysis of turbidity time series ***M2.1vi: Experiment methodology completed***									M2.1vi			
O2.1xi: Analysis of SNH data on redox condition in FPM SACs												M2.1xi
O2.1xii: Experimental design Design monitoring for (deposited) fine sediment and agree sites (with CEH) ***M2.1xiii Sites agreed*** and techniques for monitoring fine sediment.												M2.1xiii D2.1xii
O2.2i: Reporting on best practice in microbial source tracking and other source tracking methodology (report).									D2.2i			
O2.2ii: Selection of methods and sampling plan for microbial experiments. ***M2.2ii sampling plan complete***												M2.2ii
O2.2iii: Optimised methods to enable the recovery, concentration, quantification and genotyping of protozoan parasites from water samples and faecal samples derived from livestock and wildlife.. ***M2.2iii(a) Quantification methodology established for protozoan parasites. M2.2iii (b) Established recovery & concentration methods for protozoan parasites from water***						M2.2iii (a)						M2.2iii (b)
O2.3i: Optimise extraction, chromatography and mass spectrometry method for emerging contaminants determination (month 12).												D2.3i
End of year reporting to RESAS (ALL OBJECTIVES)												R1

RESEARCH DELIVERABLE NUMBER: 1.2.1

Work planning and timetable for Year 2 (M= Milestone; D= Deliverable; KE= KE output; R= reporting to RESAS).

Year 2: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i Data analysis and site update reports Continuation of a long term evidence database for the effectiveness of measures, yearly update reports and analysis on data gathered from Hutton catchment management research platforms (Links to O1.2 covering hydrology and morphology). Note: Covers all activities in O1.1. ***M1.1i: yearly data collection and reporting complete.***												D1.1i (y2)
O1.1ii Stakeholder engagement/advice meeting: Discuss yearly findings with key stakeholders and engage and interlink with other research platforms throughout the UK. Also, A meeting with policy and stakeholder working group to 'health check' deliverables for years 3-5.												KE1.1 ii(yr2)
O1.1viii Presentation on peri-urban management: Presentation/poster at international conference (science and policy)	KE1.1 viii											
O1.1ix Data analysis briefing and impact of change (peri-urban): Short briefing on the evidence database from the peri-urban case study.												D1.1ix
O1.2ii: Ecological and morphological monitoring at research sites. ***M1.2ii(c): Year 2 ecological sampling at Tarland complete. M1.2ii(d): ID and analysis of Year 2 monitoring samples complete – contract.***									M1.2iii (c)			M1.2ii (d)
D1.2vi: Publication / report development Summarising 6 years of geomorphic monitoring on the Logie Burn (publication)												D1.2vi
KE (O1.1/2) Event: International conference session / participation (Science and Policy)	KE1ii											
KE (O1.1/2) Event: "Input into Sniffer Flood risk management conference" (Policy, Practitioners and Science event)											KE1iii	
KE (O1.1) Events: Input to CSC/LEAF technical days						KE1iv						
O2.1ixv: Fine sediment sampling undertaken and completed. ***M2.1ixv Sampling campaign complete***											M2.1ix v	
O2.1xv: Reporting on the effects of macrophytes on fine sediment and native range for Ranunculus (*with CEH*)												D2.1xv
O2.1ii: Analysis of the samples from the TIMS and analyse the land use markers. ***M2.1ii Complete sediment source sampling.***						M2.1ii						D2.1ii
O2.1vii: Characterisation of turbidity-water quality-discharge relationships to identify impact of measures, alongside other drivers and conference paper on turbidity method												D2.1vii
D2.2iv: Development of a qPCR assay to quantify zoonotic Cryptosporidium. ***M2.2iv(1): Generated sequence alignment***						M2.2iv						D2.2iv

of Cryptosporidium species to identify targets for qPCR development (EH).												
D2.2iii: Optimised methods to enable the recovery, concentration, quantification and genotyping of protozoan parasites from water samples and faecal samples derived from livestock and wildlife ***M2.2iii(3) Established recovery & concentration methods for protozoan parasites from faeces***						M2.2iii (3)						D2.2iii
D2.2v: On farm engagement meetings to discuss minimising environmental contamination with zoonotic pathogens										KE2.2 v		
D2.2ii: Sampling and DNA extractions. Microbial source tracking on NWIS DNA completed & interpretation in context of land use and FIOs												D2.2ii
D2.3ii Apply method in catchment and analyse data and conference paper on instrumental analysis of emerging contaminants.												D2.3ii
End of year reporting to RESAS (all objectives)												R2

Name of RD: 1.2.2. Impacts of change on water

Research aim and key drivers: RD 1.2.2 provides research to address RQ1 and RQ3 to support a range of Scottish policy priorities including:

- **Flooding** e.g. helping local authorities incorporate uncertainty into Flood Risk Management (FRM) plans; meeting the requirements of the Floods Directive (FD); and planning for the Tarland Natural Flood Management (NFM) Pilot Catchment.
- **Freshwater ecology** e.g. meeting the requirements of the Water Framework (WFD) and Habitats (HD) Directives; informing the management of Special Areas of Conservation (SACs); and providing guidance on managing flows from hydropower schemes to maximise economic and environmental benefits (as part of the next cycle of River Basin Management Planning, RBMP).
- **Water quality** e.g. providing evidence for the Nitrates Directive (ND) review; informing regulation of shellfish and bathing water protected areas; reducing water treatment costs through improved catchment management; and meeting the requirements of the Drinking Water Directive (DWD) and WFD.

The work proposed will address questions such as: What changes may take place in the future, where and why? What determines sensitivity, resilience and response to change? Can we detect change? What statistical methods are appropriate? Can we separate the effects of policy interventions from other factors? What management approaches are effective in controlling water quantity and quality at catchment scale? How might this change in the future? What are the key uncertainties and how do they affect decision making?

RD 1.2.2 will develop a range of models and data analysis tools to: (1) Characterise Scotland's present-day water resources (quantity, quality and ecology), including any existing trends, and (2) improve our understanding of how these may change in the future. The work will support WP and Theme level objectives by considering the possible effects of land use and climate change on Scotland's water resources, and by helping to define limits for the fair and sustainable use of natural assets such as water, land, energy and nutrients (e.g. nitrogen and phosphorus).

Summary of the proposal: This RD will assess the resilience of Scotland's water resources by developing, testing and applying a range of novel modelling and statistical tools. The research is divided into three primary objectives, each with several sub-objectives (*Fig. 1*).

Objective 1: Water quantity: This objective provides research to support WP level aims for improved management of both low and high flows.

O1.1: Environmental flows (Policy contact: Richard Gosling (SEPA); Time horizon: 2021): By 2021, SEPA plan to have reviewed abstractions licencing for hydropower in Scotland, aiming to address the fact that current flow regulation regimes are often neither optimal for energy generation nor for aquatic ecology. This objective will inform the review process by considering the relationship between discharge and 'wetted usable habitat', which is a function of channel geometry. The work will incorporate results from O3.1 linking wetted area to ecological response, enabling this objective to provide guidance on the cost-effectiveness of the 'wetted area approach' to flow management.

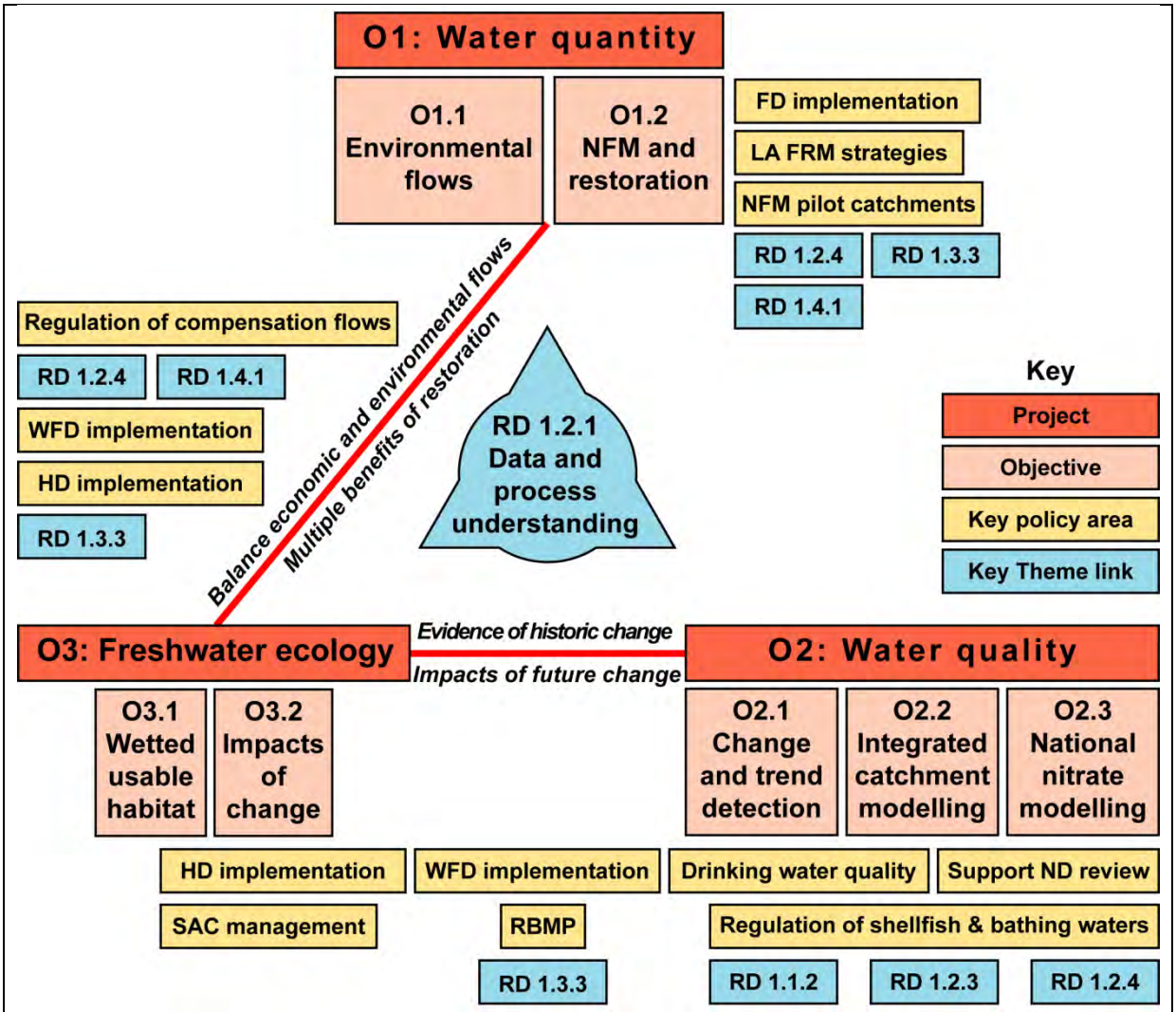


Fig. 1: Key linkages for RD 1.2.2. Abbreviations: FD, Floods Directive; FPM, Freshwater Pearl Mussel; FRM, Flood Risk Management; HD, Habitats Directive; LA, Local Authority; ND, Nitrates Directive; NFM, Natural Flood Management; O, Objective;, P, Project; RBMP, River Basin Management Planning; SAC, Special Area of Conservation; WFD, Water Framework Directive.

O1.2: Modelling of NFM and river restoration (Policy contacts: Kat Ball, Fiona McLay (SEPA); Time horizon: 2021): During the first cycle of FRM planning, local authorities will be required to develop strategies for potentially vulnerable areas, including consideration of NFM. The effectiveness of NFM measures is highly uncertain, and Government guidance recommends accounting for this in modelling assessments. This objective will support FRM planning by modelling NFM approaches to reducing flood risk in a number of data-rich catchments. Working closely with BioSS, we will characterise sources of uncertainty in model outputs, communicating key results to regulators, contractors, consultants and policy makers.
This objective will make extensive use of data gathered in RD 1.2.1. Outputs will be used to support water quality modelling in O2.2 and consideration of the ecological benefits of river restoration in O3.2.

Objective 2: Water quality: Protecting, maintaining and improving the quality of Scotland's waters are core aims of the WFD and the second cycle of RBMP. This

objective will develop improved methods for characterising historic conditions and assessing future change, and will apply these across a range of catchments to support WP level water quality objectives.

O2.1: Tools for change and trend detection (Policy contact: Brian McCreadie (SEPA); Time horizon: 2021): Understanding drivers of change and the reasons some catchments respond differently to others are key issues in achieving Good Ecological Status (GES) under the WFD. Working closely with BioSS, this objective will develop robust, novel statistical tools for change and trend detection, designed to handle the complexities and imperfections of environmental data. This objective will address questions such as (1) what change can we expect to achieve using catchment management? And (2) what monitoring programme is necessary to detect these changes? Answers are of relevance to SEPA's monitoring strategy and the second cycle of RBMP, as well as to catchment managers and industry stakeholders (e.g. Scottish Water).

O2.2: Integrated catchment modelling (Key contact: SEPA; Time horizon: 2021): Integrating plot-, field- and farm-scale knowledge to catchment level is a key research question and a priority for both SEPA and Scottish Water (SW), with implications for the WFD, HD and Shellfish & Bathing Waters Directives, as well as for the cost-effective supply of clean, safe drinking water. This objective will develop and apply a range of tools to support RBMP, including:

At plot scale: our understanding of the behaviour of phosphorus in the soil/water environment will be improved by using state-of-the-art geochemical models to simulate the filtering and buffering capacity of soils.

At catchment scale: work will address questions such as: (1) What 'family' of measures is most appropriate for a given catchment typology? (2) How does this vary for different pollutants? (3) What are the potential time lags in the system? A range of land use, climate and social & demographic change scenarios will also be used to explore questions of future resilience such as: (1) What is the risk of adverse effects in the future? (2) How does this vary between Scottish regions? (3) What is the main driver of any increased risk? (4) Can risks be reduced through land management?

This objective will inform better-targeted and more cost-effective catchment management by developing a suite of models to simulate the transport and fate of nutrients, suspended sediment, pesticides and Faecal Indicator Organisms (FIOs). Models will be calibrated and tested against baseline datasets selected to encompass a range of catchment typologies, augmented by data collected in RD 1.2.1. Outputs will support regionalisation of typologies to data-poor areas in RD 1.2.3, and results from the future simulations will also be used in the ecology and eutrophication work in O3.2, as well as in a wider assessment of integrated management in WP 1.4. Characterisation and effective communication of uncertainty will be fundamental throughout this objective, with knowledge exchange activities aimed at highlighting dominant policy-relevant uncertainties in modelling results.

O2.3: National scale nitrate modelling (Key contact: Vincent Fitzsimons (SEPA); Time horizon: 2017/18): A spatially-distributed nitrate leaching model developed during the current programme will be improved to address limitations identified during the 2013 ND review, and then applied via CREW to support the 2017 ND review. The majority of the work will take place during years 1 and 2 to keep pace with policy timelines, but further development may take place in years 3 to 5, subject to discussions with SEPA and the Scottish Government.

Objective 3: Freshwater ecology: This project will support WP level aims by contributing research on multiple stressors and ecological resilience.
O3.1: An assessment of wetted usable habitat (Key contact: SEPA; Time horizon: 2021): The aim of this objective is to link the 'wetted area' guidance from O1.1 to indicators of ecological health for key aquatic species. The work will consider the likely effects of wetted area management on ecological and morphological processes over a range of time scales, providing evidence to support SEPA's reassessment of hydropower abstractions licensing.
O3.2: Impacts of change on freshwater ecology (Key contact: SNH; Time horizon: 2021): This objective aims to identify areas most vulnerable to environmental change by considering highly sensitive indicator species. Questions to be addressed include: (1) Which future changes most threaten specially protected areas? (2) Which catchments are most vulnerable? (3) How can resilience be increased? Answers will help to better target funds and improve the management of Scotland's SACs. This objective links closely to work on environmental flows (O1.1 and O3.1) and catchment modelling (O2.2). It is also relevant to work on typologies in RD 1.2.3, research on the resilience of terrestrial ecology in RD 1.3.3 and a wider assessment of natural capital in WP 1.4.

Key deliverables and milestones*:* (format: D: Deliverables/output; **M: Milestones**; KE: KE event/session).
Objective 1:
O1.1:
KE: Workshop with SEPA to identify how best to extend existing wetted area work; D1: Guidance on pragmatic methods for linking discharge to wetted area (Nov 2017); **M1: Completion of wetted area assessment (D1); results to O3.1**; KE: Appraisal meeting to assess way-forwards on wetted area with SEPA; **M2: Guidance on the cost-effectiveness of the wetted area approach (years 3 to 5)**
O1.2:
D1: Method for estimating flow uncertainty at high river stages (report; Feb 2017); D2: Conference presentation on effectiveness of NFM measures (Jul 2017); D3: Paper on the effectiveness of NFM measures (Dec 2017); D4: Guidance on assessing & representing uncertainty in NFM modelling (years 3-5); D5: Stakeholder workshop on NFM modelling uncertainty (years 3-5); **M1: Completion of stage-discharge work (D1)**; **M2: Completion of first phase of NFM modelling work (D3)**
Objective 2:
O2.1:
KE: Review meeting to decide on study catchments; D1: Multivariate time series analysis tool (open source repository) (Sep 2018); D2: Brief describing water quality trends in study catchments (Mar 2018); D3: Report on trends in broad range of Scottish catchments (years 3-5); **M1: End of statistical tool development (D1)**
O2.2:
KE: Meeting with SW, SEPA to decide study catchments; D1: Paper on the change-point concept for soluble phosphorus leaching (Sep 2016); D2: Conference presentation on plot-scale phosphorus modelling results (Mar 2017); D3: Plot-scale results available for use in catchment-scale modelling (Mar 2017); D4: Report detailing study sites selected, rationale and data availability (Aug 2016); D5: Database for calibration and testing of water quality models (Dec 2016); D6: Publically-available catchment scale nutrient and sediment model (Mar 2018); D7:

Nutrient model presented at a conference (Mar 2018); D8: Conference presentation of pesticide model development work (Mar 2018); D9: Brief/report describing FIO model options and data availability (Mar 2018); **M1: Completion of plot-scale geochemical phosphorus sorption work (D1-3)**; **M2: Nutrient model available e.g. for KE and CREW call-down projects (D6)**; KE: Meeting with SEPA to review progress and prioritise years 3-5.; **M3: Pesticide model available e.g. for KE and CREW call-down projects (years 3-5)**; **M4: Integrated modelling of effectiveness of measures for water quality (years 3-5)**; **M5: Assess potential impacts of future change and options for mitigation (years 3-5)**

O2.3:

D1: NIRAMS III developed and emulated (Oct 2016); D2: Preliminary NIRAMS III results to support the ND review (Mar 2017); KE: Progress review meeting on N modelling with SEPA.; D3: Final modelling results for the ND review (Aug 2017); **M1: NIRAMS III available for use to support the ND review (D1, D2).**

Objective 3:

O3.1:

D1: Report describing ecological responses to wetted area management (Mar 2018); **M1: Recommendations to SEPA on efficacy of wetted area approach (years 3-5).**

O3.2:

D1: Database of FPM survey data and supporting information (Aug 2016); D2: Advisory briefs for SNH & SEPA on (1) factors influencing FPM vulnerability, and (2) the methodology for assessing risk/vulnerability for sensitive species (Mar 2018); D3: Conference presentation on FPM vulnerability (Mar 2018); **M1: Communicate results of FPM vulnerability study to SNH (D2-D3)**; KE: Progress review and year 3-5 direction with SNH; **M2: Freshwater indicators data to RD 1.4.1 (Natural Asset Inventory) (Mar 2018)**; **M3: Completed assessment of future FPM vulnerability (years 3-5)**; **M4: Completed assessment for wider range of species (years 3-5).**

Technical approach

Objective 1: Water quantity

O1.1: Environmental flows: Work on this objective will be undertaken in partnership with the Centre for Ecology and Hydrology (CEH; HEI bid 8) and will begin in year 2. By considering relationships between discharge and channel geometry, guidance will be developed for assessing the potential for effectively managing wetted habitat downstream of hydropower stations. Results will be linked to work in O3.1, focusing on how changes in wetted area may affect WFD Biological Quality Element (BQE) scores. Outputs will include a report on the likely efficacy and cost of adopting wetted area management for abstractions regulation. At the end of year 2, progress will be reviewed with SEPA and priorities identified for years 3 to 5, potentially including more detailed modelling and/or site-specific assessments.

O1.2: Modelling of NFM and river restoration: This objective will consider flooding and geomorphological change at river reach scales. Research in year 1 will focus on calibrating and evaluating the models HEC-RAS and CAESAR-LISFLOOD in several contrasting watersheds, including the River Dee (Logie Burn, Tarland Burn NFM Pilot Catchment, Mar Lodge) and the Bowmont Water. The models will be calibrated and evaluated using existing datasets together with new information gathered in RD 1.2.1. In parallel, BioSS will work to develop improved methods for constraining uncertainty in flow ratings curves, which are often subject to large errors during high flows. This work will use modern statistical methods to characterise the relationship

between river stage and flow in a way that fully accounts for uncertainty and makes minimal assumptions about the parametric form of the relationship. Outputs will provide a better understanding of the uncertainty associated with estimates of high flow, making it easier to design and select appropriate measures for the subsequent modelling work. In year 2, research will focus on designing, selecting and modelling different combinations of NFM and restoration measures in each catchment, with an emphasis on understanding the uncertainties associated with different model conceptualisations and parameterisations. The models will be used to simulate changing hydrologic regimes (e.g. travel-time to peak flow, floodplain connectivity) and morphological change in response to different measure combinations, and to explore how uncertainties in the simulated hydrograph relate to uncertainties in our knowledge and representation of particular NFM features. At the end of year 2, a meeting will be held with SEPA and local authority stakeholders to discuss progress and identify priorities for years 3 to 5. Subsequent activities are likely to include developing guidance and statistical tools to enable local authorities and consultants to incorporate practical considerations of uncertainty into their river restoration and NFM assessments.

Objective 2: Water quality

O2.1: Tools for change and trend detection: The monitoring database collated in O2.2 will be used to develop novel statistical models to extract robust, decision-quality information from large-scale, real-world datasets. During year 1, study catchments will be identified (in collaboration with SEPA) and existing methods for change and trend detection will be reviewed. In year 2, new methods will be developed, tested and applied in the selected catchments. The models under consideration belong to the class of Markov switching vector auto-regressions (MSVARs) which, when combined with techniques from compositional data analysis, are particularly well suited to environmental datasets due to their ability to account for missing data, non-normality, non-linearity, non-stationarity and long memory. Parameters for the MSVARs will be estimated using MCMC techniques to numerically integrate posterior densities. To deal with problems of non-informative prior specification and stochastic model selection, a variety of different MCMC algorithms will be implemented and compared. The new methods will be developed working closely with SEPA and catchment managers to discuss any implications for monitoring strategies and achieving WFD compliance. In years 3 to 5, the tools will be further refined and made available as an open source R package aimed at scientists, regulators and consultants. This package will also be used extensively elsewhere within the RD to support catchment modelling (O2.2) and the identification of ecological trends (O3.2).

O2.2: Integrated catchment modelling: In year 1 we will collate and quality-assess the key datasets required for model calibration and testing. This data will then be used to underpin work across the whole RD. Catchments of interest will be chosen together with SEPA, Scottish Water and the DWQR, but will likely include: SEPA's Priority Catchments; the Harmonised Monitoring Scheme; catchments upstream of bathing or shellfish protected areas; areas of interest for drinking water quality (e.g. Ugie and Lintrathen); and long-standing Hutton study catchments such as Tarland and Lunan.

Also in year 1, plot-scale phosphorus modelling will aim to better characterise sorption reactions in soils, with implications for work on soil resilience in RD 1.1.2 and soil nutrient requirements in RD 2.3.4. For a given soil phosphorus content, the degree of phosphorus adsorption can change by several orders of magnitude,

according to factors such as pH, ionic strength and the presence of iron, calcium and organic matter. Analytical techniques such as x-ray diffraction and fluorescence will be combined with geochemical models such as CD-MUSIC to simulate the surface complexation and soil-solution partitioning of phosphorus for a broad range of soil properties. Also linked to this work, catchment scale nutrient modelling will take place using a process-based phosphorus and sediment model developed in the current programme. This model is much simpler than other popular catchment-scale models (e.g. INCA-P, SWAT, HYPE, HSPF), yet still captures dominant modes of behaviour. Further improvements to the model will be made by incorporating results from the plot scale work and drawing on data and knowledge collected in RD 1.2.1.

In year 2, modelling capabilities will be extended to pesticides and FIOs. New pesticides and emerging contaminants become apparent every year, and for many we do not have sufficient data to characterise their behaviour in the environment. We therefore propose to simulate their fate by comparing their behaviour to more routinely-monitored variables with similar physicochemical properties, potentially adopting fugacity principles to simulate the partitioning of different pesticides between solid, dissolved and gaseous phases. The work will build upon existing pesticides research in the Ugie Drinking Water Protected Area. For FIOs, existing process-based and empirical tools will be identified and their suitability assessed for application in Scottish catchments. Appropriate tool(s) will then be linked to FIOs work in RD 1.2.1, integrating plot and field scale data to predict FIO loadings to areas of interest such as shellfish and bathing waters (e.g. Lunan), and exploring potential mitigation options.

All catchment scale modelling will take place within a Bayesian MCMC framework for calibration and uncertainty estimation. Models will first be evaluated against baseline data and then extended to consider a range of future scenarios in years 3 to 5. The approach taken for the scenarios work will be decided at a workshop (end of year 2), where the latest research on how to incorporate uncertain future simulations into adaptation studies will be discussed. Policy makers will be asked to assess a range of options for dealing with and communicating uncertainty in order to identify a strategy for years 3 to 5 that is both practically useful and scientifically robust.

Work in years 3 to 5 will link closely with the catchment typologies research in RD 1.2.3. Typologies will be used to extrapolate calibrated model parameter sets from data-rich to data-poor areas, thereby supporting a wider assessment of catchment resilience which will feed into WP 1.4. Consideration of DOC will also be included in years 3 to 5 via links to a NERC Macronutrient Cycles project and a RESAS Innovation submission that will explicitly consider risks posed to drinking water from DOC. By the end of the programme, it is anticipated that an improved range of modelling tools will be available to support immediate policy needs (e.g. via CREW) on topics such as catchment management for drinking water quality and protection of shellfish and bathing waters.

O2.3: National scale nitrate modelling: In year 1, the national scale Nitrogen Risk Assessment Model for Scotland (version 2; NIRAMS II) will be refined to include groundwater denitrification and the effects of protective clay layers, two issues identified as significant limitations during the 2013 ND review. Uncertainty estimation in the model will also be improved by working with BioSS to develop a Gaussian process emulator, which will be used to explore a wider set of parameter combinations than would otherwise be possible. NIRAMS III will then be used to support the 2017 ND review (delivered via CREW).

It is anticipated that preliminary model results will be required by the end of year 1,

more detailed outputs delivered early in year 2 and completed by the end of year 3.

Objective 3: Freshwater ecology

O3.1: An assessment of wetted usable habitat: Beginning in year 2, this objective will evaluate the likely response of aquatic ecology and BQE scores to possible changes in wetted usable habitat resulting from flow regulation. Additionally, the work will consider possible impacts on in-stream chemical and morphological processes over medium to long time scales. The research will be undertaken in collaboration with CEH (HEI bid 8) and will build upon an existing approach developed by SEPA for linking wetted area concepts to salmonid spawning habitat. A report describing the suitability of the wetted area approach to flow regulation will be delivered by the end of year 2 and, following discussion with SEPA, the analysis may be refined and extended in years 3-5.

O3.2: Impacts of change on freshwater ecology: Work in years 1 and 2 will make use of recent survey data for more than 100 catchments to identify variables with the potential to affect FPM populations (e.g. flow, nutrient & suspended sediment concentrations, fish populations, geology, land use, etc.). Values will be determined for each variable in each catchment through liaison with stakeholders (e.g. SNH and local fisheries), through the terrestrial ecology work in RD 1.3.3 and from baseline datasets gathered in O2.2. A spatial mixed effects model will then be developed with BioSS to identify which factors best predict FPM population status, based on extensive SNH survey datasets. This will be used to provide a current risk classification for FPMs in Scotland's SACs.

From year 3, catchment-scale modelling results from O2.2 will be used to estimate the future resilience of FPM populations under scenarios of land use, climate and social & demographic change. The methodology will also be extended to other key species (e.g. salmonids and bryophytes) by collating and incorporating additional data into the model. Towards the end of the programme, this work will provide an overall picture of SAC vulnerability from the point of view of aquatic ecology, which will contribute to an overall resilience assessment in WP 1.4.

Key linkages, interdisciplinarity & collaboration

RESAS: Data and process-understanding gained in RD 1.2.1 will support model development, testing and application in this RD. Modelling results will then link to work in RD 1.2.4 on governance and adaptation, as well as contributing to RD 1.2.3 by informing the development and regionalisation of catchment typologies and by providing simulations for case studies. More widely, the detailed geochemical modelling of phosphorus in O2.2 will support work on sustainable soil management in RD 2.3.4, while the freshwater ecology work in O3.2 forms part of a larger analysis of ecosystem resilience, linked to terrestrial ecology research in RD 1.3.3 and timed to deliver an integrated assessment at the end of year 2. Information regarding sensitive freshwater species will also be passed to RD 1.4.1, where it will be incorporated into the Natural Assets Inventory (end of year 2).

CREW & CXC: This RD will develop a range of new tools to tackle issues commonly requested through CREW, including: (1) assessing the efficacy of diffuse pollution monitoring; (2) developing indicators of changing water quality; (3) estimating effectiveness of measures; and (4) understanding how catchment management can be used to regulate water quality. This RD will also link with CREW to support the 2017 review of the ND and, from year 3, new catchment modelling tools will be available via CREW for call-down projects. The future scenarios and climate adaptation work in this RD are also relevant to work by CXC and Adaptation Scotland on indicators of change.

CEH: This RD has strong links to CEH Edinburgh (HEI bid 8), who will undertake research linking regulated hydropower discharges to the concept of 'wetted area' in O1.1, as well as supporting development of ecological indices in O3.1.

Other Funding Bodies: The aims of RD 1.2.2 are well aligned with the priorities of a range of funders, including UK research councils and the EU. The research team has an established track record of securing grant funding on topics relevant to this RD, including: model development and integration (e.g. DEFRA LM308); catchment scale water quality modelling (e.g. EU FP7 REFRESH); climate adaptation (e.g. InterregIVB WaterCAP); and NFM, river restoration & freshwater ecology (e.g. via SNH). The work undertaken will provide a strong foundation for leveraging further funding throughout the research programme.

Added Scientific Value: The topics addressed in this RD are high priorities elsewhere in the UK with, for example, ongoing DEFRA projects targeting the development of integrated modelling platforms and the NERC Macronutrient and Water Cycles programmes investigating inter-linked nutrient and carbon transport and processing. More widely, modelling of water resources under future scenarios of change has been a key aim for a number of international projects, such as EU FP7 REFRESH. However, the vast majority of existing nutrient models are arguably too complex for practical decision making, and there are still relatively few models available for FIOs and pesticides. Many catchments do not have sufficient observational data for calibrating complex hydrological and geochemical models. RD 1.2.2 will draw upon research from across the scientific community by attempting to simplify and integrate the best features of existing environmental modelling tools. The knowledge gained by training and testing these new models in data-rich catchments will then be translated elsewhere using the typologies developed in RD 1.2.3. Rather than repeating existing work, the research will focus on streamlining and extending present-day capabilities.

KE, Audiences and Impact

KE: This RD will work closely with the policy contacts named in the 'Summary' section to ensure that work is delivered on time and to specification. Initial working groups have been identified with SEPA to provide informal points of contact for issues relating to water quality, flow regulation and river morphology & restoration. More structured meetings, such as the progress reviews timetabled for the end of year 2, will be used to ensure key stakeholders are kept well informed. Two targeted workshops on uncertainty – in NFM and water quality modelling respectively – have been proposed to ensure important messages are disseminated effectively to a wider audience. Invited participants will include regulatory stakeholders (e.g. SEPA), local authority representatives, and the consultants, contractors & managers responsible for implementing catchment management plans. The RD will make full use of contacts already established through CREW, with several aspects of the work proposed (e.g. the 2017 ND review) designed to use CREW mechanisms to communicate work more widely. Selected high-level outputs from the research (e.g. guidance on uncertainty) will also be fed to the CKEI for incorporation into e.g. annual showcase events or practitioner workshops.

Models developed in this RD will be made available as open source code repositories (e.g. via CRAN or GitHub), together with supporting documentation and illustrative examples. The availability of these tools will be advertised to wider international audiences via popular online newsletters (e.g. PythonWeekly) as well as through blogs, interactive online notebooks (e.g. IPython) and dedicated 'opt-in' e-mail bulletins (as described in the WP level text). New datasets will be made

available in formats that can be hosted easily online (e.g. via SEWeb), making them more accessible to the wider public.
Practical aspects of the work will be communicated using well-established demonstration sites at e.g. Tarland and Lunan, and we will also work closely with groups such as the Dee Catchment Partnership (the manager of which is leading the ecology work in this RD) and the Tweed Forum.
Audience: Key audiences include regulators (e.g. SEPA, SG policy teams) & responsible authorities, industry stakeholders (e.g. Scottish Water, SSE), contractors, consultants, the general public (e.g. farmers affected by diffuse pollution regulations; home owners affected by flooding) and research scientists. The research team has established effective working relationships with all these groups and will use a range of methods to consult and engage them. These include involvement with steering groups such as the SEPA/SNH working group on FPM and groups co-ordinated through CREW and DPMAG, together with active farmer focus groups (e.g. Lunan), and links to industry (e.g. through British Hydrological Society meetings and conferences).
Impact: The work proposed will improve water management in Scotland by: (1) contributing to revised legislation for hydropower discharges, leading to better environmental management and more effective energy generation; (2) providing local authorities and contractors with better knowledge and tools to assess NFM and restoration options, thereby allowing better targeting of funds and more effective FRM; (3) providing evidence for the 2017 review of the ND, which has a significant impact on farmers Scotland-wide; (4) providing modelling tools to improve our understanding of what can (and cannot) be achieved through catchment management, with implications for RBMP and targets under the WFD and HD; (5) providing tools to support improved regulation of shellfish and bathing waters by simulating FIO loadings to estuarine and coastal areas; and (6) developing an evidence base for improved management of Scotland's SACs, including prioritising areas for optimal targeting of funds.
Anticipated impacts span the range of audiences identified above to be assessed based on: evidence of policy uptake and/or regulatory impacts; adoption of guidance and modelling tools by industry stakeholders; publication success in the peer-reviewed literature and at conferences; and evidence of further demand for the tools developed via CREW projects or in other research proposals.

RESEARCH DELIVERABLE NUMBER: 1.2.2

Work planning and timetable for Year 1 (M= Milestone; D= Deliverable; KE= KE output; R= reporting to RESAS).

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i: Work with SEPA to identify how best to extend existing wetted area work											KE	
O1.2i: Collate data and review existing methods for relating river level to flow												
O1.2ii: Develop a statistical methodology for estimating uncertainty in flow at high river stages. ***M1: Completion of stage-discharge work (D1).***											M1 (D1)	
O1.2iii: Model effectiveness of novel engineered features for FRM (Scottish Borders)												
O1.2iv: Modelling to explore river restoration effects on flood risk for sites on the River Dee												
O2.1.i: Decide on study catchments and review existing statistical methods for change & trend detection		KE										
O2.2i: Review change point concept for leaching of soluble phosphorus						D1						
O2.2ii: Geochemical modelling of effects of soil properties on phosphorus sorption. ***M1: Completion of plot-scale geochemical phosphorus sorption work (D1-3).***												M1 (D2, D3)
O2.2iii: Identify study sites for catchment-scale modelling (together with e.g. SEPA, SW)		KE			D4							
O2.2iv: Collate data for model setup, calibration and validation									D5			
O2.2v: Design monitoring programme to fill data gaps												
O2.3i: Refinement and emulation of national-scale nitrate model to support the 2017 ND review							D1					
O2.3ii: Apply model to simulate nitrate loadings from agricultural areas to groundwater bodies. ***M1: NIRAMS III available for use to support the ND review (D1, D2).***												M1 (D2)
O3.2i: Create database for FPM survey data from ~100 Scottish catchments (in collaboration with O2.2)					D1							

End of year reporting to RESAS (all objectives)												**R1**

RESEARCH DELIVERABLE NUMBER: 1.2.2

Work planning and timetable for Year 2 (M= Milestone; D= Deliverable; KE= KE output; R= reporting to RESAS).

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1ii: Explore applicability/cost-effectiveness of the 'wetted area' approach for different channel geometries												
O1.1iii: Produce guidance describing pragmatic methods for linking discharge to wetted area. Results to O3.1. ***M1: Completion of wetted area assessment (D1); results to O3.1.***								M1 (D1)				
O1.1iv: Review progress with Richard Gosling (SEPA) and decide priorities for years 3-5											KE	
O1.2v: Investigate NFM uncertainty in hydraulic models												
O1.2vi: Modelling work on the effectiveness of novel engineering features for reducing flood risk, with uncertainty analysis. ***M2: Completion of first phase of NFM modelling work (D3)***				D2					M2 (D3)			
O1.2vii: Review progress with Kat Ball and Fiona McLay (SEPA) and local authorities to decide priorities for years 3-5										KE		
O2.1.ii: Develop novel statistical algorithm/software for change detection and test in selected sites. ***M1: End of statistical tool development (D1)***						M1 (D1)						
O2.1iii: Apply new change detection algorithms, working with SEPA and catchment managers to discuss implications for monitoring strategies and WFD compliance												D2
O2.1iv: Review progress with Brian McCreadie (SEPA) and decide priorities for years 3-5											KE	
O2.2vi: Link plot and catchment scale phosphorus models												
O2.2vii: Extend phosphorus model to include nitrogen												
O2.2viii: Catchment-scale nutrient model tested, documented and publically-available. ***M2: Nutrient model available e.g. for KE and CREW call-down projects (D6).***											KE	M2 (D6, D7)
O2.2ix: Review existing pesticide models and pesticide usage in Scotland												

O2.2x: Refine an existing pesticide model or develop a new model (to be tested/released years 3-5)												**D8**
O2.2xi: Review existing empirical and process-based FIO models. Decide on an appropriate tool for applying in Scotland												**D9**

RESEARCH DELIVERABLE NUMBER: 1.2.2

Work planning and timetable for Year 2 (M= Milestone; D= Deliverable; KE= KE output; R= reporting to RESAS) (continued)

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O2.2xii: Review progress with Mark Hallard (SEPA) and decide priorities for years 3-5												KE
O2.3iii: Review progress with Vincent Fitzsimons (SEPA) and the Scottish Government, and refine the methodology as necessary to ensure policy needs are met. Decide whether further model development is necessary in years 3-5	KE				D3							
O3.1i: Evaluate effects of changes in wetted area on ecological and morphological indicators												
O3.1ii: Incorporate considerations of channel morphology (O1.1) to provide overall assessment of 'wetted area' approach												D1
O3.2ii: Build a spatial mixed effects model for FPM survey data												
O3.2iii: Use to identify vulnerable catchments and recommend mitigation actions. ***M1: Communicate results of FPM vulnerability study to SNH (D2-D3).***										M1 (D2, D3)		
O3.2iv: Freshwater indicators data compiled for RD 1.4.1. ***M2: Freshwater indicators data to RD 1.4.1 (Natural Asset Inventory).***												M2
O3.2v: Review progress with Iain Sime (SNH) and decide priorities for years 3-5												KE
All objectives: Workshop(s) on uncertainty in environmental modelling (water quality, quantity & flooding), including how best to carry out meaningful scenario analysis												D1 KE
End of year reporting to RESAS (all objectives)												R2

Name of RD: 1.2.3 Water environment, resilience and adaptation to change

Research aim and key drivers: *To evaluate the capacity of water resources to adapt to changing environmental and socio-economic conditions, in order to maintain key functions, goods and services (resilience).* Resilience can be defined as *"the capacity of an individual, community or system to adapt in order to sustain an acceptable level of function, structure and identity"* (Scottish Government, 2012), and not exceeding safe limits or boundaries. This RD addresses RQ2 by exploring, using case studies, (1) the concept of multiple stressors acting on a water body now and under future scenarios; (2) that the water environment provides goods and services (safe water supply, effluent disposal, lowered flood risk) without negative impact according to a level of resilience; (3) that according to the level of demand for a service and the multiple stressors acting on it, the ecosystem has a natural resilience that we can characterise and utilise in managing change. This natural resilience may be utilised as an alternative or complement to conventional management approaches. We may also need to manage this resilience with engineering (e.g. flood defence; water treatment) and accompany it with actions to enhance community resilience.

Systems-Based Approaches are used to investigate interactions of land use, climate change and the water environment, together with the role of different adaptation strategies (particularly hard vs. soft interventions) in maximising natural resilience [i.e. Ecosystem-based Adaptation]. Policy impact is provided by an integrated Risk-Based Approach to identify critical/safe levels, standards of service, and synergistic interventions in the context of the regulatory framework whilst recognising that some change is inevitable and may be beneficial. Smarter regulation necessitates making decisions which recognise the resilience of ecosystem functions whilst also acknowledging essential services provided by a catchment. RD1.2.3 recognises the role of resilience is particularly crucial in managing the impacts of climate change and other evolving risks in association with implementation of the EU Floods Directive (FD) and Water Framework Directive (WFD). The 5-year workplan is therefore designed to address important knowledge gaps pertinent to the timescales of these developing Directives.

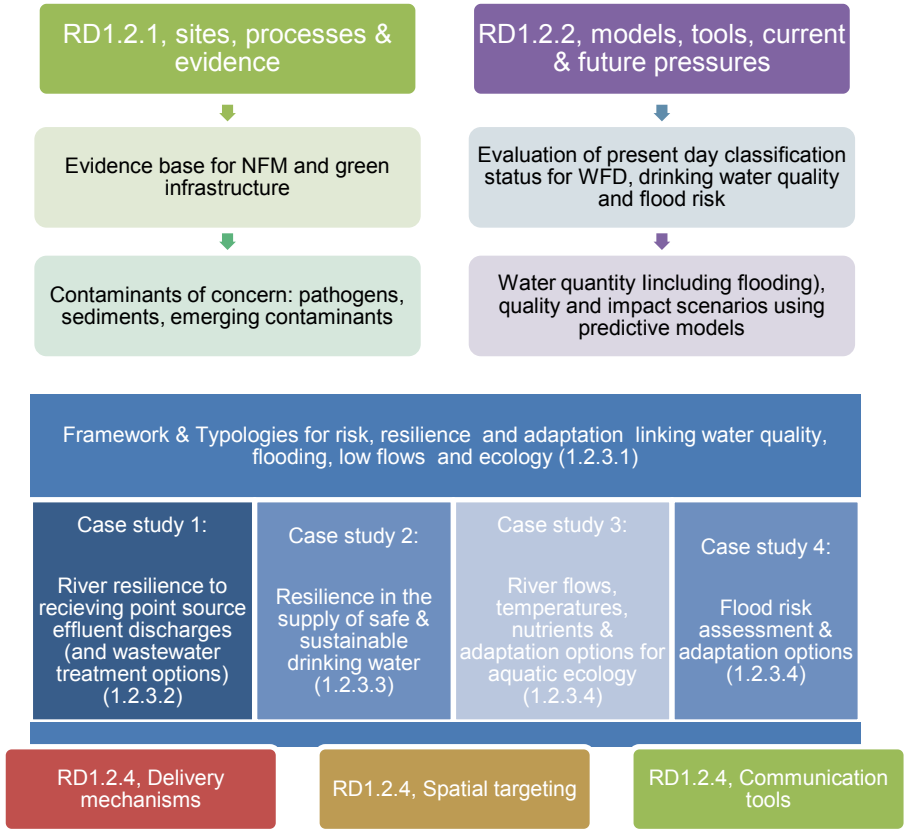
Currently, WFD action prioritisation does not directly relate to the crucial ecosystem functions that maintain goods and services to people. Establishing these relationships, and the influence of different multiple stressors on ecosystem function, is complex because of spatial/temporal variations that exist in functions and demand for services (between places and across scales, including associated costs and benefits). In addition, setting of baseline conditions and detection of long-term trends can be confounded by considerable natural variability (yearly or decadal scales). Hence, regulatory measures have often been implemented in isolation rather than maximising potential synergies for maintaining resilient functioning ecosystems. It also means that full costs and benefits of different measures have not yet been assessed across design life cycles.

Lack of knowledge on how key ecosystem functions relate to multiple stressors and drivers of change (notably climate & land use) therefore constrains effective resilience-based responses. This has implications for meeting current policy targets and prioritisation of adaptation actions to avoid future loss of function and service.

Policy Context: Further development of resilience-based approaches is recognised as a priority by the SEPA R&D strategy; by the proposed launch of a Centre for National Resilience in 2016; as a strategic issue for water supply in the Scottish

Water Business Plan; and as a key theme for sustaining the natural environment by SNH. This proposal responds to these research needs whilst also being aligned with the 6-year cycles of the WFD, FD and Habitats Directive and 5yr cycle of the Climate Change Adaptation Programme (2012-2017; 2017-2022).

Research Structure: In terms of WP1.2, RD1.2.3 integrates national and catchment-level data from key sites (RD1.2.1) with outputs from modelling tools (RD1.2.2) then feeds into approaches to improve delivery of water management and governance (RD 1.2.4). Use of risk/resilience procedures to integrate adaptive management and spatial targeting for multiple benefits links with work in WP1.4 and WP3.4. RD1.2.3 therefore provides a national and catchment-scale framework to link drivers and multiple pressures with adaptation responses through improved understanding of functional relationships together with knowledge of how they support goods and services and socio-economic priorities in catchments.



Summary of the proposal: The RD contains five objectives: an overarching systems typology framework to address the national-scale policy context and four case studies that investigate major adaptation challenges for the water environment. The integrated framework also provides a structure to show how these challenges can be better addressed together to maximise synergies.

Objective 1: Framework and catchment typologies for risk, resilience and adaptation: O1.1: Conceptual Framework: The need for a more holistic approach to water-related issues has been highlighted in a recent stakeholder report by the UK Water Partnership (Wharfe et al., 2015). Responding to this need, a working framework will be developed to assess multiple risks and opportunities across the water environment, including trade-offs and synergies between different objectives. This will provide a common systems-based structure to integrate case studies through the course of the programme using a modification of the well-known DPSIR (Drivers-Pressures-State-Impact-Responses framework (as used in setting

regulatory limits) to include relationships between functions, goods and services. Research will build upon previous work on the use of the ecosystem approach in the 2011-2016 SRP, the UK National Ecosystem Assessment (NEA), EU WISER and MARS. O1.2: Typologies: The need to evaluate resilience at national-level defines a high-level policy requirement to assess present and future risk and adaptive capacity across all catchments in Scotland, despite detailed data being available for only a few catchments. This task will address this need by grouping catchment types according to their key characteristics, current status and dominant processes, integrating both water quantity and quality assessment. Development of typologies will build upon previous work on flood risk (e.g. by CEH) and for WFD water body status but incorporating a wider assessment of hydrological sensitivity (low and high flows), temperature and water quality, including interaction of internal catchment variables with external drivers of change. This will allow the relative influence of different risk factors to be summarised at national level, notably climate and land use change. Typologies will include catchments in SEPA's Priority and Pilot catchment initiatives. Outputs will identify the more vulnerable (or resilient) catchments providing the basis for a national-level risk assessment and recommendations for adaptation responses to manage risk. The opportunity will also be taken to link the analysis with international typology initiatives (e.g. European Environment Agency).

Objective 2: Strategies for wastewater effluents: Understanding and improving river ecosystem condition as ways to increase resilience to effluent discharges compared with using novel wastewater treatment processes [Case study 1]: Despite advances in treatment, point source effluent disposal is a major pressure on river ecosystems. The sources are various from industrial, WWTW and septic tank discharges. Rivers, estuaries and coastal waters have long been considered a route to 'dispose of wastes' and this brings considerable degradation of chemical and ecological condition. There is, therefore, a need to understand and enhance resilience factors for waters receiving effluents so that key water quality downgrades for WFD and wider pathogen and drinking water safety parameters can be prioritised to tackle greatest risks first by (i) pollution source measures, (ii) ecosystem restoration measures (*O2.1*) and (iii) by improved sustainable treatment options for risk reduction *(O2.2 and O2.3).* This informs a key area of wastewater review as part of SEPA's RBMP2 strategy incorporating Scottish Water's Quality and Standards review, delivering a risk framework of wastewater interactions with resilience 'typology' factors and management options by year 3.

Objective 3: Drinking water risk and resilience [Case study 2]: Natural and managed distribution and removal of waters). Using existing data sets, system configurations and novel resilience tests, research will deliver deterioration models of assets that inform life cycle analysis and risk assessments that can be applied in Scotland and internationally. Research will also develop benchmarking criteria to gain a deeper understanding of the resilience of the Scottish Water asset base compared to international managed water systems. The research will support the strategic vision of Scottish Water to improve interconnectivity and resilience of supply as well as enhanced environmental stewardship that supports improvements to raw water quality (Scottish Water: *"Your future water and waste water services, Strategic Projections", 2013)*. Data generated in WP1.2.2 together with parallel projects on Dissolved Organic Carbon management will provide further collaborative opportunities between research partners to deliver enhanced resilience of supply.

Objective 4: River flows, temperatures, nutrients and adaptation options for aquatic ecology [Case study 3]: This work will develop resilience concepts to meet a requirement to incorporate resilience and functional attributes in definitions of Good Ecological Status for WFD. O4.1: Ecological components of aquatic ecosystems can experience multiple and interacting pressures and respond suddenly to environmental change, sometimes flipping to a new equilibrium. However, our understanding of resilience to environmental change at the individual, population or community level is poorly understood due to the difficulty in detecting ecological stability across pressure gradients at various spatio-temporal scales. A further challenge is that ecological stability is not adequately represented by current monitoring and reporting systems. In order to better understand the likely responses of ecosystems to impending environmental change it is important that both ecological stability and mechanisms of resilience be quantified. CEH (HEI bid 8) and BioSS will use long-term data, assessment of ecological stability including indicators (e.g. phytoplankton biomass, macroinvertebrate community composition, and fish) and pressures (e.g. nutrients, temperature, rainfall) to detect sudden divergences from 'normal conditions'. O4.2: Evaluating options to increase resilience to climate change in rivers and their associated ecosystems are a specific requirement of the Association of Salmon Fishery Board (ASFB), and Marine Scotland, in the development of the current and future Climate Change Adaptation Plan for Scotland. Salmon are key indicators of the health of the aquatic environment and a priority conservation species. Salmon fishing is a vital part of the Scottish economy and the impact of change needs to be understood and adaptation measures (e.g. use of riparian vegetation; proactive management of river flows) investigated to protect this iconic species into the future. Salmonids rely on timely, abundant, cold, clean water to spawn and rear young. Low flows in spring and summer result in warmer water which holds less oxygen and stresses fish. In recent years summer temperatures in the River Dee have been approaching a threshold of 27^{o}C, which, if sustained for several days, can be lethal to juvenile salmon and trout. When fish are stressed by one process, they are less able to deal with other environmental stressors and more susceptible to infection and death. Climate change (including changes in snow cover), loss of riparian tree cover and/or water abstraction can change water temperatures, particularly in summer.

Objective 5: Flood risk assessment/and adaptation options [Case study 4]: addresses the need to include changing risk factors in flood risk management strategies as required for the National Flood Risk Assessment and Climate Change Adaptation Programme. Changing risk consists of both exposure (e.g. increased rainfall) and vulnerability (e.g. built development on floodplains). Risk assessment will be developed based on the baseline typologies (Obj. 1) and specific catchments in collaboration with SEPA and other stakeholders. Risk communication will be facilitated by research on public/stakeholder attitudes, including perceptions of change and appropriate adaptation measures to manage risk. This will investigate divergent risk attitudes amongst different groups drawing upon research that suggests direct experience of extreme events can particularly influence behaviours. Use of visualisation tools for risk communication will be included to explore potential use as complements to SEPA indicative flood risk maps.

Key deliverables and milestones: (D: Deliverables; KE; **M: Milestones)**

Objective 1: KE1.1: Inception workshop to develop working groups for Objectives

(month 3); D1.1: Systems framework reported for integrated assessment of water-related risks and opportunities; D1.2: Report on Ecosystem-based Adaptation, including potential barriers/ enablers, and current adaptation measures; D1.3: Report on scenario framework (climate change and key socioeconomic drivers) with adaptation measures to be used for case studies; D1.4: Report on spatial/temporal trend analysis of seasonal flows; KE1.2: Small expert judgement workshop developing what's known and gaps on typologies data and knowledge; D1.5: Report following expert workshop (KE1.2) and data collation on ecological risk attributes leading to the attributes-pressures = functional state change matrix; D1.6.: Filter buffering index using digital soil mapping (with WP 1.1); **M1.2. Combined evidence base for available data and knowledge on typologies of catchments informing risk and resilience appraisal;** D1.7: Report on typologies and transfer functions for classifying Scottish catchments (month 20); KE1.3: Stakeholder workshop to evaluate typologies; **M1.3: Database of typologies and transfer functions available for agreement with stakeholders and consideration GIS spatial data plotting into national risk maps in years 3-4; M1.3: Integration of case studies with typologies/systems framework (month 36);** KE1.3: Final workshop, case studies & integrated framework (Report: month 56).

Objective 2: D2.1: Synthesis report on wastewater and septic tank effluent quality; D2.2: Report: mesocosm experiments resilience to wastewater inputs; **M2.1: Experimental and monitoring evidence base for effluent contaminants impacts and novel new indicators**; KE2.1: Stakeholder event for catchment selection for effluent impacts evaluation; D2.3: Mapping: effluent inputs/diffuse pollution inputs for 2 catchments; D 2.4: Reporting of improved scenarios of effluent vs diffuse pollution sources of P and ecological stressors in relation to waterbody characteristics using typologies approaches; KE2.2: Stakeholder workshop on results of weightings of source impacts on water quality downgrades; **M2.2. Completion of assessment of point source effluent role in WFD and Drinking Water downgrades in agreed subset of problem catchments;** D2.5: Matrix completion for expert judgement weightings approach (month 30); D 2.6: Wider external expert workshop, data analysis and synthesis report (month 36); **M2.3: Completed analysis of expert workshop into strategies for effluent resilience under different typologies-risk-resilience scenarios (month 36);** D2.7: Report: treatment of emerging contaminants from wastewater effluent by adsorption informing the sorbents chosen for ECs removal testing; **M2.4: Completed analysis of kinetics & mechanisms of the sorption process for ECs;** D2.8: Report: experimental effectiveness of different materials for EC removal (month 36); D2.9: Report: optimised conditions for effective removal of ECs (month 42); D2.10: Report: the extent and boundaries of the systems model approaches for optimising sustainable small-scale wastewater treatment works; **M2.5: Novel media selected for inclusion in filter bed at Dinnet; M2.6: Completion of systems model appraisal and recommendations;** D2.11: Media options appraisal report; D2.12: National risk map of typologies for susceptibility to waterbody status impairment from point source effluents (month 42); D2.13: Report on best management options for reducing wastewater derived risks to WFD compliance (and other directives) (month 48).

Objective 3: KE3.1: Stakeholder workshop to confirm work-plan and align research to Scottish Water Strategic Priorities, incl. resilience of water distribution systems; D3.1: Report on maturity of Water Safety Planning applications; D3.2: Report on Best Practice case studies of Water Safety Planning; D3.3: Reporting on application of qPCR approaches for cryptosporidium; KE3.2: First-phase

stakeholder workshop on Water Safety Planning; D3.4: Analysis of gaps in risk assessments & recommendations for improvement (including emerging risks from planned systems interconnectivity); M3.1: Completion of design of assessment tool for asset risk & resilience; **M3.2: Completion of molecular typing of genotypes in water**; KE3.3: Workshop for zoonotic protozoa risks for drinking water sources; D3.6 Summary report on key risks in the managed water system and prototype systems model for integrating risks (month 36); D3.7 Report on applying systems model to verify scalability/operability (month 48); D3.8 Final report on systems model including international comparison and validation for multiple scenarios.(month 60)

Objective 4: **M4.1: Completed collation of catchment typology/hydrology & temperature data;** D4.1: Report: exposure to lethal temperature thresholds for salmonids; D4.2: Report on stability assessment tools for case study lake (L Leven); **M4.2: Complete analysis of changes in snow-fed summer baseflows;** D4.3: Guidance note: catchment typologies at risk from temp. limits; **M4.3: Stakeholder adaptation 'opportunity mapping' workshop completed; M4.4: Complete model development for adaptation measures;** D4.4: Assessment of catchment resilience for temperature using transfer functions; D4.5: Report on spatial distribution of habitat structure and associated ecological structure/function in aquatic macrophyte communities; **M4.5: Completion of stakeholder workshop: to present and discuss outcome and discuss ways to maximise impact from this research (month 30);** D4.6: Historical stability changes: ecological response indicators/types (month 36); **M4.6: Revised model application completed to suit stakeholder needs (month 40);** D4.7: Demonstration case study: resilience based' management plan (month 48); D4.8: Catchments at risk to high temps/adaptation measures:web tool (month 44); D4.9: Guidance on national scale monitoring/intervention programmes (month 58).

Objective 5: D5.1: Evaluation of land use/ management for adapting to flood risk; D5.2: Catchment vulnerability to changing flood risk: national-level assessment linked to typologies; D5.3: Report on stakeholder flood risk perception; KE5.1: visualisation of catchment flood risk (with RD1.2.4); D5.4: National catchment flood risk assessment with changing drivers (month 36); D5.5 Case study: integrated climate change/ land-use flood risk modelling (month 48); D5.6 Evaluation of different adaptation strategies for catchment types (month 56)

Technical approach:

Objective 1: Framework and catchment typologies for risk, resilience and adaptation: O1.1: Conceptual Framework: Identification of multiple drivers of change and their relationships will be used to develop a high-level systems framework for sensitivity testing and scenario analysis. This will include socioeconomic factors (e.g. demographic) and climate change (UKCP09 projections and updates such as the High++ scenario); together with the role of these drivers in modifying land use change and existing pressures on the water sector (e.g. diffuse pollution). Cross-referencing will be made to other scenario exercises including C4C (Environment Agency), UK NEA, and IPCC. Scenario development will include reference projection of current policy and trends as Business-as-usual. In addition, time-series scenario data will be used to analyse issues of changing variability/trend, particularly relating to frequency of extreme events. Systems analysis will allow sensitivity characterisation of slow and fast variables, together with identification of feedbacks and thresholds.

O1.2. Catchment Typologies: Characterisation will include biophysical and socioeconomic data, including topography, climate, geology, soils, land use,

demographics, and recent changes. Observed climate data from the UK Met Office (available through UKCIP and BADC) will be used to analyse river flow data from the National River Flow Archive and other sources in terms of statistical detection and attribution of hydroclimatic trends (O1.2.i). Previous work has shown that relationships between precipitation and seasonal flow patterns in the UK are complex and an important knowledge gap. Scotland (particularly west Scotland) has distinctive patterns of flow related to the North Atlantic Oscillation climatic phenomena which may be amplified by catchment topography, soils or land use. Sensitivity analysis will therefore include both climate *variability* as well as climate *change*. In O1.2.ii results of the trend analysis will test hypotheses for catchment sensitivity in Scotland and inform O1.1's conceptual framework. In O1.2.iii. available physical, chemical and biological freshwater data will be screened to populate a matrix of attributes vs pressures = risks/resilience by joint Hutton/ CEH experts. Within this a specific component will investigate the filter and buffering capacity of soils using soil chemical modelling (O1.1iv). Data rich sites (research and SEPA WFD sites) will be used to improve knowledge on waterbody sensitivity, validate typologies approaches (O1.2.v; by generating appropriate transfer functions or pooling of data for similar types). The viability of different adaptation strategies, and requirements for further targeted monitoring to address key knowledge gaps will be examined. In O1.2.iii-v the HEI bid 8 facilitates expert appraisal of risks/resilience for both rivers (Hutton-led) and standing waters (CEH-led). In years 3-4 the expectation is to review the data availability, produce a knowledge/data gaps report, then to advance to spatial representation of transfer functions for combined hydroclimatic, biophysical and ecological typologies at a national level. This will be linked to the work of RD 1.1.4 on the National Soil Inventory allowing large scale digital mapping. Improved knowledge of the function of soils in water purification/regulation underpins ecosystem services such as clean water availability (link with RD1.1.1). With consultation with SEPA and Scottish Water/DWQR the knowledge and maps will be used to guide the strategies for prioritisation of wastewater regulation (O2); drinking water protection plans (O3), and to analyse the successes and limited areas of improvement in Good Ecological Status in the national Priority Catchments under the RBMP (linking to the emerging role of effluents explored in O2.1).

Objective 2: Improving river ecosystem condition and using novel wastewater treatment as strategies to increase ecosystem resilience to effluents {CS1]

O2.1. Ecosystem resilience to effluents: Due to (i) variability in effluent compositions and (ii) complex interactions between point source discharges and river conditions, relative impact of point vs. diffuse pollution sources is difficult to predict. Risk is a function of source nature/composition (concentrations, bioavailability, source delivery, cumulative inputs) and river conditions (flow, dilution, temperature, light etc). A synthesis of wastewater and septic tank data will be made initially (O2.1.i) and used to guide targeted mesocosm experiments to evaluate ecosystem processing and resilience factors and indicators (O2.1.ii). In O2.1.iii point source inputs will be mapped for selected catchments with WFD and Drinking Water protection needs and data on typologies of risk (linking to O1.2.v). Then the ecological impact procedures for phosphorus from a CREW project (Eco-P) will be evaluated in terms of the contrasting point and diffuse P source impacts in relation to waterbody typologies/risk factors (O1.2.iv) using national WFD status and cyanobateria exceedance thresholds in relation to WHO drinking water standards. P load is a planetary boundary currently being exceeded (Sayers et al, 2014). In year

3, following an expert workshop to better understand typologies-ecosystem functions-effluent pressure relationships, a national risk map and report will be generated for interactions of catchment typologies specifically for effluent risks and discussed with SEPA in light of progress on waterbodies highlighted through regulatory monitoring. This also links to be outputs of a CREW project ongoing (Eco-Phosphorus part 2). In years 4-5 it is anticipated that guidance will be developed for options of source removal (i.e. lowering consents), source treatment or ecosystem management/ restoration to identify best strategies contributing to 2027 WFD good ecological status (linking O2.1, 2.2 and 2.3).

O2.2: Novel, sustainable treatments to remove contaminants from wastewaters and increase resilience in receiving waters: The ability of current WWTW is highly variable and often inefficient to remove emerging contaminants (ECs), of which many are a significant risk to the aquatic environment and water quality. Advanced processes to address ECs have been developed but they are often expensive to produce, use and recycle and may not be applicable/sustainable in the real WWTW systems. Therefore, an assessment of low cost and effective polishing treatments (e.g. biosorbent and activated powdered glass etc.) for the removal of ECs from wastewater effluent is required. This task aims to develop novel sorbent materials with low cost, little processing and abundant-in-nature or by-product/waste materials from industry or agriculture, to be used as an efficient and cost-effective removal material for ECs. The combined WWT/Biomass production platform at Dinnet, Aberdeenshire (WP2.2: RESAS SRP 2011-2016) will be used to investigate potential of different novel constructed wetland substrates, as well as flow regimes, for removal of contaminants/ nutrients in a 'real world' situation. We will also investigate impacts of different substrates on biomass production/quality under different regimes, together with nutrient recovery from "spent" substrates.

O2.3: Novel circular systems to meet future economic:environmental challenges: This further develops current life cycle analysis work (WP2.2: RESAS SRP 2011 – 2016) to assess the economic and environmental benefits and risks of novel AD-energy crop-WWTP systems. It will use an existing economic:environmental model to identify potential assets/areas having greatest potential for AD from energy crops, both in terms of economics and carbon abatement, and where the system therefore could be most feasible; and investigate the potential contaminant leaching/balance implications associated with the system using a re-parameterised model.

Objective 3: Drinking water risk and resilience [Case study 2]: This will develop Water Safety Planning as a strategic initiative to fully understand end-to-end drinking water systems and identify key risks at any scale. Plans will be developed that inform both operational practice and capital investment choices. In Scotland many if not all of the water safety plans exist for the water systems managed by Scottish Water. Working with key stakeholders (Scottish Water, Drinking Water Quality Regulator (DWQR)) the developed plans will be embedded into day-to-day operational activity and ongoing capital investment. DWQR requires the capital investment strategy to be aligned to the risks within the safety plans. The risks considered will be both chemical (e.g. DOC and interactions with disinfection by-products), physical (eutrophication and blocking of filtration) and microbiological (pathogens) and will draw upon existing and new data (with 1.2.1 e.g. pathogens) working with Scottish Water's Sustainable Land Management catchments, recognising problem treatment works as well as private supplies (feeding into CREW's Sustainable Rural Communities initiative). In consultation, research outputs

will support delivery of Scottish Water aspirations for 100% water quality compliance by 2040 and the ambition to have a great interconnectivity within the distributions system to enhance resilience of supply and reduce the impact of “extreme events”.

Objective 4: River flows, temperatures, nutrients and adaptation options for aquatic ecology: O4.1: Spatial analyses framed within the Discontinuity Framework have been developed to identify patterns in ecological process indicators (e.g. functional distribution, species diversity, abundance, body mass, competition, predation) with the potential to regulate resilience across scales, and to identify sensitive early warning indicators of non-linear responses to environmental. These approaches will be developed and validated using available data for key species, communities and populations associated with aquatic ecosystems in Scotland. *O4.2:* will enhance understanding of how catchment typologies/hydrology influence river flows/temperature and the effectiveness of adaptation measures to reduce summer river temperatures. This understanding is critically important to resource managers who are anticipating the impacts of climate change on already limited water supplies during summer months, and land managers whose livelihoods depends on healthy salmonid stocks. We are drawing on existing collaborations with Marine Scotland, supporting the SNH-led PiP project and using SEPA/Hutton-led long term datasets around the Cairngorms National Park. This task contributes vital physical attributes into the resilience framework and links to ongoing work in NERC Macronutrient Cycles and ecological process work with CEH.

Objective 5: Flood risk assessment and adaptation options: At catchment level, risk-based exposure to extreme events (large-scale long duration rainfall; changes in snow-melt patterns; and changes in rainfall intensity) will be identified from both observational data and climate models. Data on changing exposure will be combined with land use change data (eg. urbanisation, afforestation) to assess combined risk factors associated with enhanced or reduced resilience. In combination with RD1.2.2, modelling of adaptation options (including NFM versus hard engineering schemes) will be used to assess performance under different hydroclimatic conditions. Resulting information on changes in both frequency and spatial extent of flooding will be presented to stakeholders to investigate perceptions of changing flood risk, including interactive visualisation tools to investigate attitudes and behaviours with regard to risk and adaptation options.

Key linkages, interdisciplinarity & collaboration: In addition to other RDs in WP1.2, benefits will occur through the following collaborations:

- Theme 1, particularly RD 1.1.1, RD1.1.2, RD1.1.4, RD1.4.3 & RD1.3.3
- RD2.3.4 has particularly strong links with Objective 2 of RD1.2.3/2
- WP 3.4 for resilience and adaptation (rural industries & communities).
- *Wider RESAS Programme:* Further development of the Eco-P modelling framework developed by Hutton, CEH for SEPA under a CREW project
- *Other funding bodies:* NERC Resource Recovery from Waste program (PI, M Stutter with Lancaster U); Hydro-Nation PhD studentships
- *Other collaborations:* UK Climate Change Committee, Alex Elliott (CEH), Mark Everard (UWE), EU Pearls in Peril (Iain Malcolm, Marine Scotland),Markus Hrachowitz (Delft University of Technology, TU Delft).

Added scientific value: Development of systems-based approaches for understanding resilience and adaptation in the water environment is a priority topic both within the UK and internationally. Work on typologies provides the opportunity to further develop the EU-level initiative of the European Environment Agency in a

Scottish context. Work on resilience related to flooding and water quality is highly topical both with regard to the priorities of the Scottish Government, SEPA and Scottish Water but has increased relevance in terms of knowledge exchange with Defra/Environment Agency projects and also EU or country-specific projects that are proceeding towards further implementation of the WFD and FD. Scope for enhanced collaboration exists with the Global Water Partnership (GWP), International Water Association (IWA) and Ecosystem Services Partnership. The proposed research has strong links to the UK Climate Change Risk Assessment, integrating findings from Scotland with those from elsewhere in the UK, including projects commissioned by NERC, UK Climate Change Committee, Defra and the Environment Agency, and development of LWEC climate change report cards.

KE, audiences and impact: In collaboration with the CKEI, by using targeted KE with stakeholders identified above and wider outreach activities, RD1.2.3 will evaluate key existing and emergent risks for the water sector and provide policy-based and practical recommendations to enhance resilience and support successful adaptation. Outputs have been designed to have direct policy relevance to current WFD and FD objectives and link with the Scottish Climate Change Adaptation Programme, Land Use Strategy, UK CCRA, and ongoing review of regulatory standards and Scottish Water strategic planning. Significant KE will also occur at an operational level to understand current decision strategies and opportunities to enhance resilience-based planning. Planned highlights are identified in the Deliverables list. Working groups will be developed at an inception meeting to further develop the schedule for planned outputs with stakeholders, review progress and identify new opportunities. The following measures of impact are identified:

- Uptake of scientific guidance in Scottish Water Strategic Plan/Review
- Use of results/recommendations in regulatory reviews to set appropriate risk-based standards to incorporate resilience and adaptation
- Incorporation of results into UK CCRA 3rd report 2019-2020
- Liaison and briefings for the National Resilience Centre
- Articles in stakeholder periodicals (eg. farming magazines, CIWEM, IES)
- Publication of data and findings through KE portals including SEWeb, WaterWiki
- Incorporation of findings into UK and EU activities with regard to improved KE on delivery of EU Directives, notably for WFD and FD implementation

RESEARCH DELIVERABLE NUMBER: 1.2.3

Work planning and timetable for Year 1 (M= Milestone; D= Deliverable; KE= KE output; R= reporting to RESAS)

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i. Conceptual framework: Working systems framework (modified from DPSIR) to represent drivers, pressures and responses			KE1.1									D1.1
O1.1ii.Report on Ecosystem-based Adaptation, including potential barriers in water and land use systems									D1.2			
O1.1iii: Analyse drivers of change for water environment to provide reference scenarios												D1.3
O1.2.i. Catchment typologies: Analysis of river flow data against climate trends for detection of hydroclimatic trends.												D1.4
O1.2.iii. Generation of matrix of water quality catchment attributes vs pressures and functional links to risk/resilience factors.				KE1.2					D1.5.			
O1.2.iv. Development of typologies of soil's capacity for filtering and buffering as risk factors for nutrient, sediment and pathogen delivery to waters. ***M1.2. Combined evidence base for available data and knowledge on typologies of catchments informing risk and resilience appraisal.***												D1.6 M1.2.
O2.1.i. Ecosystem resilience to effluents: Synthesis of wastewater and septic tank data to inform source apportionment modelling for contaminants and impacts from effluents relative to other land sources (e.g. agriculture).				D2.1.								
O2.1.ii. Mesocosm experiments exposing river ecosystem components (e.g. bed sediment communities) to wastewater effluents across a range of good to poor condition (ie hypothesised high to low resilience) rivers to derive risk indicators. ***M2.1. Experimental and monitoring evidence base completed for effluent contaminant impacts and novel new ecosystem indicators of impact.***												D2.2. M2.1.
O2.2i. Research on current wastewater treatment technology for emerging contaminants removal: Report on treatment of emerging contaminants from wastewater effluent by adsorption informing the sorbents chosen for ECs removal testing.							D2.7					
O2.3i. Research on the extent and boundaries of the systems model approaches for optimising sustainable small-scale wastewater treatment works, including advantages of approach and expected policy-relevant outcomes.												D2.10
O2.3ii. Research on filter media assessment for additional experimental testing bed at Dinnet wastewater treatment works. ***M2.5. Novel media selected for inclusion in filter bed at Dinnet.***												M2.5
O3.1i Research on Water Safety Planning applications		KE3.1						D3.1				

O3.1ii Best Practice case studies of Water Safety Planning											D3.2	
O3.1iii Application of qPCR for cryptosporidium											D3.3	
O 4.1i The development and validation of stability assessment tools in a case study lake (Loch Leven) for which over 40 years of ecological monitoring data is available across multiple trophic levels and pressures (e.g. temperature, nutrients, hydrology).											D4.2	
O4.2i: Evaluate catchment typology (link to O1.2) /hydrology and river temperatures data to determine the current status of summer river temperatures and potential risk to climate change. -***M4.1: Collate and analyse catchment typology/hydrology & temperature data***				M4.1								
O4.2ii: Analysis of mean maximum river temperatures in Scotland and exposure to the lethal thresholds for salmonids.							D4.1					
O4.2iii: Long term data analysis of snow-fed summer baseflows in Scotland to quantify the contribution of snow in maintaining summer base flows and cooling rivers; ***M4.2: Complete analysis of changes in snow-fed summer baseflows to feed into guidance for practitioners***									M4.2			
O4.2iv Guidance note (ASFB, Marine Scotland & SEPA) on catchment typologies at risk from temperature limits.											D4.3	
O5.1i Evaluation of land use and land management options for adapting to climate-change related flood risk linked to catchment typologies (O1.2)												D5.1
Reporting to RESAS												R1

RESEARCH DELIVERABLE NUMBER: 1.2.3

Work planning and timetable for Year 2 (M= Milestone; D= Deliverable; KE= KE output; R= reporting to RESAS)

Year 1: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.2v Catchment typologies. National map of catchment types and associated risk factors						KE1.3						D1.6
O1.2vi Report on soil inventory chemical data for filtering and buffering												D1.7
O2.1.iii. Selection of catchments with regulatory and water industry consultation of interest for WFD and Drinking Water protection, mapping of point source effluent inputs and collation of typologies data.			KE2.1			D2.3.						
O2.1.iv. Calculation of the ecological impacts of P delivery from effluents vs agricultural inputs to a subset of river and lake waterbodies, bringing the typologies procedures into the analyses already expected available on completion of the CREW Eco-P 2 project. ***M2.2. Completion of assessment of point source effluent role in WFD and Drinking Water downgrades in agreed subset of problem catchments.***											D2.4.	KE2.2 M2.2.
O2.2ii Analysis of sorption kinetics and mechanism for Emerging Contaminants: Report on the sorption process of selected sorbents for ECs. ***M2.4: Completed analysis of kinetics & mechanisms of the sorption process for ECs.***												M2.4
O2.3i. Application of systems model to selected case study wastewater treatment works. ***M2.6. Completion of systems model appraisal and recommendations***.												M2.6.
O2.3ii. Research on filter media assessment for additional experimental testing bed at Dinnet wastewater treatment works.												D2.11
O3.1 Development of risk assessment tool for Water Safety Planning including identifying gaps & recommendations. ***M3.1: Completion of design of assessment tool for asset risk & resilience***			KE3.2						D3.4			M3.1
O3.1iii Application of qPCR for cryptosporidium. ***M3.2: Completion of molecular typing of genotypes in water.***												M3.2
O4.1.v. Generation of transfer functions for catchment attributes that enable rules to generate categories of risk and resilience linked to best data evidence sources and future spatial data properties nationally in subsequent years. ***M1.3. Database of typologies and transfer functions available for agreement with stakeholders and consideration GIS spatial data plotting into national risk maps in years 3-4.***								D4.4	Work-shop M4.4			
O4.1vi Report/paper on assessment of spatial distribution of habitat structure and associated ecological structure and function in aquatic macrophyte communities [or other good spatial data set] to develop understanding of resilience											D4.4	

mechanisms operating across scales in Scottish Lochs (e.g. SNH's Site Condition Monitoring data).												
O4.2.v Appraisal of knowledge from an 'opportunity mapping' workshop with stakeholders on adaptation measures for the whole river network ***M4.3: Stakeholder adaptation 'opportunity mapping' workshop completed.***			KE M4.3									
O4.2 vi Model development & application for different adaptation measures. ***M4.4: Complete model development for adaptation measures.***										M4.4		
O5.1ii Assessment of catchment vulnerability/resilience for flood risk linked to national-scale typologies					D5.2							
O5.1iii Report on stakeholder flood risk perceptions												D5.3
O5.1iv Visualisation of catchment flood risk												KE5.1
Reporting to RESAS												R2

Name of RD: 1.2.4 Effectiveness of water management

Research aim and key drivers: This RD aims to inform policy on how to facilitate and improve instruments for integrated water management (IWM) to deliver measures that support sustainable land-based industries and communities, while ensuring resilience of aquatic natural assets and maintenance within safe limits. The 2016-2021 River Basin Management Plans (RBMP) for Scotland identifies >350 river water bodies that are not at good status due to water quality issues and >300 due to flow and water level issues. Physical condition and barriers to fish movement are each implicated in downgrading of >200 river water bodies. These individual issues, originally highlighted by the Water Framework Directive (WFD), are relevant to other policy initiatives, such as the Floods Directives (FD) and Drinking Water Directive (DWD) and need to be addressed within an IWM framework. Research is needed to improve the effectiveness, targeting, integration and delivery of IWM. This includes use of a range of established measures and economic instruments, and beyond 2020, other innovative approaches may also be relevant. Via four objectives the work answers the need of the regulators to develop tools to quantify and produce guidance on the impacts and best placement of measures that can achieve water management cost-effectively while also enhancing rural economic resilience:
Objective 1. Assesses international best practice as to how water basin management can deliver multiple benefits, to deliver insights for Scotland, particularly in how to integrate delivery of policy goals. Objective 2. Develops, monitors and evaluates integrated and innovative plans to achieve water quality and flow ecosystem service goals, in collaboration with stakeholders, across a range of case study catchments. Objective 3. Develops innovative approaches to understanding and evaluating effectiveness of integration across functional responses/benefits, guidance and governance of mitigation across scales and policy goals to improve resilience of water assets. Objective 4. Draws together current knowledge to assess the effectiveness of 'nature based solutions' to improve their design and application, and to provide tools and guidance to practitioners to facilitate uptake and implementation.

Critical problems that motivate this research are identified in the recent RBMPs. There is already information about how some measures can improve the water environment, and how these may be implemented (e.g. SEPA Natural Flood Management (NFM) handbook, new SRDP plans). However SEPA and EA have expressed a need for more robust and detailed guidance on the technical installation, costs, funding and multiple benefit assessment. Furthermore, even when the effects of measures are understood, these are not always reflected in the actions taken on the ground that affect the water environment. We need to understand better how to promote integrated delivery of these measures using existing and novel mechanisms and instruments. Identifying how to deliver multiple benefits that integrate policy goals, is particularly challenging.

Summary of the proposal:

Objective 1: Learning from international good practice to identify opportunities for integration to achieve WFD and FRM objectives: **WHY?** Building on the success of current approaches to water governance in Scotland, this objective seeks to learn lessons from international best practice, and identify opportunities for greater integration of objectives. This is delivered by two sequential activities. The first activity will assess international best practice on how water basin management can deliver multiple benefits, to deliver insights for Scotland. Conceptually grounded in the literature on environmental governance, we will identify exactly where and how

the objectives (e.g. for water quality, flood management) are negotiated and connected in practice, and the consequent implications e.g. for avoidance of un-intended side effects, effectiveness, equity and efficiency. Methods include cross-national collation and review of documentary evidence, survey and interviews with those involved in water management from selected cases within and beyond the EU. This will deliver summaries and academic analyses of international insights on governance, including literature assessment of where and how integration of different objectives currently occurs, and how un-intended side effects occur.

The second activity, in years 3-5, will focus on the level of catchments, which are often thought to be a key scale or venue at which multiple goals and interests can be best considered and integrated in order to deliver multiple benefits. It is therefore important to understand exactly when and how institutional arrangements at the catchment scale can support integrated delivery. We will characterise the history, process and outcomes of selected catchment-scale partnerships and collaborations both across Scotland (e.g. Tweed, Leven, Lunan, Dee), and beyond (both UK and internationally) to establish exactly how and when catchment-scale collaboration is able to facilitate integration and appraisal of multiple benefits. We will explore the effect of information and knowledge use, contrasting cases with more or less formal data and expertise to build on; other questions and angles will be informed by the outcome of the first activity. The analysis will be relevant to understanding institutional arrangements that support Integrated Water Management.

Objective 2: Mechanisms to deliver multiple water ecosystem services. **WHY?** Evidence of water ecosystem service benefits is needed at EU level under the Common Monitoring and Evaluation Framework and government at all levels needs to justify public spending on water management, regulation and rural payments. To meet this objective, we take a case-based approach to explore the feasibility and potential outcomes (in terms of ecosystem services) of targeted regulatory, voluntary, or market-based approaches to delivering water management goals. Measures to be considered will include SRDP/NFM/Water Environment Fund payments as well as licensing and general binding rules regulations. A framework using the Payment for Ecosystem Services (PES) paradigm (Muradian et al.,2010), will be used to assess outcomes and identify opportunities for improved benefits to be obtained. Case studies will consider both schemes where payments are in the form of government grants and incentives, and those which utilise nearer-market and community-driven approaches. Appraisal of the likely pros and cons of different approaches will focus on a small group of catchments where there is good information on trade-offs for water management and historic monitoring infrastructure.

The first activity analyses data (from SEPA's Priority Catchments) on regulation of rural diffuse pollution sources and the effects of farmer visits in changing behaviour. This will be compared with UEA-led work in the English Demonstration Test Catchments and will inform activity 2/3 and Objective 4, as well as being directly relevant to those tasked with managing the water environment (e.g. Rivers Trusts, SEPA). The second activity focuses on two catchments. In the Lunan Water (main drivers: diffuse pollution, abstraction, flooding and ecology; partner - CEH) catchment-scale plans for targeted improvements to water quality and extreme flows management will be developed, implemented, monitored and appraised, with local facilitation and stakeholder engagement and CAMERAS partners. Experience and joint workshops shared with CEH (HEI bid 8) partners in Loch/River Leven catchment (main drivers: diffuse pollution, abstraction and ecology), will enable data interpretation and comparison of catchment, river and loch-based measures. Drawing

on peatland valuation work conducted in RD 1.1.4, this activity will also involve assessing the effect of water level changes in the provision of ecosystem services from wetlands. CEH (HEI bid 8) will provide data and background information to help a PES based framework to be theoretically developed and applied. Building on this framework, the second activity, developing in years 3-5, focuses in 2-3 other catchments such as Eddlestone (main drivers: flood mitigation and ecology; partner- Univ. Dundee), River Ugie (main driver drinking water, partner, Scottish Water) and Moriston (main drivers: hydropower and ecology; partner – SEPA and electricity generators). Desk-based approaches will use available data to appraise the feasibility and impact on ecosystem services of existing and potential instruments, drawing on insights from Objective 1 and 3.

Objective 3: Assessment of the effectiveness of interventions to achieve increased effectiveness of water policy objectives*:* **WHY?** There is a strategic research need for evidence to assess and improve the effectiveness of measures and programmes to meet WFD, FD and DWD targets by 2021. Linked to this is the need for strategic research to assess the effectiveness of CAP Pillar 1 and Pillar 2 schemes and options to improve Scotland's 'water quality'. There is also a strategic research need for "Tools to prioritise and target the delivery of measures in order to improve cost effective use of public funds" for water quality and quantity.

Six activities under explore the effectiveness of measures and programmes, with a particular focus on agri-environment programmes such as CAP Pillar 1 and Pillar 2, in meeting policy goals for water and catchment management.

These aims will be delivered through six interlinked activities. Activity (a) is to co-develop with Scottish Government and CAMERAS stakeholders a 'logic chain/ model' approach to understanding the effectiveness of interventions for Scotland's water environment. Activity (b) is to develop logic chains/models based on policy objectives for Scotland's water environment to meet Water Framework Directive targets" by 2021. Activity (c) will involve co-producing the digital evidence base (based on logic chains/models) of CAP Pillar 1 and 2 effectiveness of interventions for Scotland's water environment (WFD). Activity (d) is to demonstrate application of linking evidence base of CAP Pillar 1 and 2 interventions with WFD water body objectives for SEPA WFD water body case study sites. Activity (e) is to co-develop with Scottish Water a 'logic chain/model' approach to understand the effectiveness of 'sustainable land management' interventions for drinking water quality. Activity (f) is to co-develop with Scottish Government and CAMERAS partners a 'logic chain/model' approach to understand the effectiveness of natural flood management interventions.

The outputs of this research are relevant to several policy needs. They will contribute to the evidence base of the effectiveness of land and water schemes/programmes and measures/options for Scotland's water environment including: SRDP Agri-Env Climate Scheme options i.e. regional water and soil priorities 16-20; mandatory diffuse pollution water quality policy measures (General Binding Rules); and mandatory CAP Pillar 1 basic payment schemes water quality requirements (GAEC and Greening obligations); Scottish Water's evidence base of the effectiveness of 'sustainable land management' interventions for Drinking water quality targets; and the Scottish Government evidence base on the effectiveness of natural flood management measures. The project will also develop and demonstrate an automated approach that links WFD requirements at the water body level with evidence base of CAP Pillar 1 and 2 interventions and mandatory diffuse pollution water quality measures. The overall analysis will be relevant to understanding

institutional arrangements that support Integrated Water Management.

Objective 4: Development and appraisal of guidance and spatial analysis tools to facilitate pro-active and constructive dialogue with stakeholders on effectiveness of measures for WFD and NFM: **WHY?** There is an urgent need for practical advice that is informed by evidence to guide the placement of Natural Flood Management measures in the rural landscape. This research gap has been highlighted by the Scottish Government, SEPA, SNH and an array of councils and rivers trusts. This will help to improve the delivery of FRM plans. In a work package stakeholder workshop to identify research needs this point was expressed the most mentioned by more than five organisations. This objective will make use of, and enhance, knowledge networks, to synthesise the existing knowledge regarding key mitigation measures both in the UK (e.g. Eddleston, Belford) and elsewhere, into guidance and bespoke interactive tools (e.g. GIS based, categorisation, optimisation, visualisations). These will be developed interactively with stakeholders for stakeholders (i.e. bottom up tools and guidance to help people implement measures on the ground informed with empirical evidence), and used in case studies to examine and compare how best to combine different measures in different catchments. This area delivers guidance documents (e.g. on woody debris, offline pond placement) and a GIS-based tool for spatial planning of NFM and diffuse pollution measures that disconnect flow pathways for cost-effectiveness and multiple benefits. This work will complement the NFM handbook and NWRM manual by providing more relevant technical notes and complement the Environment Agency's agenda on working with Natural Processes. Dissemination of this integrated work will be performed in close collaboration with other RDs (e.g. 1.4; 2.3.12) and will engage the relevant stakeholders through an innovative dissemination package including presentations, publications, policy briefings, technical notes, technology, demonstrations and workshops.

Key deliverables and milestones: format: D: Deliverables (numbered); M: Milestones (capital letters); first number relates to objective area; months on where after year 2.

Objective 1: **M1.A Extract lessons from international best practice and experiences of integration (m28).** D1.1: Produce brief research summary highlighting case studies across their world: incl. country, objectives, and progress to date; D1.2: Full report describing all cases analysed and our analysis of international best practice and comparison; D1.3 and KE5: Briefing on key insights for encouraging integration in water management; D1.4: Submit academic paper on international review of integration for water management (m28). **M1.B Understand how catchment-scale delivery can integrate goals for water management (m60)** D1.5: Report describing conceptual framework and consequent selection of Scottish and international cases (m30); D1.6: Full research report on results our analysis of catchment scale delivery (m48); D1.7: Report of transdisciplinary workshop on catchment-scale delivery (m52); D1.8: Academic paper on catchment-scale delivery (m60). *Objective 2:* **M2.A Complete analysis of SEPA database on catchment walks for lessons on uptake of measures;** D2.1. Report showing the efficacy of SEPA DP strategy.*KE1. Presentation summarising guidance at DTC conference***. M2.B Facilitate plans for water management and diffuse pollution measures in Lunan Water;** D2.2; Stakeholder engagement and facilitation events; D2.3 Plan describing water management and diffuse pollution measures for Lunan Water. *KE2. Plan on Rivers Trust Website for consultation and response***. M2.C Implementation of plans in collaboration with local stakeholders;** D2.4 Installation of tilting weir and operation protocols; D2.5 Installation of SRDP DP mitigation measures on Burnside sub-catchment**.** *KE3. Local stakeholder event to review installation and*

*operation of measures***.** *KE7. Presentation at Scottish Freshwater Group***. M2.D monitoring of input, output, impact and outcome of implemented plans (m 60);** D2.6-D2.9 monitoring and annual monitoring reports (ms 24-60)**.** *R1 Annual reports on project website and flagged to stakeholders (ms 12-60)***. M2.E Development and application of PES framework for analysis of measures on Lunan Water and Loch Leven catchments;** D2.10 Review and local conceptualisation of PES/other water ecosystem services approaches for Lunan Water and Loch Leven case studies, benefiting from CEH's existing experience and data; D2.11 Develop socio-bio-economic framework of measures and impacts based on PES approach in study catchments, considering in-river, in-loch and catchment based approaches, informed by stakeholder dialogue (see D2.2) and CEH experience on loch responses**;** D2.12 Ongoing collection of relevant biophysical and socio-economic data to inform PES analysis in Lunan Water and Loch Leven study catchments**;** D 2.13 Generate ecosystem service outcome analysis for Lunan Water and Loch Leven study catchments (m 30)**.** *KE 2.6. Presentation at SRUC/SEPA conference (m 36)***.** *KE 2.7. Presentation to SG re comparison of PES analysis and societal outcomes at Loch Leven and Lunan Water (m 36)***.** *KE3 JHI and CEH to hold joint local stakeholder workshops to inform on progress and elicit feedback on measures effectiveness***. M2.F Revision and application of PES framework for eg. Eddlestone and Moriston Waters (m 60);** D 2.13 Review meeting with SG and stakeholders re. application and adaptation of water ecosystems framework to flooding and hydropower case study catchments (m 30); D 2.14 Revision of framework for PES analysis framework for flooding (Eddleston) and hydropower (Moriston) catchments (m 33)**;** D 2.15 Review and local conceptualisation of PES/other water ecosystem services approaches for case studies. (m 36); D 2.16 Collection of relevant biophysical and socio-economic data to inform PES analysis in Eddleston and Moriston study catchments (m 48). *KE 2.17 Local stakeholder workshops to inform on progress and elicit feedback on measures effectiveness (ms 30, 42 and 54)***.** *KE 2.18. Presentation to CAMERAs re comparison of PES analysis and societal outcomes at all catchments to inform next cycles of RDP and RBMP (m 48). KE 2.19. Presentation at SAC/SEPA conference (m 60)*

Objective 3: **M3.A: synthesis of effectiveness of interventions for Scotland's water environment (WFD);** D3.1: Short briefing report for Scottish Government and CAMERAS partners on logic chain/model approach to effectiveness of measures; D3.2 **and R2:** Short briefing report Scottish Government and CAMERAS partners on developing logic chains/models based on policy objectives for Scotland's water environment; D3.3: SRUC-SEPA conference abstract and poster based on logic chains/models; D3.4 and KE8**:** Stakeholder workshop with Scottish Government and CAMERAS partners (and summary); D3.5: Outline of revised approach to synthesis of evidence base based on discussion with Scottish Government and CAMERAS stakeholders; D3.6: Short draft report and database for Scottish Government and CAMERAS partners on synthesis of effectiveness of interventions for Scotland's water environment (WFD); Years 3-5. D3.7 Revised report and database for Scottish Government and CAMERAS partners on synthesis of effectiveness of interventions for Scotland's water environment (WFD) (m 30); D3.8: Draft scientific paper on development of logic chain/model approach (m 30); D3.9: Summary of justification of water body case studies (m 30)**;** D3.10: Draft report Scottish Government and CAMERAS partners on logic chains/models linking interventions with WFD water body targets for case study sites (m 36). **M3.B Completion of revised report and stakeholder feedback (m 39);** D3.11 Revised report and stakeholder feedback (m

39); D3.12 Draft web based application Scottish Government and CAMERAS partners of logic chain/models intervention effectiveness (m 54); D3.13 Draft scientific paper on application of logic chain/models (m 54)**;** D3.14 Meeting summary on co-develop approach with Scottish Water (m 30); D3.15 Draft report and database on logic chain/model effectiveness of sustainable land management incentives for Scottish Water (m 48); **M3.C Reporting to Scottish Water (m 54);** D3.16 Meeting summary on co-develop approach with Scottish Government and CAMERAS partners on effectiveness of natural flood management options (m 30);D3.17 Draft report and database for Scottish Government and CAMERAS partners (m 48)**;** D3.18 Report and database (m 54).R2. Report on logic chains to SG.

Objective 4: **M4.A: Collate evidence on placement of selected measures rules and cost-effectiveness of measures;** D4.1: reporting on existing GIS tools and required data and developing outline of guidance for selected measures. KE4: Expert Stakeholder workshop; D4.2 and KE9: Conceptual GIS tool demonstrated to stakeholders; D4.3: Produce technical factsheets on selected measures (linked with RD1.2.1); Years 3-5: **M4.B: Complete refinement of GIS tool (2nd cycle) ;** D4.4 Second expert stakeholder workshop (year 3) D4.5. GIS tool refinement following feedback and data evaluation (year 3). D4.6. Further refinement of factsheets and comparing to international examples (m 48). KE4.* Input into international forum on catchment management highlighting Scottish guidance reports (m60) **M4.C: Development of report cards (m60).** D4.5 and R3. Short report on report card work in other countries. D4.6 and KE10 consultation meeting with dee stakeholders on report card approach. D4.7 Expert workshop on indicators to underpin report cards (month 36, with CEH). D 4.8 pilot report card system for Dee/Tarland (month 60).

Technical approach (first 2 years):

Objective 1: Learning from international good practice: We will first confirm and establish the set of feasible and relevant cases to be studied, before collecting and comparing the evidence associated with these different cases. It is likely that evidence of how integration occurs is not always available solely from documentary evidence (e.g. high level plans) so we also plan a cross-national survey and interviews with selected implementation leads, in order to understand if and how different objectives are integrated and reconciled (particularly the objectives for flooding with those for water quality and ecological status). By learning from international best practice, we will identify opportunities for water management in Scotland to integrate across multiple objectives and avoid un-intended side-effects.

We will confirm a set of international cases of water management relevant and feasible to access and learn from: provisionally identified as all EU countries implementing the WFD and FD, as well as accessible South Africa, North America and Australian examples. These will be accompanied and informed by a literature review on delivery of multiple objectives in water management. All publically-accessible documentary evidence (e.g. basin management plans) relating to the cases will be collected for qualitative analysis using Nvivo10. An e-survey may be deployed for a simple check of some experiences of basin management. Processes that allow multiple benefits to be delivered, and side-effects to be avoided, are guided by policy but also depend on the processes across levels by which policies are interpreted and implemented, so the collection of documentary evidence will be followed by semi-structured interviews and/ a further detailed survey with those responsible for delivery of multiple objectives, in order to identify the range of opportunities whereby multiple objectives and risks of side effects may be implemented. In years 3-5 we will explore collaboration for catchment-scale delivery.

Objective 2 : Water ecosystems services case studies: Lunan Water: In year 1, research will draw on data gathered by SEPA in Scotland during their priority catchment strategy to reduce diffuse pollution and also England (Demonstration Test Catchment UEA-led work). This process has identified rural diffuse pollution sources in terms of breach of GBRs, and been followed by 1:1 visits with farmers and revisits. It has led to significant improvements in riparian management in the first round of priority catchments and merits further analysis, to explore: 1) Whether and how information and awareness raising regarding rural diffuse pollution affects land managers' behaviour in relation to mitigation measures (for example, in relation to the breaching of regulatory measures and adoption of voluntary measures) and 2) What are the factors that explain the effect of information and awareness on behavioural changes in relation to diffuse pollution. (3) the mechanisms through which different information and awareness strategies channel behavioural change in relation to the uptake of diffuse pollution measures. This will deliver to SEPA, rivers trusts and SG guidance and advice on improving implementation of water policy measures and increasing uptake of diffuse pollution measures.

In collaboration with colleagues in CEH (HEI bid 8), and WP 1.3.2, we will critically assess approaches to framing and implementing measures such as the payment for ecosystem services (PES) paradigm, and then develop a suitable framework for socio-bio-economic analysis of the water ecosystem benefits. Our main initial activity will be in the Lunan Water and River/Loch Leven catchments. These are in the second tier of diffuse pollution priority catchments and also have flooding,ecology, morphology and low flow issues. Local stakeholder engagement is strong. On the Lunan Water, action research over the five year period which will develop, implement, monitor and evaluate plans for a range of field and catchment scale water management (both quality and quantity aspects) with local facilitation. These include use of (a) 2015-21 SRDP water quality options (b) Water Environment Fund measures to manage extreme water levels and flows as well as dredging (c) formation of a community-interest company to finance, install and manage a tilting weir to control flows for multi-stakeholder benefit (d) in-loch and in-river measures identified and assessed by our CEH partners. A local facilitator for this process will be sought, eg. through the Environmental Co-operation Action Fund.

In collaboration with colleagues from CEH (Spears, May), we will also undertake a comparison of ecosystem service responses to potential and implemented measures in the two catchments, focussing on comparing costs and benefits of in-loch, in-river and catchment approaches to mitigation. Such measures tend to have different funding streams and different communities of practice, so a cross-comparison will contribute greatly to development of a more integrated approach. Key technical issues include different lags in ecological response in catchment, loch and river systems and different controls on ecology including nutrient limitation and seasonality, leading to varying stakeholder costs and benefits across the catchments.

Ongoing assessment of catchment ecosystem services provision will make use of techniques such as: (a) modelling and measurement of the flow regimes (linked to RD1.2.2); (b) monitoring of water quality (with a focus on mitigation of fine sediment linked to RD 1.2.1), wetland ecology, flood events and consumptive and non-consumptive water use; (c) spatial tools for targeting mitigation measures developed in the current RESAS programme (WP 2.3) and in Objective 4; (d) stakeholder feedback using e.g. spatial analysis/GIS tools and Q-methodology, and insights from WP 2.3.12 on farmer uptake of good practice.

In years 3-5 of the programme we will increase activity in 2-3 other catchments,

with differing key drivers, in consultation with SG, CAMERAs and other colleagues. Catchments proposed by stakeholders include: ***Eddleston Water***, Driver: flooding and ecological restoration (links to guidance on NFM measures in Objective 4 of this RD). ***River Ugie***: Driver: drinking water provision, metaldehyde contamination (links Scottish Water and monitoring in RD 1.2.1). ***River Moriston***. Driver: requirement to upgrade low flow licensing for hydro-electric scheme, to reflect ecological needs more closely. The ecosystem services framework could be applied to identifying how best to tradeoff electricity generation and ecological needs. This would be enhanced by low flow/wetted area studies on the catchment proposed in WP 1.2.2.

Objective 3: Assessment of the effectiveness of interventions to achieve increased effectiveness of water policy objectives: To provide the evidence to improve the effectiveness, targeting and delivery of policy measures, evaluate their impact, and avoid unintended side-effects upon other ecosystem services. Relevant policies include the Water Framework Directive (WFD), River Basin Management Plans (2016-2021), Drinking water quality plans and Flood Risk Management Plans. This research will co-develop, apply and test with Scottish Government and CAMERAS partners 'logic chain/ model' approach to understand the effectiveness of interventions for Scotland's water environment. Over the five years of research this will involve six main groups of related activities. The first group of activities will involve co-developing the 'logic chain/model' approach for the effectiveness of measures/options that include SRDP Agri-Env Climate options for regional water and soil priorities, mandatory diffuse pollution water quality policy measures e.g. general binding rules, and CAP Pillar 1 basic payment schemes for water quality e.g. GAEC and greening obligations). The second group of activities will develop these logic chain/models based on water body level Water Framework Directive targets for 2021. These activities will involve interaction not only with colleagues across WP1.2 and WP1.4, but also with key contacts across the UK e.g. Defra funded Demonstration Test Catchments and CEH-Glastir Monitoring and Evaluation Programme (GMEP). At the end of year one we will hold a workshop with these key partners (including colleagues from 1.4 and wider 1.2), to refine our approach to co-producing the evidence base (based on logic chains/models) of CAP Pillar 1 and 2 effectiveness of interventions for Scotland's water environment (WFD) in the third group of activities. These activities will require working closely with Scottish Government, CAMERAS partners, CREW, and UK and international synthesis initiatives. Then in years three to five we will then apply the logic chain/model approach to four representative SEPA WFD water bodies with linkages across WP1.2 and 1.4 (fourth group of activities). Once the logic chain/model approach has been developed and refined to meet WFD objectives we will apply it to Drinking water quality plans and Flood Risk Management Plans through stakeholder consultation.

Objective 4: Guidance/spatial analysis tools for effective measures. There will be two parallel parts to this objective. The first will be to collate the evidence gathered in RD1.2.1 & RD2.3.12 and from wider catchments where measures have been installed (e.g. Eddleston, Belford), to review the current state of evidence and produce a range of selected measure factsheets which highlight the technical design (where possible) of a particular measure (in a case study context), indicative costs of construction, investigate co-benefits and/or negative and examples where this measure has been successful (and in which landscapes). The sheets would examine which measures work best in combination focusing on the treatment train approach providing some case study examples .This would build upon the recently published SEPA NFM handbook and complement the EA WWNP agenda which does not have

such mechanisms. It is acknowledged that the EA/SEPA are looking to produce some guidance notes/factsheets through the EA's planned WWNP. This objective will build upon the outcomes of that project (after discussions with relevant stakeholders (m3-5) to ensure our work builds upon any gaps). The guidance fact sheets will be informed by evidence from RD1.2.1/other sites. The second component of this work is to create a bottom up bespoke spatial GIS tool to advice practitioners on where to best locate measures that disconnect flow pathways (to practically advise farmers where to put measures), the aims of this would be to develop a conceptual GIS based tool, iteratively developed with a stakeholder group, to advise on locating connectivity management measures to accrue multiple benefits.

The objective will contribute to a UK NFM network activities (and possible international). Finally, in years 3-5, a report card system will be developed based on a review existing systems. We will consult with key stakeholders to develop a system and trial it for Tarland/Dee where there is a strong multi-agency stakeholder facilitation route, then consider wider applications. We will gather stakeholder feedback and refine the tool before making it available on the web for wider feedback and consider options for an app-based tool.

Key linkages, interdisciplinarity & collaboration:
Objective 1: with institutional analysis in objective 4 being informed by conceptual links with RD1.4.2 (especially Obj1.4.2bi) and RD1.3.4 (work on biodiversity management measures within Obj. 1.1, Novo) and collaboration in 1.4.3 (Work on ECAF by Prager within Obj 1.4.3b). *Objective 2: with* 1.4.2 (Obj 1.4.2c Waylen) and 1.3.4 (obj 1.1 and 1.2 Novo) on exploring the potential of different management instruments including PES to meet different goals; visualisation and effectiveness tools in RD 1.2.4 (objective 4), RD 1.2.3 and WP 1.4 (Gimona); diffuse pollution monitoring in RD 1.2.1; analysis of trends in RD 1.2.2, with 1.1.4 on wetland valuation; catchment resilience work in RD 1.2.3; with SEPA (abstraction licensing, NFM, WFD agendas), SNH (wetland ecology) and NFUS policy agendas and collaboration with staff of these organisations in co-ordinated catchment planning and monitoring. *Objective 3: with* RD 1.2.4 (Objectives/projects 2 and 4); RD 1.2.1, RD1.2.2, RD1.4.2, RD 1.4.3 (Integrated Land Use), RD 1.3.3, and RD1.3.4 (Biodiversity); *Objective 4: with* cost-effectiveness of agri-environment measures in objective 2, 2.3.12; DTCs for stakeholders and influencing behaviour change; work on knowledge use in RD1.4.2 (work on monitoring and evaluation by Waylen in Obj 1.4.2bii); *HEIs: with* CEH (HEI bid 8) for ecosystem services and measures, Chris Spray (Univ. Dundee), Kate Heal, (Univ. Edinburgh) and David Oliver, (Univ. Stirling), for Objective 3 on catchment water management and Universities of Aberdeen and Glasgow.

Added scientific value: The Demonstration Test Catchment research platform in England is endeavouring to implement measures in monitored catchments by a range of instruments, to deliver a range of water ecosystem services, and provides significant opportunities for cross comparison. CEH's expertise in wetland freshwater ecology , and in integrated catchment science, provide complementary expertise and opportunities for collaboration, e.g. through the opportunities provided for knowledge exchange via the Scottish Freshwater Group (which CEH co-ordinates), and through international links, e.g. with China through ASEM Water, and other initiatives. CEH (HEI bid 8) can also provide active engagement with stakeholder meetings (Fisheries, Catchment Management, etc.) at Loch Leven.

Research links developed through collaborative EU projects provide opportunities for comparison and transfer of measures effectiveness in a catchment context across

Europe. A Hydro Nation PhD student on governance of water in the Pantanal provides links to S. America and ongoing project MAJI: More Action for Just Initiatives for Climate Change Adaptation in Southern Africa provides links to Malawi.
KE, audiences and impact: Workshops in all objectives will deliver new understanding of the effectiveness of individual and collective measures/interventions across WFD (RBMPs), Drinking Water Directive (DWD) (Drinking Water Safety Plans; DWSP) and Flood Risk Management Act (FRM) (Flood Risk Management Planning; FRMP) which will be of use to national forums such as the Diffuse Pollution Management Advisory Group, and contribute to the UK NFM network. GIS and visualisation tools will be useful for assessing the spatial implementation and integration of measures and illustration of NFM/SRDP/Greening measures on catchment processes and impacts. International and cross-scale governance review will deliver improved mechanisms for cross-scalar water-related policy, planning and governance integration, and for policy and governance evaluation. Working with CEH (HEI bid 8) will enhance the impact of the ecosystem services assessment in a wider range of catchments in Scotland and nationally, for example by helping to inform on the balance of strategies for nutrient mitigation and climate change adaptation. The CKEI and KE Sectorial Leads will assist in integration across theme and programme. ***Audience:*** Routes to impact include membership of networks and advisory groups such as: UK Natural Flood Management network; Diffuse Pollution Management Advisory Group, EU nutrient pollution reduction Science-Policy working group and Scottish Freshwater group. Expert evidence workshops will provide opportunities for engagement of key stakeholders (CAMERAs, SG, consultants and practitioners) across all Objectives. Key stakeholders have been consulted through a workshop in March 2015, and this has led to an agreement to hold steering group events every 4-6 months as well as more informal information exchange. ***Impact:*** At a strategic level, the benefits delivered by water assets will contribute to a resilient national economy. Guidance on uptake of GBRs will deliver feedback to SG and CAMERAS on their diffuse pollution management strategy; the work will input evidence on outcomes of diffuse pollution priority catchments, evidence and guidance for management of the current SRDP; and deliver guidance for NFM planning to SEPA and SG. SEPA will benefit through evidence of impact of SRDP, NFM and other measures on water ecosystem services. SNH will benefit from better appreciation of the impact of water levels on wetland ecosystem services. JHI staff will contribute to international exchange of research and water management expertise through other links, for example: Chinese Acadamy of Sciences, Beijing; Landcare New Zealand; ASEM Water, China; Pantanal Research Centre, Brazil.

RESEARCH DELIVERABLE NUMBER: 1.2.4

Work planning and timetable for Year 1 (M= Milestone; D= Deliverable; KE= KE output; R= reporting to RESAS).

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i assess international best practice on how water basin management can deliver multiple benefits, to deliver insights for Scotland						D1.1						
O1.2i characterise the history, process and outcomes of selected catchment-scale partnerships												
O2.1i catchment-scale plans for targeted improvements to water quality and extreme flows management These will be developed, implemented, monitored and appraised, with local facilitation and stakeholder engagement and CAMERAs partners for Lunan Water and monitored and appraised for Loch Leven				**D2.2**				**D2.2**			**D2.3**	**M2.B**
O2.2i Ecosystem services appraisal of catchment scale plans for targeted improvements to water quality and extreme flows management. This would initially occur over two catchments (Lunan Water and Leven) and extend in further years to others (eg Eddlestone, Ugie, Moriston)							**D2.10**					
O2.2ii Annual Report to SG for Year 1 with emphasis on water ecosystem services and logic chains												**R1**
KE Water management plan on rivers trust website											**KE2**	
KE event: joint local stakeholder workshop												**KE3**
O2.3i analyse data on rural diffuse pollution sources and the effects of farmer visits in changing behaviour …as gathered by SEPA's recent Priority Catchment work and compare with UEA-led work in the English Demonstration Test Catchments									**D2.1**			**M2.A**
O2.3ii KE Guidance on uptake of GBRs at DTC conference and report to SG										**KE1**		
O3.1i development of 'logic chain/ model' approach to understanding the effectiveness of interventions for Scotland's water environment … with Scottish Government and CAMERAS stakeholders						**D3.1**						**D3.2** **D3.3**
O4.1i Development and appraisal of select guidance and reviewing spatial analysis tools Informed by evidence to guide the placement of Natural Flood Management and WFD measures in the rural landscape												**D4.1**
KE Expert workshop on evidence of measures					**KE4**							

RESEARCH DELIVERABLE NUMBER: 1.2.4

Work planning and timetable for Year 2 (M= Milestone; KE= KE output; R= reporting to RESAS).

Year 2: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i assess international best practice on how water basin management can deliver multiple benefits, to deliver insights for Scotland										D1.2		D1.3
O1.1ii KE Briefing on integration: report to SG												**KE5**
O1.2i characterise the history, process and outcomes of selected catchment-scale partnerships												
O2.1i catchment-scale plans for targeted improvements to water quality and extreme flows management These will be developed, implemented, monitored and appraised, with local facilitation and stakeholder engagement and CAMERAs partners for Lunan Water and monitored and appraised for Loch Leven						**D2.4**						**D2.6 M2.C**
O2.1ii KE event Stakeholder event to review measures installed												**KE6**
O2.2i Ecosystem services appraisal of catchment scale plans for targeted improvements to water quality and extreme flows management. This would initially occur over two catchments (Lunan Water and Leven) and extend in further years to others (eg Eddlestone, Ugie, Moriston)						**D2.11**						**M2.E D2.12**
KE event: presentation at Scottish Freshwater Group												**KE7**
O2.3i analyse data on rural diffuse pollution sources and the effects of farmer visits in changing behaviour …as gathered by SEPA's recent Priority Catchment work and compare with UEA-led work in the English Demonstration Test Catchments												
O3.1i development of 'logic chain/ model' approach to understanding the effectiveness of interventions for Scotland's water environment … with Scottish Government and CAMERAS stakeholders			**D3.4 D3.5**									**D3.6**
Stakeholder workshop on logic chains report			**KE8**									
O4.1i Further refinement of of guidance and development of conceptual spatial analysis tools informed by evidence to guide the placement of Natural Flood Management and WFD measures in the rural landscape						**D4.3**				**D4.2 M4.A**		
O4.1ii Annual Report (Year 2) with emphasis on best practice for integration and guidance												**R2**
KE Input into Scottish Government NFM network (or European networks via CREW) and SAIFF TnF on NFM steering group		**KE 4***						**KE 4***				
KE initial (concept) GIS tool demonstration (refined from review)												**KE9**
Consultation on report card approach												**KE10**

Name of WP: 1.3 Biodiversity and Ecosystems

1. Work package overview

1.1 Vision

By 2021, this WP will have addressed key knowledge gaps in our understanding of the processes contributing to the functioning and resilience of our natural assets, in particular biodiversity. It will have provided new approaches for focussing and delivering sustainable land management actions, and new metrics for monitoring the health of ecosystems and the services they provide. This information will have fed directly into policy developments and practitioner actions leading to a healthier and more resilient environment.

The quality of our work will have enabled us to operate at a national and international level, with substantial impacts in both the scientific and stakeholder communities, and integration of our work into international research networks thus leveraging considerable funding from external sources. We will be seen as the "go to" people for expertise on understanding and integrating the role of biodiversity and ecosystem services in sustainable resource management.

Working towards this will help answer the Theme 1 integrating Research Questions (RQs), and deliver the overall Theme 1 vision, providing information to reduce our ecological footprint, enabling us to live within sustainable planetary boundaries. We will act as Theme "champions" for biodiversity-related research and policy, playing a key role for the Programme and CKEI overall.

1.2 Context

The 2015 State of Nature - Scotland report demonstrates that work is clearly needed to promote biodiversity conservation and maintenance of ecosystem services. Despite poor understanding of the state of our natural capital, there is increasing evidence for continued decline in both Scotland's and global biodiversity. The ecosystem approach and ecosystem service concepts have highlighted the importance of natural capital for all of society in terms of the multiple benefits that it provides, and the threats to it from major environmental drivers such as land use change and climate change, and non-native invasive species. The Scottish Government Economic Strategy (SGES) states "We will also protect and enhance our natural capital, our brand and reputation as a country of outstanding natural beauty, our commitment to low carbon and the opportunities our resources and assets provide for our economy and future generations". The situation's urgency has been highlighted within the recently-launched UN Sustainable Development Goals, many of which have targets relating natural capital conservation, and Goal 15 – Life on Land is to "Protect, restore and promote sustainable use of terrestrial ecosystems…" including halting and reversing land degradation and biodiversity loss.

1.3 Structure

This WP addresses the challenge of protecting and restoring our natural capital – our biodiversity and ecosystems - by combining information on ecosystem function, delivery of benefits, resilience, and management practices. It links basic understanding of the ways in which ecosystems function – and how such functions relate to different components of an ecosystem's biodiversity – to the development of techniques for addressing and monitoring some of Scotland's major current conservation challenges. The WP's Research Deliverables (RDs) address different

aspects of this chain from fundamental understanding to the development of practical management options (Fig. 1), each focusing on particular Theme 1 RQs. Collectively they provide a coherent body of work and, along with the planned KE and stakeholder engagement activities, have the potential to help deliver the "Step Change" in conservation proposed in the Scottish Biodiversity Strategy Route Map (including its Priority Projects).

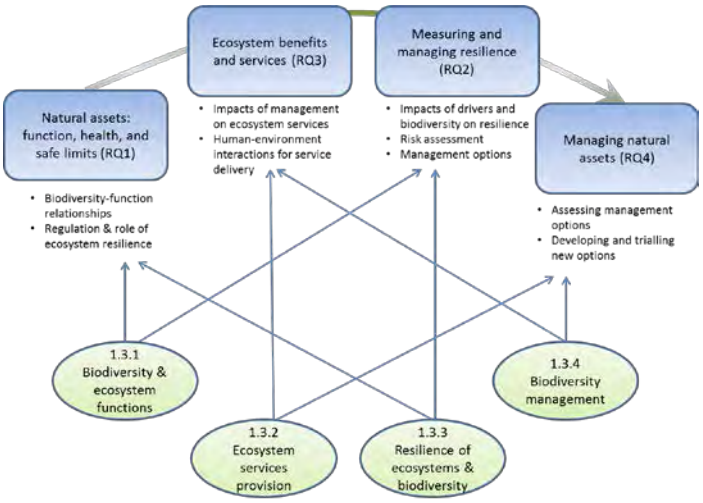


Fig. 1 Conceptual framework for integration of 1.3 research; RQ refers to Theme 1 integrating Research Questions

The WP is structured through four Research Deliverables (RDs):

RD 1.3.1 Biodiversity and ecosystem functions – What underpins a healthy ecosystem? In systems where there is a clear need for better knowledge of biodiversity-function relationships and conservation (e.g. intensive arable, extensive grazing, and woodland systems; currently all areas of major conservation concern, and likely increasing demand for future research) this RD explores how the state/health/diversity (including genetic diversity) of the system regulates key functions (productivity, diversity, resilience). Focussed, smaller-scale studies, conducted in systems representative of those found across Scotland, will be complemented by work at a larger scale using national datasets. This work looks for new ways to measure ecosystem health, including aspects of connectivity, assessing how it might be impacting on system function and to understand how habitat restoration techniques might improve limited connectivity. These studies help us to assess where and why systems are or are not healthy, and to develop methods - based on fundamental understanding – to do something about it.

RD 1.3.2 Ecosystem services supply – How do systems provide services, and can we rebuild "lost" services through good management? This RD investigates how ecosystem structures and functions turn into ecosystem services, and the impacts of ecosystem management on these processes. It uses on-the-ground empirical studies, with both natural and social scientific approaches, to develop detailed, empirical assessments of ES in selected systems, specifically woodlands (including peri-urban areas) and semi-natural extensively managed systems. Analyses will be focused on effects of management changes to determine the relative impacts of such interventions for service supply.

RD 1.3.3 Resilience of ecosystems and biodiversity – What makes a system resilient, and how can we manage for resilience? Ecosystem resilience is a key component of ecosystem health, but there are many questions about what determines ecosystem resilience. This RD considers the impact of large-scale environmental drivers (e.g. climate change, habitat fragmentation, emergent animal and plant diseases), as well underpinning biodiversity (including genetic and species diversity), on the resilience of ecosystems. This RD also considers the development of risk assessment procedures for identifying components of natural capital

(including species/habitats, such as those prioritised in the Scottish Biodiversity List) that might be considered at risk, and explores what might be done about it.
RD 1.3.4 Biodiversity management – Providing a knowledge base for key biodiversity-management actions: Implementation of all biodiversity management should be backed by a solid knowledge base. This RD examines a wide range of measures aimed at conserving and promoting biodiversity and ES provision. It starts by assessing measures currently implemented in Scotland, those implemented elsewhere which could be effectively employed in Scotland, and identifying potential novel management measures. It takes the important step of trialling a subset of these novel methods. The research focusses both on measures implemented on the ground as well as institutional mechanisms and their impact on implementation.

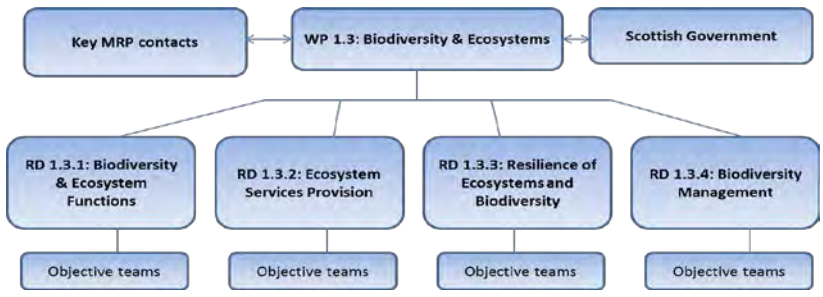
We are highly committed to this WP operating in close partnership with key stakeholders from a wide range of backgrounds, including Scottish Government, agencies such as SNH and SEPA, NGOs such as RSPB and Nourish Scotland, and industry-orientated organisations such as NFUS and QMS. Without close collaborative working – which is viable in a country such as Scotland – we will not achieve the key goal of the WP in getting the right information to the right people at the right time, as reflected in RD Impact Statements, plans for close collaborative working, WP management structures and the KE plan. This WP can help deliver the step change that is needed for Scottish biodiversity by acting - in conjunction with resources/platforms such as the MRP farms - as a Theme 1 hub for research thinking, activity, and knowledge related to biodiversity conservation, ecosystem services, and environmental restoration in Scotland.

2. Coordination and Management

2.1 Management and coordination within the Strategic Research Programme

Mechanisms for coordination and management of the WP - Details of the Theme Governance Structure are given in the Theme Overview. Here we provide details of management structures within WP 1.3 (Fig. 2). WP and RD Coordinators in WP 1.3 have been allocated time specifically to cover management activities (20% of WP Coordinator time). A WP 1.3 Management Group (WPMG) is the main management mechanism, also delivering integration within Theme 1. WPMG will meet quarterly, consisting of WP and RD Coordinators, Theme Coordinator, and KE Sectorial leads (KESLs) where relevant. Key MRP WP contacts will be invited to attend, helping with WP delivery across MRPs and maintaining cross-WP and MRP dialogue. RESAS Science Advisors will also be invited to WPMG with the aim of attendance on at least a six-monthly basis (and notes provided when necessary).

Fig. 2 Management structures within WP



Specific tasks for the WP Coordinator, WPMG, and RD Coordinators are detailed in the Theme Overview document. In brief these include checking performance against activity tables and Gantt charts, facilitating opportunities for cross-MRP working, provision of data for reporting, horizon scanning and identifying opportunities for KE (see Section 3). RD Coordinators will provide the WP Coordinators with summaries of progress and key

outputs, and reporting against the proposed schedule. RD Coordinators will also monitor action for integration across RDs including the delivery of specified linkages.

Progress will be assessed by RD Coordinators with respect to the tender's schedule, and coded according to an agreed scheme (e.g. green – on schedule, amber – slightly delayed, red – significant delay), then collated by the WP Coordinator with a proposals for mitigating any difficulties arising. Feedback on ambers and reds will be dealt with by RD Coordinators. DEC will be informed of any red on the risk register (see Section 2.5). Annual reporting will depend upon requirements specified by RESAS. Collation of metrics will be the responsibility of each MRP for the outputs that they lead, as will provision of metadata. WP Coordinators will be responsible for supplying narrative examples, delivered via the internal WP management processes outlined above. QA for the data underpinning narratives and metrics will be the responsibility of the WP Coordinators.

Promoting Integration within the WP and Theme - As per the Theme Overview, Theme 1 WPs will act as a "champion" for one particular policy area, with WP 1.3 taking this task for Biodiversity and associated policy (see Table 2). WP 1.3 will act as the go-to point for information in this area, and much of our KE activity will focus on this issue. This approach is mirrored in the WP 1.3 structures. Four key research areas are common across Theme 1 (Fig. 1, square upper boxes). Each WP 1.3 RD champions one of these research areas, and RD leads will be responsible for coordinating information from across the WP on these areas in response to requests from the WP, Theme or CKEI. This provides a clear line of responsibility for handling integrating activities. However, RDs will not address these areas in isolation; strong conceptual and practical linkages (i.e. based on joint research) across the RDs, detailed within each RD description, mean the RDs will operate as a collective unit to address these research areas. These four research areas are also central integrating concepts running across Theme 1 (with WP 1.4 undertaking integrating activities on each topic). Organising around these four areas helps the WP and Theme efficiently and collectively address these important issues, and contribute to cross-WP activities including WP 1.4's integrating work and KE at the Theme and CKEI level.

The ability of each RD to operate as a research unit will be strengthened by adoption of a co-ordinated approach to the research, with RDs contributing jointly to WP and Theme KE activities (see Section 3). Research will utilise and extend the biodiversity and ecosystems knowledge from the earlier SG programmes as well as other relevant UK and international research. This will provide SG, CAMERAS and other stakeholders with information relevant to policy and management, as well as identifying key gaps in current understanding which will then form the focus for new research (years 3-5) designed in collaboration with stakeholders to maximise relevance. Furthermore, given the interconnected nature of these RDs, much of the proposed work shares datasets, study sites and key staff (see details in RDs).

To aid delivery of relevant, collective activity across the WP, we will establish a WP Working Group (WPWG) with representatives from key stakeholders (e.g. SNH, SEPA, ESCom representatives, member bodies of SE LINK). Its role (detailed in Section 3) will be distinct from that of the WPMG; it will help guide the work across the WP, and will be a key mechanism for identifying KE opportunities.

Finally, in order to deliver specific pieces of work within individual RDs, small groupings will be formed which also involve both SRP researchers and stakeholders. However, in order to keep management structures simple and efficient, these will be constituted when needed for specific activities. Whilst playing a vital role in research

delivery they will not be a formal part of the WP management structures, with activity and delivery being monitored along with other ongoing work by RD Coordinators.

2.2 Mechanisms for networking and collaboration

This section focusses on networking and collaboration within the SRP. Networking and collaboration outwith the SRP is discussed in Section 3 (Impact and KE).

Conservation of natural capital is a cross-sectoral issue, as recognised in the SBS 2020 Challenge and the Land Use Strategy. Consequently, within the SRP it is important WP 1.3 makes strong linkages to work that spans multiple sectors, rather than focussing only on biodiversity conservation. This is reflected in linkages detailed within the RDs, recognising in particular the need to link fundamental and practical work in 1.3 to work on the same issues but in other systems, particularly soils (WP 1.1) and water (WP 1.2). This fundamental information then needs to inform work on integrated land management (WP 1.4) and development of sustainable production systems (Theme 2) and human health (Theme 3). Acting as a biodiversity and ecosystems hub for the Theme and SRP overall, WP 1.3 will thus further one of the primary goals of the SBS, i.e. mainstreaming of biodiversity. Linkages across WPs and RDs operate through a number of channels, including the movement of data (for example from WP1.3 to the 1.4.1 asset register), sharing field sites and common platforms (for example IPM barley mixtures trials in 2.1.4), sharing knowledge on techniques and approaches (e.g. structural equation modelling in 1.3.1 and 1.1.2) and through joint stakeholder engagement (for example the BLUPU initiative with WP 1.4). These linkages will be strengthened by staff working across RDs and WPs. Opportunities for involvement in CKEI initiatives such as Think Tank visioning, campaigns, responsive model funding, and leadership training will be encouraged.

2.3 Interactions with Underpinning Capacity

Interactions with Underpinning Capacity will occur through several routes, including: use of facilities such as the Balruddery Centre for Sustainable Cropping and Hartwood and Glensaugh extensive farming platforms; use of existing data archives (e.g. national soil archive); use of national collections (e.g. the barley collection); support for statistical analyses from BioSS. Research studies will be developed in discussion with BioSS staff, drawing on their experience in statistics, bioinformatics and mathematical modelling. We anticipate collaborating on questionnaire and survey design, and modelling and receiving support with data interpretation and presentation (e.g. for stakeholder engagement activities). BioSS support for advice and collaboration will be funded from the BioSS Underpinning Capacity budget except where specific research is carried out by BioSS staff.

PhD studentships funded through Underpinning Capacity Service 2 (Seedcorn), and participation in international projects supported through Service 11 (Platform) will add value to the research of WP 1.3 and facilitate strong scientific networks between the MRPs and HEI sector. For all underpinning support, well-established links are already formally in place with all scientists responsible for the required resources.

2.4 Enhancing additionality

Two forms of scientific networking relevant to WP 1.3 are “academic” scientific networking, often focussed on fundamental research, and “applied” scientific networking, developing broader links from research to application for biodiversity conservation and sustainable management. Both types of scientific networking are essential for additionality and consequently will be supported in WP 1.3.

Where possible, PIs will actively seek appointments on national or international committees to help shape the scientific rationale around conservation and restoration of our natural assets (e.g. IPBES) and will attend relevant 'sand-pit' events for RCUK funding calls, such that expertise from the MRPs is recognised and used to support the overall scientific innovation in the relevant areas. Furthermore we will encourage engagement of WP PIs with relevant learned society's and similar organisations (e.g. BSSS, CIEEM, RSoB and the BES), invaluable routes for both publicising research and developing collaborative networks.

In terms of "applied" scientific networking, engagement with organisations such as CIEEM can provide conduits for moving fundamental research knowledge into the realms of conservation practice. Targeted work in particular systems will also build on existing relationships with research scientists in agencies (e.g. SNH and SEPA) and the NGO sector (e.g. RSPB, LEAF). Finally we will – through the WP-level KE activities and activities within individual RDs – run topic-focussed workshops to share developing knowledge with researchers and practitioners within CAMERAS partners and beyond. These stakeholder meetings will also enable us to discuss the work at all key stages, with co-construction of plans for focused research.

2.5 Work package risk management

Risk management strategies for the WP will be a component of Theme-level risk management. The WPMG will establish a risk register. At meetings of the WPMG: 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 the research implications for cross programme links and external collaborations including implications for stakeholders; an assessment will be agreed (e.g. tolerate, monitor, take action, including escalate). The WPMG will send risk register update to Theme Management Group. Projected key risks for the WP are shown in Table 1.

Table 1. Summary of assessed key risks for WP1.3

Risk Descriptor	Risk Ass.	Impact	Controls	Risk owner
Disease outbreaks or unexpected severe weather may restrict access to study sites.	Med	Limitations on field work.	Work programmes can be modified to take existing data further or postpone field work to subsequent dates.	RD Coordinator & PIs
Disagreement about how to proceed.	Med	Reduced rate of delivery/progress.	Inter-disciplinarity and collaboration often means conflicting ideas. Conflict resolution mechanisms to be used.	RD Coordinator & PIs
Low engagement from other WPs when needed.	Med	Reduced rate of delivery/progress.	Staff allocated time to foster engagement and goodwill to be generated by proactive engagement and mutual outcomes.	WP & RD Coordinator
Recruitment of social science survey participants.	Low	Reduced rate of delivery/progress.	Recruit in association with wider events and use consultative groups and experience of running such surveys.	RD Coordinator & PIs

3. Impact and KE

KE Structures and Processes - We have identified the following main audience groups for WP 1.3:

Research and Practice Collaborators - Includes bodies such as ESCom, Centres of Expertise, OPERAS, Valuing Nature Programme, Natural Environment Research Council BESS Programme, Centre for Ecology and Hydrology, Forest Research, Natural Capital Initiative, ERA-Net BiodivERsA, European Union BESAFE programme, Rural Economy and Land Use programme, Ecosystem Knowledge Network, ALTERNet: Europe's ecosystem research network (incl. leading HEIs

and institutes from 18 European countries). We already actively engage with these bodies, e.g. by sitting on committees, delivering shared events, and MoU's.

"Other" Research Funders - Non-SG research funders including RCUK, DEFRA, EU and non-UK research councils. Our interactions with these organisations will be fostered through scientific networking and additionality, as discussed above.

Direct stakeholders - Includes Government (UK, Scotland, local) and agencies incl. SG Biodiversity and Land Use Team, SNH, SEPA, FC, CNP, DEFRA, JNCC, Natural England, CSGN; Professional bodies and learned societies incl. NFUS, SLE, LEAF, ESCom, NCI, BES, SEB, RSoB, CIEEM; Conservation organisations incl. RSPB, SWT, Woodland Trust, GWCT, SE Link.

KE structures must enable communication with all audience groups, but the KE mode must be adapted accordingly. As elsewhere in Theme 1, our overall KE approach involves a pyramid of activities (Fig. 3). Activities within RDs focus on "getting the job done", delivering KE outputs such as research papers, conference presentations, specific tools or products to stakeholders, and the exchange of data and skills between RDs and WPs. RD-level KE deliverables are included and budgeted in the RD plans; their delivery will be monitored by RD Coordinators.

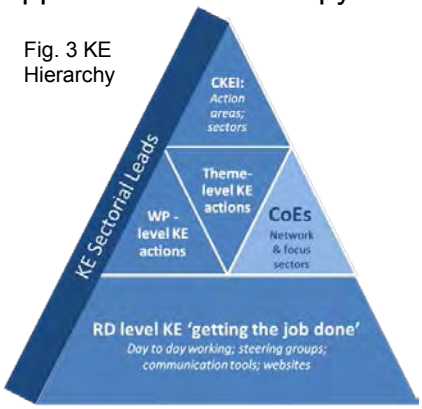


Fig. 3 KE Hierarchy

At the next level is more integrative KE activity within the WP, Theme and CoE, building on work within individual RDs to produce synthetic outputs based around the major research themes and key policy areas as outlined in the Theme Overview and WP management plan (Section 2.1), or relevant to CoE focus (e.g. waters, climate change, plant health). In addition, and to ensure coverage of all audience groups, and targeting of 1.3 KE activities on key policy areas, there will be a number of WP 1.3 specific WP-level KE activities which address in particular the Direct Stakeholders audience group:

WP Working Group (WPWG) - The WPWG focusses on strategic direction of the WP, providing guidance on tailoring research and outputs in order to make a difference on-the-ground (e.g. linking them to the SBS Evidence Delivery Plan). Working Group membership will be much wider than for the BLUPU initiative (below), involving individuals from multiple stakeholder types, building on existing strong working relationships. Six-monthly meetings will be a mixture of progress updates, horizon scanning for research and KE opportunities, and discussions on selected topics, thus enabling two-way flow of information. Impacts will be measured through uptake of research outputs across stakeholder bodies.

Biodiversity and Land Use (BLUPU) KE process - This continues a process initiated during the current SRP designed to increase the flow of information between researchers and SG policy-makers/advisers (including relevant staff from agencies and other SG units, e.g. Scottish Planning Policy, Forestry Strategy, and Placemaking). The focal policy unit covers land use and biodiversity, and so this process will be jointly run with WP 1.4 (resources allocated in WP 1.4) and co-managed by the WP 1.3 and 1.4 WP Coordinators. It will involve quarterly meetings and discussion of short progress reports, upcoming outputs from the WP, and a "heads-up" on major policy initiatives.

ESCom - To help address all three audience groups the WP will build on existing links to the ESCom initiative (a partnership of HEIs, research institutes, SG, agencies and businesses). At the RD level individual projects and researchers will contribute to ESCom Process Areas; at the WP level we will contribute to ESCom Central and ESCom KE activities (with delivery responsibility sitting with the WPMG). Strengthening and targeting ESCom links will help WP 1.3 raise its national and international profile, and integrate its research work (and that from across the Theme) with complementary research activities particularly in the HEI sector.

Natural Capital Initiative (NCI) - The WP will enhance its impact through continued active involvement in the NCI, in particular by initiating and running joint solution-focused activities on 'hot topic' areas (such as the Dialogue session on "putting the Ecosystem Approach into practice" held in Oct 2015). The NCI aims to initiate and facilitate dialogue between key academic, policy and business decision-makers to find shared solutions and approaches – it gives a high profile forum for impact of (and action from) the research findings from all four WPs in Theme 1.

Working through the Theme, the WP will contribute to the main Activities of the CKEI (and thus overall programme) including provision of: research findings in formats accessible/useable by different types of stakeholder, including non-technical summaries; scientific outputs for dissemination via/linked from the central programme website; content for the CKEI media outlets; promotion of the common programme brand (to launch on 1st April 2016) amongst WP stakeholders; content for cross-theme signature events (e.g. at Royal Highland Shows, in support of international activities); providing links to international and European projects which align with WP activities. It will co-operate with the other WPs to add value for stakeholders through linked KE activities within the Theme, and with the other Themes and CoEs. The WP Coordinator will provide the KE Sectorial Leads with updates on WP activities, opportunities arising, and receive updates on wider Theme and Programme opportunities.

Pathways to Impact - Linked to this KE strategy is the development of impact pathways for each RD, which work back from milestones or policy goals to the point at which KE can be most effective and useful. Both the BLUPU and Working Group activities will help us to orientate RD-level activities (e.g. workshops, reports, papers) towards the genuine needs of stakeholders. Impact will be generated by linking our work to developing policy needs, for example developments of the UN CBD, EU Biodiversity Strategy, SBS, Natura 2000, Scottish Climate Change Adaptation Programme, The Nature Conservation (Scotland) Act 2004, and the anticipated Land Use Strategy Action Plan for 2016 onwards. Major pathways for impact for the WP are illustrated in Table 1. Delivering KE for these impact pathways will involve WP 1.3 in corralling information from across Theme 1, and into Theme level contributions to international KE activities (e.g. side events at CBD CoPs). Similar activities in other WPs will enable our information to feed into impact pathways for other policy areas. Planned work takes into account the needs of these policies as detailed within each RD. We will tailor the work to emerging policy and practitioner needs over the first two years of the programme, guided by considerable detailed discussions which have taken place to make sure that the planned work for years 1 and 2 addresses critical policy issues and conservation challenges (e.g. Big Steps for Nature as detailed in the SBS 2015 Route Map, SRDP targeting and optimisation of measures, CNPA Capercaillie management plan – see details within individual RDs).

Table 2. Summary major policy timeline for key stakeholders of WP1.3

Policy priorities	Impact routes	Audience	Timeline	RDs			
				1	2	3	4
Scottish Biodiversity Strategy (and associated CBD incl. Aichi Targets and European Biodiversity Strategy.	Revised Natural Capital Asset Index	SNH	Ongoing	✓	✓		
	Revised Ecosystem Health Indicators for SBS monitoring incl. monitoring of UN Sustainability Goals.	CAMERAS and SNH	2017-2018	✓	✓	✓	
	Support for SBS Route Map to 2020, including "Big Steps" incorporated within this (timetabling for individual Steps to be clarified).	Scottish Government (NATRES) and SNH	2020+	✓	✓	✓	✓
Report on Policy and Practice (RPP4) – agriculture and other land uses.	Indicative woodland strategies taking account of multiple benefits.	Forestry Commission; Local Authorities	2017-2019+		✓		
Invasive Non-native Species.	Advice on assessing risks from and managing invasive non-native species, pests and diseases.	SG INNS team and CAMERAS, STHAG	Ongoing			✓	
Scottish Rural Development Plan.	Advice on new measures or combinations of measures for SRDP 2021+.	Scottish Government (NATRES)	2017-2018		✓	✓	✓
	Trialling of existing and potential new measures to assess benefits for biodiversity.	Scottish Government (NATRES)	2017-2020	✓	✓		
Cairngorms National Park Development Plan; CSGN plans; Capercaillie Action Plan.	Advice on options for land management and consequences for biodiversity and ES provision.	Scottish Government (NATRES, Environmental quality, Planning); SEPA, SNH; CNPA, CSGN	2018-2019+		✓	✓	
Scottish Forestry Strategy; Scottish Strategy for Red Squirrel Conservation.	Advice on disease management to help promote conservation of squirrel populations.	Forestry Commission, CAMERAS, SNH	Ongoing			✓	
Support from our results input to relevant impact pathways in WP1.1, 1.2 and 1.4, and relevant CoEs							

4. Quality assurance (QA)

The MRPs associated with WP 1.3 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 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
- Utilise the relevant Quality Management Systems, or equivalents, in each Institute which 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 the SG
- 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

Use of GM organisms is governed mainly by the Biological Agents and Modified Organisms (Contained Use) Regulations. Environmental protection is enacted through the Environmental Protection Act 1990 (and amended Scotland 2001), 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. Use of animals for research is regulated by Animals (Scientific Procedures) Act 1986. All work using animals is done under authority of Project Licences issued by the Home Office after Ethical Review.

Surveys: 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: http://www.britsoc.co.uk/new_site/index.php?area=equality&id=63. Surveys undertaken as part of the research programme are subject to completion of the RESAS Research Approvals *pro forma* and subsequent clearance.

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

At this stage there are no planned experiments using animals in this WP apart from farm livestock used for grazing as per normal farm practice.

7. Sustainable development

The Scottish MRPs associated with WP 1.3 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. Through these the MRPs:

- Regularly assess and review environmental aspects and impacts of their operation
- Implement operational control procedures and monitor environmental performance through management reviews of environmental issues, meetings and audits
- Comply with all relevant environmental legislation and other requirements
- Operate an environmental management system which is systematically maintained, reviewed and revised to ensure continuous improvement. Some institutes currently operate to the ISO 14001 standard
- Set environmental objectives and target, including CO_2 emissions reduction.
- Allocate sufficient resources to achieve its environmental objectives and targets within budgetary constraints
- Ensure that energy consumption is monitored to explore potential for reduction.
- Minimise waste, promote re-use of materials and maximise recycling

- Minimise the use of chemicals, radioisotopes and other toxic materials and to adhere to statutory regulations relating to their storage, handling, use and disposal
- To protect and promote biodiversity on the “campus”
- Exploring alternative technologies to improve environmental performance
- Senior management within the MRPs receive advice from Environment Committees or their equivalent
- Ensure competency through provision of training and communication.

Name of RD: 1.3.1 Biodiversity and ecosystem function

Research aim and key drivers: 'Ecosystem functions' are the biological, geochemical and physical processes that take place within an ecosystem, e.g. decomposition, production and the provision of habitats. Ecosystem services, and associated benefits, are underpinned by ecosystem functions. Sometimes called "supporting services", functions are critical in assessing ecosystem health.

There remain large gaps in understanding how changes in management and the environment alter community composition and, hence, ecosystem functions. This Research Deliverable (RD) addresses how ecosystem functions are regulated by the traits of species present, how potential limits for the maintenance of ecosystem function can be captured in ecosystem health metrics and how the connectivity between ecosystems might affect ecosystem function. It has the overall aim of identifying indices of connectivity and ecosystem function that can be applied to assess ecosystem health at a range of scales (from field to national) so that management action can be targeted to improve ecosystem health and conserve biodiversity (e.g. by developing the National Ecological Network).

The primary rationale for the research in this RD is to support the Scottish Biodiversity Strategy (SBS) and its associated international commitments to deliver the Aichi Targets of the Convention on Biological Diversity and the European Biodiversity Strategy. Specifically, the research will underpin the SBS adoption of the Ecosystem Approach which highlights the need to "take account of how ecosystems work." The RD will contribute, via research on indicators, to the SBS goal of "improving ecosystem health" through helping "devise a simple but robust way of assessing it" and "know what needs to be done to maintain or improve it". The research will also support Priority Project 10 of the SBS Biodiversity Route Map "Improving ecological connection" through research aimed at identifying the role of connectivity in preserving ecological function. Through integration with other WPs in Theme 1 (particularly WP 1.4), WP 1.3 will also contribute to the targets in the Scottish Climate Change Adaptation Programme and the Land Use Strategy.

To meet its goals, the RD will employ standardised and well-tested approaches (building on existing work in the 2011-16 SRP) to examine the networks of ecological interactions operating in study systems. These systems, detailed below, have been selected on the basis of scientific criteria, conservation relevance, the likely wider applicability of findings and through close discussion with stakeholders. The RD will also develop new ways of measuring ecological connectivity and focus work on systems where knowledge for environmental management is urgently needed. *The RD will contribute to the WP and Theme visions by addressing key knowledge gaps in our understanding of the links between biodiversity and ecosystem function and providing new metrics for monitoring ecosystem health, in particular addressing Theme 1 integrating RQ1.*

Who has been consulted in developing this proposal?: The research has been developed through detailed discussion with the following organisations: Scottish Government (Land Use and Biodiversity Team), SNH (Biodiversity Team and Knowledge and Information Management Team), SEPA, JNCC, PlantLife Scotland, SASA and Scottish Environment LINK, as well as research colleagues in the Centre for Ecology and Hydrology and RSPB. We also used discussion with LEAF, Nourish Scotland and NFUS to develop the ecosystem function work and the Birsay Heritage Trust, Orkney Islands Council, SASA, Scotch Whisky Research Institute, Bruichladdich Ltd., Uist Asco Ltd., PlantWorks Ltd., Soil Essentials Ltd., Headlands Ltd. and KWS UK for the arable and bere barley work.

Summary of the proposal:
This RD addresses three of the six Theme-level strategic aims of understanding:

- How do Scotland's natural assets function, how healthy are they, what are their trends and are we exceeding 'safe' limits to their sustainable use?
- How can we improve the management of our natural assets through existing and novel policy instruments?
- How can we support sustainable land-based industries and vibrant communities whilst protecting and restoring Scotland's natural assets?

The RD leader will be responsible for monitoring research progress within the RD against the agreed timetable. This will be achieved by frequent meetings with each project to ensure progress and integration within the RD and with other RDs. The RD leader will coordinate the annual reporting to RESAS.

Key objectives: RD 1.3.1 focuses on identifying the linkages between species and ecosystem function, better understanding limits to ecosystem function (i.e. tipping points, including associated uncertainty), and the role of ecological connectivity in regulating ecosystem functions. Overall its aims are to:

- Understand how ecosystem functions are regulated by species traits in semi-natural and cropped systems;
- Develop and refine indicators of ecosystem health and improve biodiversity metrics to support policy and targeted action;
- Provide information on ecosystem function and connectivity to support conservation practice.

These aims are inter-dependent: improved understanding of biodiversity-function relationships (strategic research) supports development of applied outputs such as refined metrics; and both improved understanding and refined metrics support conservation practice. The research focusses on key ecosystems chosen after detailed discussions with stakeholders to address future needs for policy delivery (e.g. SBS Big Steps for Nature, National Ecological Network, SBS Evidence Delivery Plan), and to directly address the RD specification. They are unified utilising common scientific concepts and approaches (allowing cross-comparison), and providing focal systems for developing widely-applicable understanding. Further integration will be delivered through developing new studies for years 3-5 in consultation with the WPWG and working closely with other RDs, including 1.1.1, 1.3.3, 1.3.4 and 1.4.1.

Objective 1: Understanding regulation of ecosystem function: Exploration of existing project data, integrative studies in selected systems, and mechanistic modelling will provide new understanding of the relationships between different components of biodiversity (genetic, species, above- and below-ground biodiversity) and ecosystem functions (e.g. productivity, nutrient cycling, pollinator activity, pest biocontrol), and their resilience in response to environmental perturbation. This work delivers against the RD aims by assessing drivers of ecosystem functions, testing potential novel indicators and by providing information relevant to conservation practice.

Work in years 1 and 2 will focus on a small number of systems to develop integrated approaches: (a) lowland arable crop systems; (b) semi-natural upland systems; (c) wild and cultivated Scottish plant species of conservation concern (linking to related work in Theme 2). These have been selected with stakeholders because they build on existing experimental resources, they are of high conservation concern, are representative of key Scottish systems, are readily manipulated, and provide platforms for integrated working across WPs/RDs. Unifying research approaches will be applied, i.e. functional diversity and statistical analysis, in

particular Structural Equation Models (SEMs) (building on the current SRP and in collaboration with RDs 1.1.1, 1.4.1). These unifying approaches will help build an integrated RD research team that can work with stakeholders (via the WPWG) and other RDs (particularly 1.1.1, 1.3.3, 1.3.4 and 1.4.1) to apply standardised approaches to a wider range of systems (Years 3-5).

Objective 2: Developing and refining Ecosystem Health Indicators: We will build upon an existing strong relationship with the SBS Indicators Working Group and SNH's Knowledge and Information Management Team. We will work closely with them and with scientists in other parts of the SRP (especially WP 1.1) in underpinning the development of Ecosystem Health Indicators, especially new metrics that take account of multiple species in single indicators. In addition, cross experiment analyses will be used to identify potential novel ecosystem health indicators, and research in conjunction with RD 1.3.3 and RD 1.4.1 will assess these indicators against currently accepted national indicators.

Objective 3: Scaling and connectivity: Research will address connectivity and the impacts of scale on biodiversity-ecosystem function relationships. Using existing national scale datasets we will: examine the role of scale and connectivity for plant diversity/trait–ecosystem function relationships; develop and test connectivity measures; apply measures to a range of habitats, scales and map resolutions to investigate correlation with species diversity measures and habitat degradation (linking to RD 1.4.1); apply connectivity assessment to landscape-scale conservation of oceanic woodlands, by identifying connectivity 'bridges' and restoration sites.

Key deliverables: The evolution of some of the research in this RD depends upon continuing co-construction with stakeholders and where this is the case the deliverables are kept broad to allow for this co-construction. Deliverables include research papers, research summaries and guidance notes, the development of new analytical techniques and modelling approaches, and opportunities for effective knowledge exchange through workshops, meetings and working groups. All outputs will be developed in close discussion with key stakeholders to assure appropriate targeting/formats.

Objective 1 – Understanding regulation of ecosystem function:
D1.1i, yr 2: Mechanistic model to investigate the effects of biodiversity and spatial heterogeneity on system resilience.
D1.1ii, yr 2: Paper on diversity regulation of ecosystem function.
D1.1iii, yr 2: Summary brief and paper on effects of diverse crop mixtures on survival and performance of rare arable plants.
D1.1iv, yr 3: Paper on effects of barley variety mixtures on productivity and pest biocontrol under different precipitation scenarios.
D1.1v, yr 4: Paper on effects of interspecific plant diversity on activity of beneficial organisms, above- and below-ground.
D1.1vi, yr 5: Validated model highlighting effects of biodiversity and spatial heterogeneity on system resilience (to climate change).
D1.2i, yr 2: Provision of ecosystem maps that target experimental reintroduction of threatened plants highlighted in the Biodiversity Route Map to 2020.
D1.2ii, yr 2: Paper on nutrient efficiency traits in barley landraces.
D1.2iii, yr 3: Paper on using genetic diversity in Scottish landraces of barley to identify novel variation in root traits.
D1.2iv, yr 5: Paper on the interaction between abiotic and biotic stress tolerance in

Scottish landraces of barley.
D1.3i, yr 2: Paper - upland management impacts on plant traits.
D1.3ii, yr 5: Summary brief and paper on the impacts of liming on resource availability for upland, insectivorous birds.
D1.3iii, yr 5: Summary brief and paper on the long-term impacts of grazing management on ecosystem function in upland grasslands.

Objective 2 - Developing and refining Ecosystem Health Indicators:
D2.1i, yr 1: Workshop report on ecosystem health knowledge gaps.
D.2.1ii, yr 2: Workshop report on tipping points and thresholds.
D2.1iii. yrs 3-5. Outputs to be agreed with SBS Indicators Working Group and SNH.
D2.2iv, yr 2: Paper on cross system comparisons of trophic linkages and their control of ecosystem function.
D2.2v, yrs 3-5. Outputs identified following target system selection with stakeholders.

Objective 3 – Scaling and connectivity:
D3.1i, yr 2: Paper on impacts of scale on biodiversity-function relationships in different woodland habitats.
D3.2i, yr 2: Paper exploring properties of new connectivity measures.
D3.2ii, yr 4: Connectivity map – first version using Cairngorm National Park as a focus area; final version whole Scotland.
D3.2iii, yr 5: Paper on integrating spatial planning tools for practical application across public-private ownership for protected area management
D3.3i, yr 2: Map showing zones of opportunity (spatial targeting) for the protection of temperate rainforest delivered in collaboration with FC, Plantlife, and SNH.

Technical approach:
The questions addressed within this RD are primarily focussed at a fundamental understanding of biophysical processes. The research will draw on expertise from ecophysiologists and from molecular, agro-, upland and spatial ecology.

Objective 1. Understanding regulation of ecosystem function:
Targeted research will use the unifying concept of the RUBICODE (Rationalising Biodiversity Conservation in Dynamic Ecosystems) trait framework to ensure consistent study design and sampling. This framework assumes that functional traits link the species present to the environment and also link the species in adjacent trophic levels. Similarly, analysis will use a common approach, namely Structural Equation Modelling (SEM). This common framework for design and analysis will facilitate the identification of key drivers of ecosystem functions (including functional traits) and indicators for ecosystem health (functions such as energy flows, productivity, soil carbon dynamics, resilience). Biodiversity is a major cultural service; focussing on systems of conservation concern (as agreed with stakeholders) will deliver outputs promoting conservation in key managed and semi-natural systems.
1.1 Regulation of ecosystem function in intensive crop systems: Field and mesocosm studies of intra- and inter-specific plant diversity, conducted at Hutton Dundee and the Centre for Sustainable Cropping (Underpinning), will examine regulation of ecosystem functions by plant functional trait and genetic diversity in intensive crop systems. These “simple” systems allow for the manipulation of starting conditions not possible in other systems and provide a robust test of the experimental framework. The results will be applicable to arable systems in eastern Scotland and will be used in the analysis of agricultural systems in RD 2.3.9.
1.1a Intra-specific mixtures: To examine the contribution of genotypic and trait

diversity to ecosystem function and rare species conservation we will use a barley variety mixtures study (constructed by RD 2.1.6) to assess effects of crop biodiversity on survival and performance of non-crop species including rare arable plants and *Capsella* ecotypes to determine how dominant plant species regulate vascular plant diversity (Yr 1). A mesocosm study of synthetic barley communities of different trait and genotypic diversity will have water inputs manipulated (rain shelters) to assess how trait/genotypic diversity determines system resilience (linking to 1.3.3) to future precipitation scenarios (Yr 2). Both studies will measure key responses: biodiversity, ecosystem function (plant productivity, nutrient use, decomposition), service delivery (biocontrol; from Balruddery CSC). These studies build on approaches developed in the 2011-16 SRP.

1.1b Inter-specific mixtures: To understand the relative roles of species and genotype diversity in structuring responses of biological systems to environmental change, we will document changes in insect visitations and plant fitness in a long-term field experiment manipulating genetic composition of six plant species in mixed species populations in four environments (highly disturbed soil (ploughed), undisturbed soil, fertilized highly disturbed soil, and fertilized undisturbed soil). Harvest is planned for Year 3 (2018). Data from both 1.1a and 1.1b underpin development of a mechanistic model predicting effects of biodiversity and spatial heterogeneity on system resilience under such scenarios as a changing climate (links to RD 1.3.3, 2.3.8).

1.2 Genetic diversity, ecosystem function & conservation management: Work on species of conservation concern enables the examination of the role of genetic diversity in species resilience and conservation; bere barley studies allow understanding of how genetic diversity regulates system functions.

1.2a Genetic diversity and species of conservation concern: Focusing on Scottish Biodiversity List plant species identified as requiring action (Cairngorms National Park Action Plan, e.g. *Cicerbita alpina*) we will test the role of ecological and genetic factors controlling population viability, in order to deliver optimised reintroduction protocols for species recovery. Controlling pollination (using flower bags), we will test the potential for genetic rescue. Cross- and open-pollinated (control) flowers will be collected to measure offspring fitness (seed set, viability, germination and survival) in common gardens. Inter-population outbreeding impacts on fitness will be tested using a generalised linear mixed-effect model. Transplant experiments will evaluate outbreeding and inbreeding effects under natural conditions.

1.2b Genetic diversity and local adaptation: Barley is Scotland's largest crop and underpins the brewing and whisky industries (the third largest contributor to the Scottish economy). To improve the sustainability of this crop we will preserve and utilise novel genetic diversity that exist within Scottish landraces. With HEI partner University of Highlands and Islands, this work will expand an existing collection of previously-identified UK 'heritage' cultivars of barley identified in the 2011-16 SRP; this expanded collection will be grown under a range of common garden conditions across Scotland to examine whether phenotypic variation (linked to mapped genes) enables adaptation to local environmental conditions. Common garden experiments will be established: a) Orkney - peatlands and Machair; b) Uist - Machair systems. Selected barley genotypes (landraces, Bere, elite lines) identified in RD 2.1.7 (links with RD 2.1.2, 2.3.4, 2.3.8) will be grown with contrasting nutrient inputs (incl. inorganic fertilisers and traditional agronomy). Complementary experiments, acting as a direct comparator to intensive agricultural systems, will be established at Balruddery CSC (RD 2.1.2, 2.1.7, 2.3.4, 2.3.8). Genomic approaches will allow dissection of gene regions involved in local adaptation and identification of specific genomic regions involved in yield stability; relevant crosses will be made to produce novel cultivars with landrace derived traits. Selected mixtures of landraces and

landrace derived material will be grown in a range of marginal field sites with different fertiliser treatments (inorganic, seaweed, compost), to assess the impact of genetic diversity on sustainable use of soils (in association with RD 2.3.4 and 2.3.8). A range of soil diversity and function studies will be performed on these field experiments in RD 1.1.1. Stakeholders are interested in preserving and utilising the genetic diversity in Scottish landraces (listed above), and knowledge generated will also contribute to the sustainability of production on marginal soils globally.

1.3 Function and resilience of upland ecosystems: At the specific request of key stakeholders (SNH) we will examine how habitat management regimes regulate biodiversity in upland ecosystems. The results from both 1.3a and 1.3b will be applicable across rough and semi-improved grasslands throughout Scotland and contribute to understanding the impact of agricultural management on the decline of upland, insectivorous bird species.

1.3a Grazing management and trophic effects: As a consequence of running a long-term upland grazing experiment (Glen Finglas, since 2002 and currently funded in the 2011-16 SRP), patches of varying forage quality with similar species composition have developed as a result of differing grazing regimes. The hypothesis that concentration of nutrients in heavily grazed plant tissues will impact on invertebrate traits and on their quality as food for insectivorous birds will be tested. Key plant traits that link the impacts of management on the vegetation to the invertebrate community to the foraging birds will be identified.

1.3b Upland management action for wading birds: The potential role of grassland management in determining food resources for upland waders will also be investigated. Diversification of semi-improved grasslands with legumes and other forbs, and boosting lime, phosphate and potassium inputs whilst reducing nitrogen inputs could shift plant and invertebrate community structure. Impacts of changing management will be assessed in terms of shifts in species and traits of plants and invertebrates and the use of treatments by passerines and waders. This work will be carried out in association with the development of Glensaugh and Hartwood as demonstration farms in the Farmland Biodiversity Initiative (integrated via 1.4.3) and with RD 1.1.2.

Objective 2. Developing and refining Ecosystem Health Indicators:

2.1 Establish collaboration with the SBS Indicators Working Group: We will develop collaboration with the SBS Indicators Working Group and SNH's Knowledge and Information Management Team to refine Ecosystem Health Indicators and to put them on a sound scientific footing as a means of assessing ecosystem health. This will particularly focus on developing assemblage level data to replace single species data in constructing indicators. We will also develop methods to combine diverse data sources to construct synthetic indicators. We will facilitate this development through targeted workshops with interested stakeholders including scientists, agency staff (SNH, SEPA, Marine Scotland, JNCC), policy makers (SG) and NGOs (e.g. LEAF Scotland, GWCT, RSPB). Initially, we will focus on bringing together previous piecemeal approaches and then integrating current understanding of thresholds and tipping points with the Scottish context, with the potential to highlight approaches for future work. We anticipate a workshop on ecosystem health (Year 1) and on tipping points and thresholds (Year 2). Further workshops will be developed as priorities are identified, including developing future monitoring.

2.2 Integrating understanding across systems: Consistent use of the RUBICODE trait framework, structural equation modelling (SEM) and a core set of measurements in all studies allows for comparison of results across study systems to assess whether: 1) similar diversity-ecosystem function interaction networks exist

in all systems; 2) within interaction networks the same key drivers are operating; 3) it is possible to identify acceptable limits to ecosystem functions; 4) these key drivers/thresholds can act as metrics of ecosystem health relevant to different applications/scales. This will be facilitated by cross RD workshops early in year 1 to ensure integration of monitoring approaches, followed by analysis workshops in years 2 and 3. Synthesis will involve researchers working on similar topics in other RDs, particularly RDs 1.1.1, 1.3.3, 1.4.1 (also applying SEMs). SEM modelling will be developed in collaboration with BioSS (Underpinning Capacity Function 7). Information on inter-trophic flow and resilience will feed into the connectivity modelling (Objective 3) and development of new management options (1.3.4). Based on this integrative analysis and in conjunction with stakeholders (via the WPWG) and colleagues in RDs 1.1.1 and 1.3.3, target systems to be investigated during years 3-5 of the program will be selected. These may include further work in systems already targeted (arable or upland systems) or application of our integrated approach to other systems where we have high quality background data (e.g. coastal grassland).

Objective 3. Scaling and connectivity:
Objective 3 will examine the role of scale and connectivity in influencing diversity-function relationships, and assess the applicability of indicators of ecosystem health at a national scale, including the development of connectivity indices. This work will also investigate application of connectivity measures to regional-scale conservation.
3.1 Scale and connectivity impacts on diversity-function relationships at a national level: Novel statistical analyses of national vegetation data (collected in the current and previous SRPs) will examine influences of scale (years 1-2) and connectivity (years 3-5, using the new metrics developed in this objective) on the impacts of a range of drivers (including climate, land use) on biodiversity and, as a proxy for ecosystem function, functional traits. Detailed data (including climatic, aerial pollutant deposition and grazing indices) will allow partitioning of influences on ecosystem function and resilience (linking to RD 1.3.3), within different systems and in different areas of Scotland. Developing new spatial connectivity metrics will allow examination of the importance of connectivity in supporting ecological function (including species range shifts under climate change) using woodland restoration as an initial test (model developed in current SRP). Further habitat types will be assessed after prioritisation with stakeholders and if resources allow.
3.2 Scaling and connectivity assessments: We will devise new connectivity measures integrating methods based on graph theory with methods based on mathematical morphology, and compare performance to metapopulation-based methods. Devised measures will be applied to a range of habitats, scales and map resolutions to investigate correlation with species diversity measures and habitat degradation measures. Habitats considered will include forest, peatlands/moorlands and grassland. This will link to RD 1.4.3 species case studies (accessible rural woodland). Scenarios of climate change impacts will be tested on modelled connectivity. We plan to use the Cairngorms National Park as an initial test area.
3.3 Application of connectivity assessment for temperate rainforest systems: We will map connectivity for epiphytes (a defining feature of Scotland's globally-important temperate rainforest habitat) to support landscape-scale conservation around protected sites through the identification of crucial connectivity 'bridges' and priority sites for restoration. Spatial isolation for records of temperate rainforest species initially will be quantified using a simple distance approach including neighbourhood analyses and patch configuration analyses. To quantify the degree of friction imposed by the landscape on species dispersal, spore-trap field experiments will calibrate a cost-distance layer based on the molecular detection of species. Analysis

will deliver an opportunity map showing the extent to which individual locations/sites are connected within the landscape and their strength as either link or recipient sites for conservation priority species. The best sites for woodland expansion/regeneration for lichens will be identified based on natural dispersal, as well as sites with low connectivity which will require active translocation. We will focus on Scotland's west coast Important Plant Area and collaborate with PlantLife and SNH.

Detailed work plan - See Summary, Technical approach and Gantt charts.

Expertise:

Hutton: Strong international reputation in biodiversity research across a wide range of habitats and scales, offering expertise in plant and invertebrate biodiversity and ecology, plant functional and genetic analysis, soil processes, GIS, spatial analysis and statistics. Expertise is demonstrated by research in the current SRP on trait-function links, cereal ideotypes for reduced input agriculture, impacts of upland management and connectivity impacts on species' range shifts.

RBGE: Considerable experience in linking genetics of rare/endangered plant, lichen and bryophyte species to their autecology, and developing management approaches for their conservation. The work here builds on research undertaken in the current SRP on endangered epiphytic lichens and developing novel connectivity indices.

BioSS: Expertise in statistical and mathematical modelling of host-invertebrate systems including modelling stage-structured populations, as part of the examination of linkages between above- and below-ground biodiversity.

Key linkages, interdisciplinarity & collaboration:

As the focus of this RD is on understanding the control of fundamental ecosystem processes, the disciplines needed are drawn from plant physiology and from molecular, agro-, upland and spatial ecology.

Links to other Research Deliverables: Ecosystem function research will link closely with RDs 1.1.1, 1.3.3 and 1.4.1 through the development of shared approaches to data analysis with SEM. Added value from the arable focussed work will provide information on the contribution of crop mixtures to ecosystem function for use in RDs 2.3.8, 2.3.9 and 2.3.11. Work will also provide fundamental understanding of barley biology for use in crop system work in RDs 1.1.4, 2.1.2, 2.1.7, 2.3.4 and fundamental understanding of soil ecosystem function (RD 1.1.1). The spatial connectivity measures will be used within modelling of natural capital assets within RDs 1.4.1 and 1.4.3. Within the WP, we will work closely with 1.3.3 by developing approaches to assess resilience, and with 1.3.3 and 1.3.4 in developing new experimental work to examine ecosystem function, resilience and biodiversity conservation measures, potentially in common study systems (yrs 3-5).

Links to the wider RESAS programme and between MRPs: The RD will link to ClimateXChange (CXC) to inform SG policy on the resilience of biodiversity and system function to future climates. It will utilise research platforms (Balruddery Centre for Sustainable Cropping, Glensaugh, Hartwood), datasets and collections (e.g. vegetation data, insect collections) and BioSS modelling expertise from RESAS underpinning funding. It strengthens existing collaborations between Hutton, RBGE and BioSS and, via links to other RDs, SRUC.

Links to the Stakeholder Community: The RD will strengthen existing links to the stakeholder (policy, agency, NGO, land managers) community through the WPWG, our existing stakeholder and policy networks (e.g. through BLUPU to the Biodiversity and Land Use Team of SG, Science and Technical Group of the Scottish Biodiversity Strategy, ESCom), a set of specific workshops and engagement with learned societies (BES, SEB). Linkages will enable the research to address directly questions of key concern for stakeholders.

Other funding bodies: The research aims of this RD are aligned with the strategic

aims of a number of national and international funding bodies including RCUK (BBSRC, NERC, EPSRC), AHDB (pest management), TSB/Innovate UK (agrifood system sustainability), EU H2020 (innovative cropping systems, restoration, etc).

Added scientific value:

The proposed research addresses significant gaps in understanding of ecosystem functioning, especially the role of traits as predictors of trophic linkages and resilience, the importance of connectivity for function at large-scales and the summary of function into suitable metrics. These research areas will deliver high impact research papers and also form the basis for collaboration with HEIs and institutes, including the universities of St Andrews, York, Zurich and Göttingen, as well as INRA, FIBL, SLU and CEH (Defra pollinator initiative), and a wider group via a H2020 restoration bid. We will also specifically address the potential to collaborate with the BESS projects, particularly Wessex-BESS. The research on cultivated biodiversity will be enhanced through collaboration with the University of Highlands and Islands, the University of Copenhagen, within an existing EU project (WHEALBI), a submitted proposal (GRANARY) and potential further H2020 applications (relating to crop mixtures and farming systems and policies for permanent grassland). Research on connectivity will be enhanced by an Esmée Fairbairn Foundation funded project mapping suitable habitat for rainforest species and from SNH measuring epiphyte dispersal-distances, and may potentially benefit from involvement in an EU LIFE+ bid on Atlantic oakwoods and RCUK funding with the University of Edinburgh to deliver best practice translocations.

KE, audiences and impact:

Linking to KE throughout the programme: Activities from this RD will contribute to WP and Theme level events, cross-Theme outputs at conferences, practitioner events and thematic events for policy teams from SG and CAMERAS partners. Via the WPMG we will liaise with the KE Sectoral Leads to integrate our KE activities with those of the CKEI. We will contribute directly to CKEI activities such as the central programme website and contributions to cross-theme signature events.

Policy: Our main link to policy colleagues will be through the joint WP 1.3/1.4 meetings with the Biodiversity and Land Use Policy Team (BLUPU). This will ensure rapid communication of new concepts and results to policy and the correct identification of suitable communications methods. Particular emphasis will be given to developments in ecosystem health indicators and biodiversity management advice to inform national policy (e.g. LUS action plan) and regional policy (e.g. local authority development plans). Specific workshop reports will be made available to relevant staff in agencies and SG via the proposed WP Working Group.

Agencies and conservation NGOs: This set of stakeholders, along with SG policy colleagues, will be engaged with to co-construct later parts of the scientific programme, especially as to the types of systems it would be most profitable to consider in years 3 to 5. We will work closely with SNH on indicators targeted to deliver towards national reporting requirements. We envisage close interaction with colleagues from SNH, SEPA, Marine Scotland, FC, CNPA, LLTNP as well as NTS, LEAF, RSPB, GWCT, Plantlife and Nourish Scotland, including via the WPWG.

Land managers: Research will be demonstrated to land managers (as well as to other stakeholders) through activities based on the Farmland Biodiversity Initiative (Glensaugh and Hartwood) and through LEAF Technical/Open Farm Sundays and open days at Balruddery (in conjunction with other RDs such as 2.3.8, RD 2.3.9).

Scientists: We will publish in high impact, international journals to demonstrate the role of key components of biodiversity in system function and improved methodological approaches. We will present key scientific findings at relevant national and international conferences (e.g. ESCom, BES, INTECOL) and contribute

to EU COST action groups (e.g. FA1405 plant-microbe-arthropod interactions).
Education: Research findings will be publicised through teaching activities at HEIs (Universities of Aberdeen, Edinburgh, Dundee, St. Andrews) and the wider public through CKEI and institute websites, John Hope Gateway Centre, news releases and podcasts.

Pathways to impact:

1. Ecosystem function/biodiversity management. Two sets of direct beneficiaries are envisaged from this work: scientists through our increased understanding of trophic interactions and land managers through our increased ability to manage for conservation. The former group will be engaged through normal channels with impact judged on the number of publications in high quality journals, talks at conferences and new collaborations. The latter group will be engaged through open days at demonstration farms, and impact will be judged through attendance and feedback. The work will feed into policy via the integration role of 1.4, potentially through the use of traits as proxies for ecosystem services.
2. Indicators. The primary beneficiaries will be policy and agency staff developing indicators of ecosystem health and for monitoring progress towards the Aichi targets. Outputs from our research could be adopted as standard metrics for monitoring, and we will work closely with the SBS Indicators Working Group and SNH to support this. Impact will be judged by the adoption of metrics developed and/or tested here.
3. Spatial metrics. Development of these will provide policy and agency staff with new metrics for assessing spatial distribution impacts on natural capital. Impact will be ensured through close working with SNH and SG policy and success will be measured by integration of spatial metrics into the Natural Capital Asset Index (SBS Route Map, Big Step for Nature No. 2). Again WP 1.4 will play a role in feeding this information through to policy via the use of new metrics in developing the Asset Register in 1.4.1. Local scale assessment will contribute to the SBS Route Map, Big Step for Nature No. 4.

RESEARCH DELIVERABLE NUMBER: 1.3.1

Work planning and timetable for Year 1 (O=Objective, KE=Stakeholder engagement and knowledge exchange, M=Milestone, D=Deliverable – see list above; for RD contributions to KE at WP level see WP1.3 description)

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i Model development Working mechanistic model of the effects of biodiversity and spatial heterogeneity on system resilience. ***M1.1a: Working model.***												M1.1i
O1.1ii Establish experiment Field studies – crop and genetic diversity effects on function. ***M1.1ii: Experiment established.***									M1.1ii			
O1.2i Establish experiment Experiment examining genetics of plant re-establishment. ***M1.2i: Experiment established.***						M1.2i						
O1.2ii Establish field trial Establish bere barley field trials and assess available diversity. ***M1.2ii: Field trial established.***				M1.2ii								
O1.3i Data analysis Analysis of grazing management impacts on plant traits/invertebrate community. ***M1.3i: Data analysed.***					M1.3i							
O1.3ii Establish liming trial Establish experiments to examine impacts of management on bird food supply at Glensaugh and Hartwood. ***M1.3ii: Trial established.***						M1.3ii						
O2.1i Workshop Workshops on Ecosystem Health (KE1).								KE2.1i				
O2.2i Internal workshop Cross RD workshop on monitoring approaches for integrative SEM analyses. ***M2.2i: Workshop.***		M2.2i										
O3.1i Data analysis Apply analytical techniques to woodland case study. ***M3.1i: Tested methods.***												M3.1i
O3.2i Method development Develop analytical approaches including developing novel connectivity metrics. ***M3.2i: Methods constructed.***												M3.2i
O3.3i Method development Develop connectivity metrics for lichens/bryophytes. ***M3.3i: Connectivity analysis.***												M3.3i
Report to RESAS.												R1

Work planning and timetable for Year 2

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1i Paper Paper describing mechanistic model of the effects of biodiversity and spatial heterogeneity on system resilience.												D1.1i
O1.1ii Establish experiment Mesocosm study: diversity regulation of ecosystem function. ***M1.1ii: Experiment established*.** Paper.							M1.1ii					D1.1ii
O1.1iii Paper Research paper on plant diversity effects on invertebrate and rare plant diversity.									D1.1iii			
O1.2i Maintain field trial Maintain field restoration trials. ***M1.2i Experimental sampling***. Ecosystem map to target the experimental reintroduction of threatened plants.					M1.2i							D1.2i
O1.2ii Maintain field trial Monitor common garden experiments. ***M1.2ii Experimental sampling***. Develop stakeholder event.					M1.2ii			KE1.2ii				
O1.2iii–Paper Research paper on nutrient efficiency traits in Scottish landraces of barley.												D1.2iii
O1.3i Experimental monitoring ***M1.3i Data collection***. Scientific paper on upland management impacts on plant traits.						M1.3i						D1.3i
O1.3ii Experimental monitoring Monitoring of liming trial. ***M1.3ii Data collection***							M1.3ii					
O2.1i Workshop on tipping points/thresholds								KE2.1i				
O2.2i Internal workshop Cross RD workshop on integrative SEM analyses. ***M2.2i: Workshop.***										M2.2i		
O2.2ii Planning workshop Synthesis and communication of results from Years 1 and 2. Select target systems for years 3-5.										KE2.2ii		
O3.1i Paper Research paper on impacts of scale on biodiversity-function relationships in different woodland habitats.											D3.1i	
O3.2i Connectivity maps and paper Connectivity maps & research paper based on								D3.2i				

connectivity measures.												
O3.3ii Spatial targeting map and paper Map showing zones of opportunity (spatial targeting) for the protection of temperate rainforest; scientific paper.										D3.3ii		
Report to RESAS.												R2

Name of RD: 1.3.2 Ecosystem services supply

Research aim and key drivers: Humans are dependent on ecosystem services from their natural environment to such an extent that they are starting to exceed planetary boundaries. This RD aims to understand and evaluate the mechanisms underpinning ES flows, with a focus on habitats and biodiversity. Although a wealth of insights into ecosystem functions, ecosystem structures and benefits (*sensu* ES cascade) exists, knowledge of the mechanisms that link these in ES delivery is often disjointed and context-specific. The RD aims to bring together such knowledge through a set of multidisciplinary, empirical analyses that build on international literature and focus specifically on the links between structures, functions and benefits (or in alternative terms, between natural capital stocks and ES flows), to identify key patterns that help us to explain and evaluate ES supply. We use here the term 'flow' as synonymous with 'supply', 'provision', 'production' and 'delivery', recognising that natural capital stocks often require additional (human) inputs to turn into flows of services that are directly or indirectly of use for humans.

Empirical work will focus on the influence of management interventions on such ES flows. In Scotland, key policy drivers at the national level include the Forestry Strategy (SFS: woodland expansion), SRDP, the Scottish Biodiversity Strategy (SBS), the National Peatland Plan, Scottish Planning Policy and the Land Use Strategy, but also strategic regional programmes such as the Central Scotland Green Network (CSGN). Of particular relevance for this RD, the SBS Route Map targets ecosystem restoration, the development of quality greenspace and sustainable land management, thereby working towards the Aichi targets and reducing adverse impacts in terms of Planetary Boundaries (see Theme 1 overview). The impacts of these policies, associated programmes and incentive mechanisms need to be understood to improve their design and delivery. Therefore, this RD will not only generate static 'snapshots' of ES flows at a given point in time, but investigate ecosystem responses to a range of management interventions and evaluate the resulting changes in ES flows. Ecosystem restoration rapidly grows in relevance at the national (SBS Route Map) and international level (e.g. EU Biodiversity Strategy), and will therefore be one of the areas of focus of this RD, but research will also investigate the impact of other management options (e.g. changes in grazing regime independent from potential restoration objectives).

This RD will contribute to the WP and Theme visions by furthering our understanding of the impacts of selected management interventions (including restoration) on ES flows, and of the associated trajectories of change, which feeds into decisions and reporting towards international commitments at the national level and helped develop our impact and collaborations in the international scientific community, *in particular addressing Theme 1 Research Question RQ3.*

The work will cover a wide range of systems and their social contexts, including a gradient of woodland systems from the peri-urban to the remote (amongst them also sites classified as 'wild land' by SNH, and ash-oak rainforests), and a set of diverse upland grassland habitats. It will generate insights into the links between management interventions and ES production; information which can assist land managers as well as higher-level decision makers to make informed choices. Through both structured and informal communication measures, at the local through to the national level, insights will be communicated in ways appropriate to decision-making at the respective level, from concrete, case-specific recommendations to actors at the study site, to generalised, transferable advice at the regional and

national level.

Who has been consulted in developing this proposal?: The proposal is informed by consultation with relevant staff at SNH and RESAS in spring and autumn 2015 and the Biodiversity and Land Use Team at Scottish Government in September 2015. The upland work has been discussed with SEPA and the Loch Lomond and the Trossachs National Park (LLTNP), the work on zoonotic pathogens with Scottish Water, NFUS, the Drinking Water Quality Regulator for Scotland and QMS, Glen Creran work with the Forestry Commission, work in the Cairngorms National Park (CNP) with the CNPA, in particular in relation to the Capercaillie Framework and woodland expansion plans (including also at the Cairngorms research meeting, October 21-22), and peri-urban research with the CSGN. Parts of the proposal related to cultural services and landscape quality have been discussed with the Royal Commission on the Ancient and Historical Monuments of Scotland (now Historic Environment Scotland).

Summary of the proposal:

This RD aims to improve our understanding of the role of habitats and biodiversity in the production of ES, and of the impact of management interventions on ES flows. It recognises that humans play a crucial role in the creation and/or facilitation of many ES, including provisioning, regulating and cultural services. Consequently, the RD employs an interdisciplinary, integrated approach to the analysis of ES flows. More specifically, the goals of this RD are:

- To assess and evaluate trends, i.e. changes in the production of ES, in response to ongoing and future changes in ecosystem management (and underpinning policy drivers).
- Building on this, where possible, to quantify the relative impact of human interventions and changes in natural capital stocks on ES flows across contexts, using statistical modelling techniques.
- To assess and evaluate the effectiveness of management interventions (including approaches to ecological restoration) in terms of ES supply.
- To develop recommendations for practitioners and policymakers on ways to improve existing policies and programs on biodiversity and ecosystem management, in order to enhance ES supply.

This RD will develop detailed, empirical assessments of ES in selected systems. Rather than providing static assessments of ES flows at a given point in time, analyses will be focused on effects of changes in management to determine the relative impacts of such interventions. Work in RD 1.3.4 will complement our research through its focus on e.g. agri-environment schemes. As part of the work, trajectories of ecosystem change on a gradient of different environmental and social contexts will be investigated. To do so, the RD draws on existing data, and collects new social scientific and ecological data as required. It will work closely together with complementary RDs, e.g. in WP 1.1 to assess the impacts of management interventions on carbon sequestration.

Apart from its foundations in the existing literature (including the UK National Ecosystem Assessment Follow-On UK-NEA (FO) and the Common International Classification of ES: CICES), the proposed research builds on the research and platforms used in the current Strategic Research Programme (SRP 2011-2016). This includes testing of frameworks for understanding ES production, drawing where relevant on established relationships with stakeholders and study sites, and building on existing insights and data in relation to ES flows across a wide range of systems from peri-urban greenspace to peatlands, grassland and woodlands. The work will

be underpinned by strong stakeholder engagement and co-construction of the concrete research agenda at both the national and the study region levels. Empirical work is organised into three Objectives (O):

- O1: Interdisciplinary assessment of the effects of management interventions on ES flows from woodlands at the local and landscape scale (Hutton, RBGE)
- O2: Investigating the supply of ES and biodiversity from semi-natural habitats in upland areas under different management regimes (SRUC, Moredun)
- O3: Additional empirical research resulting from co-construction with stakeholders.

Key deliverables (see Gantt chart for milestones, detail and timing in Years 1-2):
From across the Objectives/Integrated activities (see list of objectives below)

- D.1-3.x: Peer-reviewed journal publications – a minimum of 11 from across *all objectives*. Topics include the effects of ecosystem management on trajectories of ES flows from ecological, social science and integrated perspectives, effectiveness of restoration measures, and trade-offs between benefits and disbenefits arising from changes in ES flows (Years 3-5)
- KE1-3.x: Outputs directed at local stakeholders and decision-makers (Years 1-5, from across *all objectives*). These include e.g. formal and informal briefings on frameworks and methods for ES assessment, metrics and indicators, the assessment of CES, impacts of restoration and other management approaches on ES flows, trajectories of changes in ES flows and the resulting (dis-)benefits
- KE1-3.x: Active participation in and dissemination through ESCom and stakeholder-led workshops (Years 1-5, from across *all objectives*)
- R1-R5: Annual reports to RESAS (Years 1-5)

Objective 1: Interdisciplinary assessment of the effects of management interventions on woodland-related ES supply

- D1.1i: Interdisciplinary scientific workshop (Year 1)
- D1.1ii: Peer-reviewed journal publication: Effects of biodiversity enhancement on the delivery of cultural ES (Year 2)
- D1.2i: Description of scenarios by study site (Year 2)
- D1.3i: Set of qualitative data on human role in and perceptions of ES production (Year 2)
- D1.4i: Compilation of existing ecological datasets in study sites in relation to scenarios, with gap analysis (Year 1)
- D1.7i: Visualisation outputs, for dissemination through a centralised KE website and Scotland's Environment Web (Year 4)
- KE1.8i-iii: Stakeholder engagement weekends in study sites along the study framework gradient (Years 1-3)

Objective 2: Investigating the supply of ES and biodiversity from semi-natural habitats in upland areas under different management regimes (Years 1-5)

- D2.2i: Maps of ES and uncertainties (with RD 1.4.1) for use by stakeholders such as SNH, LLTNP, Scottish Government, and their translation into guidance for land managers and their advisors on best practice and briefings on land use impacts on e.g. agricultural production, vegetation, wildlife, soil processes and emissions, hydrological processes, zoonotic disease risk, recreational and cultural value (Years 2-5, output of *O2.1-3*)
- KE2.3i-x: On-farm meetings at Kirkton to discuss practical management of

Cryptosporidiosis in farm livestock (Years 2-4, related to <u>*O2.2 and 2.3*</u>)

Technical approach:

Research in the RD will cover two sets of systems that could, chiefly, be labelled 'woodlands' and 'upland grasslands'. However, both sets include a wide range of habitats, including, e.g. extensively grazed land, peri-urban derelict sites and moorland. The focus on woodlands was chosen as it is a priority policy area (see SFS), it spans both lowland and upland, highly accessible as well as more remote and 'wild' as well as substantially modified sites, across a large part of Scotland. This broad habitat type allows us to analyse both specific and more generalizable patterns in ES flows and their responses to management interventions across study areas. In addition to their biodiversity and C storage importance, woodlands have the potential to provide a large range of cultural, regulating, supporting as well as provisioning ES and are therefore a particularly interesting study case. In addition, woodland expansion is one of the foci for integration across WPs to which we will contribute; the Centre of Expertise on Climate Change (CXC) also has a specific strand working on the potential of woodlands for carbon sequestration under different scenarios provided by the Forestry Commission and, by ground-truthing their model, provides this RD with support in the quantification of this ES.

The focus on upland grasslands was chosen not only because uplands form such a major part of Scotland's land mass but also because of the importance of the likely future land use changes in the uplands which have the potential to impact positively or negatively on many of the environmental challenges facing wider society, e.g. biodiversity conservation, carbon sequestration or natural flood management. The location chosen as the focus for the work has two large (each 400+ ha) areas with contrasting land management history over the past 20 years and is characteristic of much of the west Highlands of Scotland. The large scale and contiguous nature of the study areas means that they are suitable as a platform for the empirical work looking at intended and unintended consequences of land use change on a wide range of ES.

Complementary work will be carried out in RD 2.3.11, which includes a focus on trade-offs between regulating, supporting and provisioning ES in arable systems.

<u>*Objective 1. Interdisciplinary assessment of the effects of management interventions on woodland-related ES supply (Years 1-5)*</u>*:*

This study investigates the influence of management interventions on ES supply from woodlands. Sites will be selected such that they form a gradient from the peri-urban to the remote and from the heavily degraded to the semi-natural, and from the lowlands to the uplands. We will complement a small selection of woodland areas within the Central Scotland Green Network (CSGN) (shared with 1.4.3 and 3.4.3) with sites of ongoing or planned woodland expansion/restoration in the Cairngorms National Park (CNP), and in Glen Creran (Argyll, ash-oak rainforest, in partnership with the Forestry Commission and SNH). In the CNP, this will likely include sites that are included in the National Park Plan and the Capercaillie Framework (link to RDs 1.4.3, 1.3.3 which also work on the Capercaillie Framework), but woodlands created as part of the SRDP-funded Croft Woodlands Project will also be considered. The final selection of sites will be made in collaboration with stakeholders (Year 1).

Using a combination of ecological and social scientific approaches, changes in ES supply in relation to different states of restoration and different contextual variables will be assessed – from past states and the *status quo* to intermediate

states (which might have very different (dis)benefits compared to either status quo or target state) up to the target state, to enable an identification of likely changes of ES flows under different management scenarios. Restoration (see ARCADIS 2013 report to the EU) is here understood as a subset of ecosystem management activities, characterised by specific *intentions* (i.e. to restore a specific state, a place's natural autonomy, or specific ecological functions). The use of a range of sites will facilitate transferability of the findings.

Two key activities will form a starting point of the multidisciplinary, team-based work. *O1.1:* First, we will jointly define a framework suitable for a multidisciplinary assessment of ES from a gradient of woodland systems. In the development of this framework, we will consider the use of the ES Indicator database and other work in the current Strategic Research Programme (2011-2016) and develop metrics for the evaluation of restoration effectiveness across different ES (Milestone M1.1i). This framework will be critically discussed and refined at an interdisciplinary scientific workshop (D1.1i), and will be drawn on by other RDs such as 1.2.4 and 1.3.4 and the Farmland Biodiversity Initiative (integrated via 1.4.3). In addition, a rapid evidence assessment literature review on the effects of biodiversity enhancement on the delivery of cultural ES will be conducted, focusing on the so far under-researched aspect of biodiversity and landscape quality (links to RD 3.4.3, which focuses on the wellbeing derived from these) (M1.1ii). In collaboration with local stakeholders and RDs 1.4.3 and 3.4.3, study sites will be identified (M1.1iii).

O1.2: Second, together with key actors in the study sites, the team will identify different states of these sites (including past, present and where appropriate multiple future states) to frame the ES assessment.

The RD will then use a complementary set of methods to produce an inventory of ES and assess ES flows in past, present and future scenarios. This means that provisioning, supporting, regulating and cultural ES will all be included to be able to investigate the interplay between flows of different ES (including trade-offs), and to obtain a systematic overview of the impacts of management interventions on natural capital (i.e. stocks) and ES flows across all four ES types. In-depth components of the work may focus on selected group of ES. Methods will include:

O1.3: Interviews and other qualitative and/or quantitative methods (e.g. participatory methods, mobile and visual ethnography) which aim to understand perceptions of and the human role in the production of ES (Years 1-4);

O1.4: Secondary data analysis, expert and/or citizen science assessments of ecological aspects of ES flows and their responses to restoration measures. This will involve analysis with ordinal statistical techniques (Years 1-3);

O1.5: A field-scale experiment in Glen Creran that involves two treatments (blocks of isolated trees (n=5) vs. blocks with trees that are sited with the retention of canopy cover (n = 5)). For twenty individual trees within each of these blocks, target species (temperate rainforest epiphytes) will be transplanted from donor sites onto the tree trunks, to test contrasting approaches in species establishment (Years 2-5). In addition to optimising translocation protocols for restoration, the field-trial will be used to assess attitudes towards restoration and its visual impact on the landscape, as well as the willingness to invest for a future gain in non-market ES, associated with highly diverse though non-charismatic species (see O1.3, O1.7);

O1.6: Ground-truthing of secondary biodiversity data (where time intervals of existing woodland inventory and countryside survey data are inappropriate for our analyses) (Year 3);

O1.7: Rapid ecosystem/biodiversity assessment where there is insufficient up-to-

date data on restoration sites, with appropriate methodological testing (Years 3-5);

O1.8: Spatial analysis of contributions of land cover change (past, current and scenarios of future states) to landscape character, including changes in visibility, feeding into visualization tools (Years 1-5);

O1.9: Based on this data, visualization of past, present and future states to allow experts, stakeholders and the general public to form opinions on the proposed interventions, using a range of approaches, whose effectiveness will be evaluated as part of the research, from still images to Oculus Rift virtual reality headsets to augmented reality. This work will be integrated where possible with outputs from the mobile video ethnography, i.e. data showing actual and socially embedded movement through the same landscapes (Years 2-5).

While no new economic work will be carried out in this RD, the research team will collaborate closely with the environmental economists in RD 1.4.1 (and where relevant also RD 1.3.4) working on a Natural Assets Register to ensure that where possible, economic approaches to the valuation of ES can be included.

O1.10: In Years 3-5, findings from all study sites will be brought together in a joint analysis. This will include an estimation of the Total ES index (Dick et al. 2014, Ecological Indicators 38: 20-30) for each site. Comparisons between sites and states through agglomerative hierarchical clustering and canonical variate analysis will provide novel insights into the relative benefits and dis-benefits of each state and therefore effective guidance on future management efforts. Additionally, we will explore statistical techniques (including ordinal approaches) to quantify the relative impact of human interventions and changes in natural capital stocks on ES flows.

Objective 2. Investigating the supply of ES and biodiversity from semi-natural habitats in upland areas under different management regimes (Years 1-5):

This study will focus on quantifying the supply of ES from large areas of semi-natural upland habitats under differing management (livestock grazed upland grass moorland, destocked upland grass moorland, low density montane woodland and scrub planted on upland grass moorland and heath). A particular focus will be put on assessing the impact of such differences in management – akin to different stages in a 'rewilding process' – on terrestrial biodiversity (vegetation, pollinators, birds and small mammals) and on ecological and hydrological processes at a sub-catchment scale linking terrestrial and freshwater ecosystems. Historic data on biodiversity (vegetation, birds) is available to characterise differences/similarities between the glens prior to destocking (*O2.1*).

The study will assess the ES linkages, benefits and disbenefits associated with changes to, for example, biodiversity, agricultural productivity, greenhouse gas and carbon sequestration functions of soils and vegetation, and cultural and recreational values (*O2.2*, D2.2i). The ES data will help provide a more detailed context to ES mapping being conducted within RD 1.4.1, where colleagues will be testing an ES mapping approach developed by SNH as part of their Natural Capital Asset Index work. The latter involves assigning ES values to different EUNIS (European Nature Information System) habitats across Scotland. Data on ES collected from the upland areas forming the focus of this study will be used by RD 1.4.1 to compare and contrast estimates of potential ES delivery with what is actually assessed on the ground. The role of livestock, wildlife and upland vegetation type and structure in affecting zoonotic disease risk (e.g. *Cryptosporidium, Giardia* and *Toxoplasma*) will be investigated using molecular detection and typing methodologies (*O2.3*).

The primary initial focus of this study will be on two large, contiguous but

differently managed glens within SRUC's upland research farms (in Loch Lomond & Trossachs National Park) to provide three contrasting levels of both management and grazing by livestock and wildlife:

- 390 ha of grazed hill pasture - moderate livestock levels (primarily sheep) and deer grazing
- 550 ha of destocked hill pasture with low levels of deer and some sheep
- 180 ha of fenced, essentially 'un-grazed' (by both deer and livestock) grass/heath with low density, planted mountain woodland and scrub.

The wider farm and catchment within which the two glens sit will also be incorporated as a case study into a largely desk-based assessment being conducted within RD 1.4.3 of: (a) the ES service implications at a landscape scale of different types and scale of habitat creation and management via agri-environment measures: (b) potential barriers to farmers of implementing such measures at landscape scales.

In addition, the team will collaborate with colleagues in RD 3.4.1 in an assessment of the effects of previous demographic and land use change in remote areas of the Highlands and the implications for ES delivery, as well as the development of scenarios of future demographic and land use change in the uplands. This will allow an extrapolation from the empirical findings and a prediction of scales of change across wider geographical areas of future ES delivery.

Objective 3: Additional empirical work (Years 3-5): Additional empirical research will be developed in discussion with stakeholders, and could, depending on funding, include work on agricultural land with a link to study sites used in Theme 2.

In addition, the interdisciplinary assessment of the effects of restoration and other management interventions on ES flows from woodlands could be expanded by examining the resulting land management decisions as a consequence of contrasting policy targets for woodland versus peatland restoration (Years 3-5, with linkages from RD 1.1.4). Results from such work would feed back into the WISE decision support tool (in CxC peatlands), and RD 1.1.4.

Detailed work plan - See Summary, Technical approach and Gantt charts.

Key linkages, interdisciplinarity & collaboration:

Work within RD 1.3.2 is highly interdisciplinary combining as it does biophysical and social scientists to address single research questions. Its interdisciplinary role is also emphasised by its strong linkages both within and outside of the SRP.

Links with other research deliverables: Links with WP 1.4 are particularly strong and consist of: (a) sharing of study areas with RD 1.4.3 (CNPA, also used by RD 1.3.3, and CSGN, also used by RD 3.4.3), which facilitates stakeholder engagement and KE; (b) the development of complementary perspectives and research activities (e.g. while RD 1.3.2 looks at the creation of multiple benefits from ecosystems, RD 1.4.2 examines how policies support or hinder the delivery of these benefits); (c) provision of case studies for natural asset mapping (linking to RD 1.4.1 which also builds on mapping approaches developed within the 2011-16 RESAS programme). For example, modelling work in RD1.4.2 will address the impacts of changing connectivity on woodlands. Such insights will be highly relevant for the assessments of changes in ES in RD1.3.2. Similarly, the landscape scale work in RD 1.3.2 will be complemented by larger tranches of work using this perspective, including mapping and spatial analysis, in RD1.4.2. In addition, added connectivity with systems work in Theme 2 will be enabled by the CKEI activities, such as at platform sites, i.e. Kirkton, and future opportunities for interdisciplinary work and visioning in the Think Tank.

Links with CAMERAS: The proposed work aligns with the CAMERAS Evidence Strategy. It will deliver to the need for evidence on (i) optimising land use and (ii) managing natural resources for multiple benefits by providing:

- better understanding of the implications of land use change and management practices for e.g. biodiversity, tourism and amenity land use
- insights supporting the identification of sites for and benefits of woodland expansion and agroforestry
- evidence on the effects of practical management measures on benefits
- new approaches to assess the societal value of natural resources.

Links with other, international research within the MRPs: The teams involved in this RD have a large portfolio of research on ecosystem services across a whole range of different systems and subjects, developed through UK-wide as well as international work. Team members are well networked across Europe, as evidenced, for example, by various projects and applications related to woodland ES with Norwegian partners (e.g. MANECO; SUSTHERB), and a Stage 2 bid recently submitted in response to an EU H2020 call on ecological restoration. At the UK-level, the team is continuously active in networks such as the Natural Capital Initiative (which is currently chaired by one of the team), ESCom (with two of the team in the management committee) and Valuing Nature (VNN) with, for example, a recent bid on woodland expansion and the values of and trade-offs between various woodland characteristics. If successful, these new projects would add value to the work proposed here through complementary data collection for the same study sites, local as well as international platforms for dissemination of findings among a wide range of stakeholders (including policymakers), and added capacity in theoretical work.

Added scientific value: In the last ten years or so, research on ES has rapidly developed, especially in the UK. A wealth of case studies, conceptual contributions and overview reports (notably, the UKNEA and Follow-On (FO)) are now available. This also includes a range of approaches to comprehensively categorise and assess ES (see, e.g. CICES, UKNEA), also in relation to biomes such as woodlands and grasslands. The RD will (jointly with relevant stakeholders) identify priority gaps that the empirical work will attempt to fill. The proposed work addresses one of the gaps that are already apparent, namely a perspective on *trajectories* of restoration and management interventions, and their impact on ES flows, using an integrated, multi-disciplinary perspective. With innovative combinations of methods (e.g. including visualisation) this RD will be able to assess perceptions of ES flows as they change in response to management measures, thereby providing a dynamic perspective on the acceptability of these interventions. The work is likely to lead to several high-impact scientific publications for ecological as well as environmental social scientific and interdisciplinary audiences. The establishment of a large-scale detailed study of the biodiversity and other ES impacts of land use change in the uplands will also serve as a platform on which to build other non-RESAS funded collaborative work with other agencies and HEIs. SRUC is in detailed discussion with colleagues in the British Geological Survey, and SRUC and Moredun are in conversation with catchment management researchers in the University of Stirling with regard to the potential for those two HEIs to bring added scientific value to this RD.

Through collaborative activities (joint workshops, conference sessions and publications and edition of special issues – e.g. through the 'Values of Nature' workshop in Wageningen, the Netherlands, in November 2015) the team is also in close contact with colleagues in UK organisations (e.g. Forest Research, University of Edinburgh, CEH) and other countries working on similar issues. Aside from major

European initiatives and projects (eg TURaS, OpenNESS, OPERAS, BioDivERsA, and URBES), the team plans to connect with: (a) work by Forest Research on the Central Scotland Green Network; (b) the GreenHealth project and follow-up research on urban greenspace and human health and wellbeing; (c) the NERC-funded BESS project on trade-offs between ES in marine environments; and: (d) the Forestry Commission's Woods In and Around Towns (WIAT) programme. These activities will allow the team to (i) ensure that their research builds on and adds to existing work (and avoid duplication) and (ii) use links with other work to create joint additional value (e.g. through joint publications and KE outputs).

KE, audiences and impact: This RD will develop mechanisms for stakeholder engagement in line with those of the other RDs in this WP. As described for WP 1.3 overall, this RD will actively contribute to the BLUPU activity, with regular lunchtime meetings in Edinburgh for policy teams and other stakeholders to share updates and feedback on the research process, and twice-yearly meetings of the WP 1.3 Working Group for wider stakeholder consultation. Specifically for this RD, we will hold regular formal as well as informal meetings with stakeholders in the study sites (CNP, CSGN, Glen Creran and Kirkton), and provide a wide range of outputs designed to aid policy, industry and communities, as well as the active participation in workshops organized by stakeholders. Through the WP management group, this RD will liaise with the KE Sectorial Leads to integrate our KE activities with those of the CKEI. The RD will also contribute directly to CKEI activities such as the central programme website and cross-theme signature events. This multi-method approach will allow us to align the research to stakeholders' aims, while also improving the understanding of our research approach and findings amongst end-users.

Pathways to Impact:

At the national level this RD's work on the mechanisms behind ecological restoration and other management interventions in relation to ES flows and on the human role in ES provision will be directly relevant for the UK's and Scotland's efforts towards the 2020 Aichi targets. BLUPU and the WP 1.3 Working Group will be employed to make the research in this RD useful for reporting towards these targets (with interim reports for the CBD due in 2017), and also in relation to the monitoring of progress along the SBS Route Map. Among the Big Steps for Nature, this RD is immediately relevant for Step 1 with Priority Project 2 (Restoration of native woodland both in general and in relation to Atlantic oakwood, by 2022), Step 3 with Priority Project 5 (More people experiencing and enjoying nature: Support better provision and quality of greenspace) and Step 5 (Sustainable management of land and freshwater, especially improving ecological connection in central Scotland). While precise details of actions are still being clarified between SNH and their partners, the dissemination of our findings for Route Map monitoring will likely run through SNH. In addition, the RD will produce recommendations for the effective and efficient design of management interventions. Work in this RD could also provide the basis for briefing notes on the UN Sustainable Development Goals, as per the Scottish Government Programme for Government 2015-16, in September 2015, in particular Targets 15.2 (restore degraded forests) and 15.6 (integrate ecosystem values into planning).

Stakeholders engaged in our study sites: This RD will have major relevance for the stakeholders with whom we work at individual sites (e.g. CNPA, CSGN, LLTNPA, Forestry Commission, SNH, land owners and land managers, the local public). A diverse set of activities and outputs developed together with these stakeholders will ensure that research has significant impact. Both formal and informal means of communication will be employed; this includes contributions to stakeholder-led

meetings (eg SNH or CNPA workshops) as well as stakeholder conversations and events organised by this RD (where appropriate jointly with other RDs working in the same study sites, in particular RD 1.4.3 and 3.4.3). Mobile visualisation techniques, such as Oculus Rift Virtual Reality headsets, allow not only the collection of data and stakeholder engagement (like most of the methods that we plan to use), but will also be employed to help land managers and other decision-makers to assess and evaluate the impact of ES management and ecological restoration. The RD will explore options to contribute to the new Cairngorms National Park Plan (due in 2017, with a consultation in summer 2016). For the Forestry Commission and SNH in Glen Creran, information on how people respond to pathways of ecosystem change (e.g. based on different levels of information/education) will help policy succeed and gain traction when dealing, e.g. with the removal of non-native species. Measures for this type of impact would include feedback from stakeholders.

Scientific audiences will be reached through publications, including synthesis articles in high quality international journals, presentations at conferences and other scientific meetings, and a small workshop in Year 1. We will also actively engage in ESCom: One of our team is a member of the management team, and we will use the Annual Event, appropriate Working Groups and smaller meetings – these may be led by us or co-organised e.g. with Forest Research or the University of Edinburgh – to disseminate and discuss our research with other interested parties, including HEIs, agencies and NGOs. Likely impacts include new collaborations for future research projects, raising awareness across a wide range of people and identification of implementation options (in the widest sense) for some of our findings. More widely, we hope that our work becomes known for addressing the production of ES in an interdisciplinary fashion, looking at the human role in ES flows as well as the dynamics of ES flows over time, in response to management interventions.

The wider public (beyond the study areas) will predominantly be addressed through news releases and public events, and will likely increase awareness and appreciation of the human role in fostering (or hindering) ES flows.

RESEARCH DELIVERABLE NUMBER: 1.3.2

Work planning and timetable for Year 1 (O=Objective, KE=Stakeholder engagement and knowledge exchange, M=Milestone, D=Deliverable – see list above; for RD contributions to KE at WP level see WP1.3 description)

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1: Development of a joint conceptual framework **O1.1i**: Development of framework for ES assessment, including inventory of ES, criteria and metrics, consultation and dissemination to other RDs (e.g. RD 1.2.4, 1.3.4) – ***M1.1i: Framework developed***, D1.1i: Scientific workshop **O1.1ii**: Rapid evidence assessment literature review – ***M1.1ii: Manuscript submitted to journal*** **O1.1iii**: Selection of study sites – ***M1.1iii: Sites selected*** KE1.1i: Dissemination to wider stakeholder arena (including ESCom) – Specification of framework.								D1.1i	M1.1iii		KE1.1i	M1.1i M1.1ii
O1.2: Identification of scenarios ***M1.2i: Scenarios drafted*** KE1.2i: Outputs directed at local stakeholders – Draft specification of scenarios.												M1.2i KE1.2i
O1.3: Interviews and social scientific data collection through other qualitative and quantitative methods: Methods development, ethics approval.												
O1.4: Analysis of existing ecological data and expert /citizen science assessments. Identification of suitable datasets, identification of gaps, method development for expert assessments and citizen science, begin data analysis and expert assessments. ***M1.4i: Available data assessed, gaps analysed, need for additional data determined.*** D1.4i: Compilation of existing datasets with gap analysis.												M1.4i D1.4i
O1.8: Spatial analysis of landscapes (including visibility) KE1.8i: Stakeholder engagement weekend in study sites along the study framework gradient.							KE1.8i					
O2.2: Data collection and analysis – ES linkages ***M2.2i: Collaborative sampling strategy established*** ***M2.2ii: Pilot assessments for above-ground biomass and biodiversity completed.*** KE2.2i: Outputs directed at local stakeholders – first findings (joint with O2.3). KE2.2ii: Dissemination to wider stakeholder arena (including ESCom) – first findings (joint with O2.3).		M2.2i				M2.2ii					KE2.2i	KE2.2ii
O2.3: Data collection and analysis – zoonotic disease risk; Sample collections – zoonotic protozoa; For KE see O2.2.											KE2.2i	KE2.2ii
R1: Year 1 Report to RESAS.												R1

Work planning and timetable for Year 2

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1: Development of a joint conceptual framework - update of framework Revision of rapid assessment evidence review and publication (D1.1ii).												D1.1ii
O1.2: Identification of scenarios - update of scenarios ***M1.2ii: Scenarios finalised*** D1.2i: Description of scenarios by study site.			M1.2ii D1.2i									
O1.3: Interviews and social scientific data collection through other qualitative and quantitative methods: Data collection ***M1.3i: Methodology designed (including interview guidelines)*** D1.3ii: Set of qualitative data (transcribed) on human role in and perceptions of ES production KE1.3i: Dissemination to wider stakeholder arena (including ESCom) – first findings (joint with O1.4).		M1.3i										D1.3i KE1.3i
O1.4: Analysis of existing ecological data and expert /citizen science assessments Design of instruments for expert and citizen assessments, data collection. ***M1.4i: Instruments designed*** KE1.3i: see O1.3.						M1.4i						KE1.3i
O1.5: Restoration of ash-oak forests Establishment of experimental trials for rainforest recovery. First stage monitoring of trials.												
O1.8: Spatial analysis of landscapes (including visibility) Database compilation, landscape analysis. KE1.8.ii-iii: Stakeholder engagement weekends in study sites along the study framework gradient.		KE1.8ii										KE1.8iii
O1.9: Visualisation of linkages in ES flows Selection of scenarios to be visualised in collaboration with key stakeholders in study sites, methods development. ***M1.9i: Scenarios selected***				M1.9i								
O2.1: Review: Land use change Demographic change (RD 3.4.1) and impacts on ES – start of the work.												
O2.2: Data collection and analysis – ES linkages ***M2.2iii: Interviews with stakeholders completed*** D2.2i: Maps of ES and uncertainties (from Objectives 2.1-2.3).							M2.2iii			KE2.3i KE2.3ii		D2.2i KE2.2iii

KE2.3i-ii: see O2.3. KE2.2iii: Dissemination to wider stakeholder arena (including ESCom) – Maps.												
O2.3: Data collection and analysis – zoonotic disease risk KE2.3i: Outputs directed at local stakeholders – update on findings/maps. KE2.3ii: On-farm meetings at Kirkton.										KE2.3i KE2.3ii		
R2: Year 2 Report to RESAS.												R2

Name of RD: 1.3.3 Resilience of ecosystems and biodiversity

Research aim and key drivers: Planetary boundaries for several ecosystem processes are now being exceeded, both at the global and Scottish level. This RD aims **'*to understand the extent to which different ecosystems are resilient and how their resilience and integrity can be restored or enhanced***.' *The RD will contribute to the WP and Theme visions by helping to ensure that in 2021 Scotland is equipped with a better understanding of the resilience of its natural and semi-natural ecosystems, and how this might be effectively conserved or enhanced, in particular addressing Theme 1 Research Question RQ2.* This will require underpinning knowledge of the resilience of central components of biodiversity and ecosystem function in the face of three key biophysical and environmental drivers: i) climate change; ii) land management changes such as afforestation/deforestation or agricultural intensification/ extensification; iii) increased impacts of pests, pathogens and invasive non-native species (INNS). This need is acute for protected species and habitats, including the vulnerable systems chosen for study in this RD. Developing our understanding of resilience will aid our ability to predict, manage and conserve the natural environment via future policy formulation or refinement of current policies e.g. 2020 Challenge for Scotland's Biodiversity (2013) and 2020 Route Map (2015), Scottish Forestry Strategy (2006 *et seq*), Land Use Strategy (2011,2016), and the Climate Change (Scotland) Act (2009).

Who has been consulted in developing this proposal?: Representatives of the following bodies were consulted in developing this proposal and selecting case studies: Objective 1 (O1): SNH, SEPA, Marine Scotland, Scottish Marine Animal Stranding Scheme (SMASS), SMRU, SEPA; Objective 2 (O2): FC, FR, CEH, Alba Trees Ltd, Health Protection Scotland, CNPA, RSPB, Univ. of Reading; Objective 3 (O3): Scottish Tree Health Advisory Group, JNCC, SNH, Botanic Gardens Conservation International, FR, Plantnetworks, FC, Univ California, Amphibian and Reptile Conservation Trust, SWT, Scottish Squirrel Group.

Summary of the proposal:

Research within RD 1.3.3 investigates various components of resilience to provide information that will help predict the consequences of environmental and climate change on species, habitats and ecosystem health, and to manage them such that their resilience is enhanced. This will be delivered via three Objectives: O1: Synthesis, meta-analysis and integration for prioritisation of resilience management; O2: The consequences of environmental and climate change for ecosystem resilience; O3: The impacts of plant and animal disease, and the spread of INNS in natural environments.

As resilience may be context- (i.e. driver or response) specific, to understand processes regulating resilience the RD focuses on three high-profile external drivers (climate, change, land use change, and INNS/pests and diseases) and three internal attributes of systems that can mediate their resilience (adaptive capacity, environmental limits, and asset degradation). O1 is an over-arching integrative activity: processing existing data and knowledge in this relatively new area; defining best current knowledge and identifying gaps; incorporating new understanding of resilience processes arising from activities in O2 and O3 and elsewhere in the research programme. O2 focuses on the impacts of environmental change and land management on key components of vulnerable ecosystems, in order to understand how system resilience is determined by how these key components are changed by, resist, adapt or recover from change. O3 focuses on the impacts of one of the main

drivers of change in the form of INNS and emerging pests and pathogens of plants and animals. The RDs will develop novel monitoring tools for measuring system resilience, risk and uncertainty assessments related to resilience, and management options and guidance to promote resilience. This integrating structure is in Fig. 1.

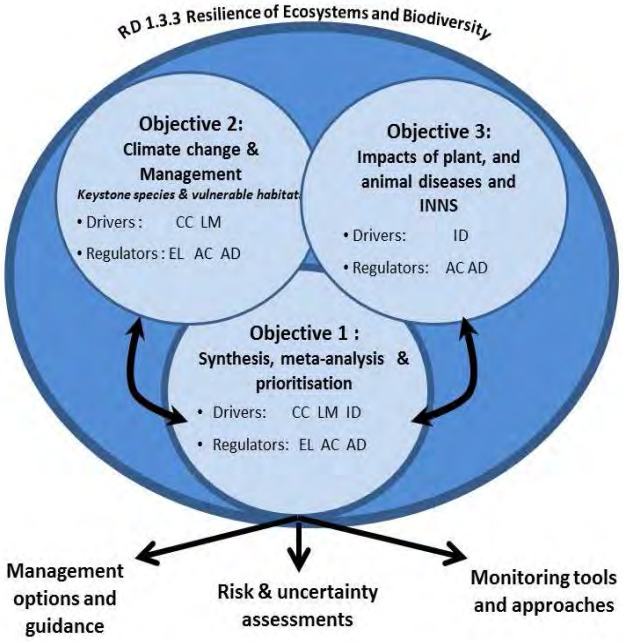


Fig. 1 Conceptual Framework for 1.3.3. **Drivers:** Climate change (CC); Land management (LM); Emerging INNS, pests and diseases (ID). **Resilience regulators:** Adaptive capacity (AC); Asset degradation (AD); Environmental limits (EL).

Component studies in O2 and O3 were chosen in discussion with stakeholders because they provide outcomes for particular vulnerable systems (woodlands, peatlands, uplands, high conservation value grasslands) or species, they are tractable, or comprise processes that are generalizable and transferable to other systems. They collectively cover the key drivers and internal system regulators defined above.

The RD leader will be responsible for research progress against the agreed timetable. This will be achieved by frequent informal contact and formal annual meetings within the RD and with the other RDs applying resilience concepts, to ensure progress and exchange ideas and outputs.

Objective 1: Synthesis, meta-analysis and integration for prioritisation of resilience management - Biodiversity resilience has not been a major component of previous RESAS research programmes. This RD will therefore initially synthesise previous work, identifying the best current knowledge and distilling elements of wider applicability of the study of resilience to a range of ecosystems in Scotland. Then as O2 and O3 progress, their outputs will feed into O1 to address gaps and strengthen its conclusions, applications and recommendations for management and policy action. This will proceed in consultation with proposed SNH work on contingency planning, and will produce outputs to inform, for example, the SRDP review starting 2017. O1 will work collaboratively with related work in arable systems (notably RD2.3.8 and 2.3.9), integrating it with the resilience science in vulnerable habitats in this RD. It will develop a typology of resilience, in order to incorporate resilience into future land management options including those driven by SRDP and Greening measures. It will also investigate the potential of novel indices of ecosystem health and resilience. O1 will run collaboratively with the integrative components and Ecosystem Health Index development in RD1.3.1, using the WP1.3 KE Stakeholder Working Group to deliver optimum engagement, synergy and impact.

Objective 2: The consequences of environmental and climate change for ecosystem resilience - The responses in distribution and abundance of important vulnerable habitats and species (keystone, foundation and umbrella species) to the effects of land use and climate change provide nodes at which to understand mechanisms that govern resilience, and at which to target future effective delivery of biodiversity benefits and resilience management. Studies of these pivotal responsive ecosystem components form the basis of O2. The responses of different species or communities

(e.g. umbrella species Scots pine, Capercaillie; ticks as major pathogen-vectors; peatlands) to environmental stressors indicates their resilience to predicted change and responsive management action. Outputs will be delivered to O1 for integration and development of common understanding, and strategically to WP1.4, for example data on species and habitat range shifts for integration into the Natural Assets Register (1.4.1) and delivery of multiple benefits (RDs 1.4.2 and 1.4.3). The outputs will also be directed to specific end-user groups requesting the work, e.g. Health Protection Scotland, STHAG, CoE for Plant Health, RSPB, CNPA.

Objective 3: The impacts of plant and animal disease, and the spread of INNS in natural environments - O3 investigates the consequences of some of the main threats to the integrity of natural and semi-natural ecosystems, endemic and non-native pests and pathogens and other INNS. They can play a crucial role as mediators of ecological interactions that determine ecosystem resilience via their effects on key components of ecosystems, and the ability or otherwise of those components to resist, adapt or recover. A significant body of work on the dispersal of fungal pathogens of plants and initially of INNS of shrubs and trees will form the basis for predictions of spread of disease or INNS, and we will develop a generalised methodology to assess the wider risks and impacts on overall biodiversity and ecosystem function resulting from plant pathogens. We will identify best practice for using grazing management to promote biodiversity benefits without compromising animal health, and we will contribute to resolving the problem caused by the INNS grey squirrel as a driving influence in the decline of the native red squirrel.

Key deliverables: - Deliverables (D) for each Objective (O) and sub-objective. For milestones for years 1 and 2 - see Gantt Chart.

Objective 1:

D1.1i , yr 1. Synthesis report (based on meta-analysis) on resilience concepts and application to systems of concern in Scotland, and in relation to intervention policies.

D1.1ii, yr 4. Paper and policy note on factors regulating resilience in agricultural and semi-natural ecosystems.

D1.2i, yr 2.Typology of resilience.

D1.2ii yr 4. Revised resilience typology (use findings from O2 and O3); pass to 1.4.1.

D1.3ai, yr 3. Appraisal report of MODIS-based ecosystem resilience index.

D1.3bi, yr 4. Peer reviewed publication on prevalence of Campylobacter in seals and coastal environments and implications for ecosystem resilience.

D1.3bii, yr 5. Policy advice/research summary note on incidence and prevalence management of Campylobacter in seals and coastal environments and implications for ecosystem resilience.

Objective 2:

D2.1 i, yr 4: Advice note, popular article and scientific publication on propensity of Scots pine provenances to support insect biodiversity under climate change.

D2.1 ii, yr 5: Scientific publication on resilience of Scots pine growth and survival of late winter frosts in relation to provenance and resistance to pests.

D2.2a i, yr 3: Scientific publication on environmental limits and range shifts of ticks.

D2.2a ii, yr 4: Popular article on environmental limits and range shifts of ticks.

D2.2a iii, yr 5: Advice note on management implications of tick redistribution.

D2.2b i, yr 3: Scientific publication and advice note on Capercaillie range shifts and management.

D2.2b ii, yr 4: Scientific publication on range shifts of a second vertebrate keystone or umbrella species (agreed with stakeholders) in response to climate and land use.

D2.2c i, yr 2: Scientific publication on effectiveness of MODIS-based model in estimating peatland condition.
D2.2c ii, yr 5: Research note on predictive modelling of restoration management impacts on peatland habitat composition.
Objective 3:
D3.1a i, yr 2: Policy note on the potential ecological impacts of tree diseases on the wider environment.
D3.1a ii, yr 2: Meta-analysis for model fits to groups of INNS, consider potential for results to inform management and submit paper.
D3.1a iii, yr 4: Paper on enhanced inference methods for INNS to better account for data and invasion processes.
D3.1a iv, yr 5: Policy note on generalised methods to assess the impact of plant diseases on the wider environment.
D3.1a v, yr 5: Scientific paper on selection of alternative trees and the role of non-native tree species in enhancing resilience of woodlands.
D3.1a vi, yr 5: Assess suitability of INNS modelling tools for application to plant pathogens and produce a report or paper if suitable data available.
D3.1b i, yr 1: Protocol for disease impact assessment of oomycete fungi on focal threatened plant species.
D3.1b ii, yr 4: Scientific publication on how resilience to fungal infection depends on the dispersal of pathogens and landscape-scale spatial distribution of hosts.
D3.1c i, yr 2: *Phytophthora* - metabarcoding, bioinformatics, interpretation and publication of results from year one samples of *Phytophthora*.
D3.1c ii, yr 4: Research summary on the range and possible impact of native and non-native *Phytophthora* species in selected Scottish ecosystems.
D3.2a i, yr 3: Research summary – Protocol for management of grassland for fluke and natterjack toads.
D3.2b i, yrs 1-5: Provide data and advice to the Scottish Squirrel Group on the distribution and relative prevalence of SQPV in the grey squirrel population.

Expertise:
Hutton: has multidisciplinary expertise in habitat and species biodiversity data collection, analysis of species distributions and interpretation of the consequences, along with expertise on ecological function, functional diversity, and associated molecular and chemical technology.
RBGE: will contribute practical experience in the taxonomy and all aspects of the biology of fungal diseases in threatened plants for native Scottish ecosystems.
MRI: has experience and a proven track record with respect to PCR diagnostics of *Campylobacter* spp., diagnosis of liver fluke infection in livestock and in the detection of liver fluke stages in the environment, and over 15 years of experience of developing and using diagnostics for SQPV.

Key linkages, interdisciplinarity & collaboration:
This RD combines information from different types of study and system and is therefore highly collaborative both across and outside of the MRPs.
Links with other deliverables and the wider RESAS programme: This RD will extend relevant work from the current RESAS programme and the CXC whilst contributing to the emerging CoE on Plant Health. Numerous reciprocal connections have been forged with participants in other Themes, which helps embed resilience work in the new SRP. The main ones are: 1) Linking knowledge on vulnerable ecosystems in this RD with that on resilience of arable systems in RDs 2.3.8 and 2.3.9 via scientific development meetings planned for years 1 and 3; 2) Funnelling integrative outputs

from O1.1 and b, along with specific outputs on redistribution of species from O2.2a and O2.2b to WP1.4, including the Natural Assets Register (1.4.1) and multiple benefits (RDs 1.4.2 and 1.4.3); 3) Transfer of results from O2.2c (Peatland Community resilience) to CXC peatlands, and ecosystem service delivery in 1.1.4 and functional (versus community) resilience effort in 1.2.2; 4). Collaborative INNS work in O3.1 through **HEI bid 4** (BioSS, UoE,SRUC) which will reciprocally share results with WP2.2.6 and 2.2.10 on dispersal of INNS and pathogens; 5) Derivation of data from other objectives for studies within 1.3.3, e.g. O1.1 will draw data from synthesis work in WP1.3.1, O1.2 will use a CXC generated risk assessment protocol, peatland modelling will modify a CXC developed model, tick range shift work will be informed by 2.3.3 work on deer-tick relationships, and O3.2 will use molecular methods developed in 2.2.6 to quantify pathogens and environmental vectors.

Links with other national and international research: The proposed work on adaptation and resilience of woodlands will extend work on established collaborative projects between Hutton and CEH, FR, SRUC, RBGE and the Universities of Aberdeen and Edinburgh, funded via the BBSRC LWEC Tree Health and Biodiversity Initiative phases 1 and 2 and a further initiative on the impact of diseases of oak funded by phase 3 of THAPBI (with University of Reading, CEH and FR). Tick distribution models will draw upon information from Australian and Norwegian Research Council-funded projects. Work on resilience indicators using *Campylobacter* in seals forms part of a large collaborative project involving SMRU and University of St Andrews. Overall 11/14 component studies are collaborative with non-MRPs and most of these (9/14) were co-constructed with stakeholders.

Research links to the Stakeholder Community: In several cases stakeholders will be closely involved in the research effort, e.g. RSPB (peatlands work), SNH and ARCT (grazing and liverfluke), FC (spread and impact of tree pathogens and pests), Health Protection Scotland (tick redistribution), SMASS Campylobacter resilience indicators.

Added scientific value: This RD will deliver added value by virtue of the numerous productive collaborations already existing, listed under 'Links with other research'. It will also facilitate further leverage of research into resilience science, and tree health. For example, work on *Phytophthora* and other tree diseases and the arising resilience issues will contribute to further collaborative proposals under H2020, LWEC, FORMAS (Sweden), and a bid to NERC. Work on *Campylobacter*, ticks and tick borne diseases will contribute to the knowledge of their impacts on both human and wildlife health. Peatland condition modelling will be extended to include climate change scenario modelling through a Joint Hutton/Univ of Reading SCENARIO PhD studentship (from October 2015).

KE, audiences and impact:

One of the main cross-cutting KE streams for WP1.3 will be 'Resilience' and this RD will coordinate contributions to that joint KE effort, and contribute to other WP, Theme level and CKEI KE activities. The WP1.3 Working Group will act as a hub for relevant communication for all aspects of biodiversity including resilience.

Audiences:

Links to the Stakeholder Community: The RD will build strong links to the stakeholder (policy, agency, NGO, land, forest and horticulture managers) community through the Theme and WP level workshops, the WP1.3 Working Group, our existing stakeholder networks, contributions to ESCom working groups and events, and a Forest Resilience stakeholder group which is part of the LWEC forest resilience project (PROTREE), membership of STHAG, UK Forum of Plant Diagnosticians, and as advisor to the Scottish Squirrel Group. Other such specialist groups such as the

Capercaillie BAP Group, SMASS, and ARCT will provide additional routes for KE.
Policy: Our main link to policy colleagues will be through the joint WP1.3/1.4 meetings with the Biodiversity and Land Use Policy Team (BLUPU initiative), and the Science and Technical Group of the Scottish Biodiversity Strategy. In the area of woodland resilience, membership of STHAG, and UK Forum of Plant Diagnosticians will facilitate KE with FC, FCS policy advisors. Synthetic outputs will be made available to all relevant policy teams.
Scientists: via peer-reviewed publications and conference presentations.
Education: training and teaching including on University MSc and BSc courses.
Public: magazine articles, shows/displays, TV and radio interviews and our websites.

Pathways to impact:

Currently the SRDP targets resilience outcomes, mainly for woodland management. The general syntheses and system-specific outputs of this RD will facilitate transfer of resilience directed actions to other vulnerable habitats (e.g. peatland and uplands) by timely information flow to SG policy advisors, for the mid-term CAP review starting 2017. This is facilitated by BLUPU. The RD outputs addressing woodland INNS and diseases will assist prediction of disease or pest dispersal and impact assessments of future epidemics. Uptake of this knowledge by practitioners and policy makers is enabled by membership of STHAG and the CoE for Plant Health. All outputs related to INNS will be transferred to the SG INNS team via an on-going dialogue. Significant engagement with specific stakeholder groups or agencies such as Capercaillie BAP group, ARCT, SSG make uptake of outputs of these component projects highly likely.

RESEARCH DELIVERABLE NUMBER: 1.3.3

Work planning and timetable for Year 1(O=Objective, KE=Stakeholder engagement and knowledge exchange, M=Milestone, D=Deliverable – see list above; for RD contributions to KE at WP level see WP1.3 description)

Year 1: 2016/17	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Analysis of resilience concepts in relation to Scottish ecosystems. Scientific consultation with specialists on vulnerable and agricultural ecosystems KE1.1i; Stakeholder consultation KE1.1ii; Science brief containing summary and advice for potential use of resilience in e.g. SRDP D1.1i .						KE1.1i			KE1.1ii			D1.1i
O1.3b Developing novel indicators of whole system resilience via agricultural run-off and sewage disease carriage. ***M1.3bi Obtain seal rectal swabs samples*** ***M1.3bii Process samples assess methods*** ***M1.3biii Data collation/ analysis***									M1.3bi			M1.3bii M1.3biii
O2.2a. Data collation ***M2.2ai Synthesis of available data on tick distribution***						M2.2ai						
O2.2b Data collation Range shifts and resilience - synthesis, review and collation of data, including gathering expert opinion (KE2.2bi) for ***model case 1 Capercaillie. M2.2bi.***						KE2.2bi						M2.2bi
O3.1a. Model production; *M1.3ai Fit models to spatio-temporal data on INN trees and shrubs.*									M1.3ai			
O3.1b Protocol development Pathogens of conservation priority plants - protocol for disease impact assessment D3.1bi.												D3.1bi
O3.1c. Sampling Dispersal of invasive *Phytophthora* ***M3.1ci Sampling water and analysis for diversity***.							M3.1ci					
O3.2a Sampling; *M3.2ai Sampling snails on designated sites; M3.2aii Determination of liver fluke infection status of grazing livestock.*						M3.2ai			M3.2aii			
O3.2b Data and information provision Provision of data and advice to SSG on Squirrel pox Virus D3.2bi,KE3.2bi.											D3.2bi	KE3.2bi
End of year reporting to RESAS (ALL OBJECTIVES) D1												R1

RESEARCH DELIVERABLE NUMBER: 1.3.3
Work planning and timetable for Year 2

Year 2: 2017/18	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1. Report on identification of knowledge gaps in resilience following scientific consultation incl with SNH contingency planning group KE1.1i, ***M1.1i***.							KE1.1i			M1.1i		
O1.2. Report – Research brief : Typology of resilience D1.2i following stakeholder appraisal, KE1.2i.							KE1.2i		D1.2i			
O1.4 Developing novel indicators of whole system resilience via agricultural run-off and sewage disease carriage. ***M1.4i Analysis for Campylobacter year 1 samples*** ***M1.4ii Obtain further seal rectal swab samples (Jan)*** ***M1.4ii Collation of campylobacter data & prelim analysis***						M1.4i				M1.4ii		M1.4iii
O2.1. Monitor pine insect biodiversity ***M2.1i.***						M2.1i						
O2.2a Create tick environmental limit models over National and European scale ***M2.2aii.***										M2.2aii		
O2.2b GIS model: habitat suitability for Capercaillie D2.2bi.						D2.2bii						
O2.2b Select case study 2 with stakeholder consultation KE1 and collate data; ***M2.2bii.***								KE2.2bii				M2.2bii
O2.2c. Scientific publication on MODIS peatland condition model D2.2ci.												D2.2ci
O3.1a. Risk assessment ***M3.1aiii Produce draft protocol*** to assess environmental risks from tree disease and produce policy brief on Policy note on potential impacts of tree disease D3.1ai.										M3.1aiii	D3.1ai	
O3.1a. Meta-analysis ***M3.1aii Develop meta-analysis*** for groups of INNS and produce scientific paper D3.1aii.									M3.1aii			D3.1aii
O3.1c. *Phytophthora* dispersal metabarcoding analysis ***M3.1cii*** and publication from year one samples D3.1c.										M3.1cii	D3.1ci	
O3.2a. Monitoring and species identification ***M3.2ai Monitoring stock use of natterjack habitat*** ***M3.2aii Identify snails species*** & determine fluke infection level.							M3.2ai					M3.2aii
O3.2b.**Provide information** on the prevalence of squirrel pox virus D3.2bi.											D3.2bi	KE3.2i
End of year reporting to RESAS (ALL OBJECTIVES)												R2

Name of RD: 1.3.4 Biodiversity management

Research aim and key drivers:

This RD aims to deliver research that helps Scotland meet biodiversity goals as set by the Aichi Targets, the EU Biodiversity Strategy and, specifically, the Scottish Biodiversity Strategy through considering management measures and potential options for safeguarding against biodiversity loss. EU policy requires no net loss of biodiversity by 2020 and the research in this RD will identify and develop biodiversity management measures and assess their feasibility in addressing this requirement. The research will also contribute to Scotland's Economic Strategy (2015) by providing insights into the mechanisms for protecting and enhancing the natural capital of Scotland and will provide useful insights to Sustainable Development Goal 15 as defined in "Transforming Our World – the 2030 Agenda for Sustainable Development". *This RD will contribute to the WP and Theme vision by addressing key knowledge gaps in the development and implementation of biodiversity management measures and informing relevant policy development processes, in particular addressing Theme 1 Research Question RQ4.*

The research will assess measures currently implemented in Scotland and elsewhere which could be effectively employed in Scotland to fill gaps in biodiversity conservation, and will identify potential novel management measures. A subset of these novel methods will then be trialled (supporting development of the Farmland Biodiversity Initiative, integrated via 1.4.3). The research will focus both on the actual measures implemented on the ground and the institutional mechanisms to promote implementation. The latter will include possible integration into the next round of the Scottish Rural Development Programme and into actions such as the Greening elements of the Common Agricultural Policy. This research will mainly inform the Big Steps 5 (Sustainable management of land and freshwater) and 2 (Investment in Natural Capital) defined in Scotland's Biodiversity – A Route Map to 2020, in particular Projects 11 (Sustainable Land Management) and 4 (Securing economic and social benefits from, and investment in, natural capital), respectively.

The research in this RD will also provide insights with regards to biodiversity offsetting. Although offsetting is increasingly being promoted as a mechanism to compensate for unavoidable losses due to development, implementation has been controversial due to the inherent difficulties associated with regulatory biodiversity trading. The research will investigate the potential of the different measures by looking at options for designing and implementing these schemes and assessing their implications and perceptions by end-users and stakeholders.

Key stakeholders, such as government and conservation agencies, developers, planners and farmers, will be engaged at all stages of the research. To evaluate the potential effectiveness of the different measures it is crucial that all sectors are involved in the research and contribute to assessing practical issues and overall feasibility. For this purpose, workshops, interviews and policy meetings will be conducted from early on in the research.

Appropriate case study areas will also be selected in Scotland in consultation with stakeholders, and will be supplemented by non-Scottish case studies to shed light on the potential of measures not currently employed in Scotland (e.g. biodiversity offsetting pilot areas in England). To investigate the potential of on-the-ground management measures, farm trials will be conducted at SRUC's Kirkton farm (funded via WP2.3), and the Glensaugh and Hartwood farms of the James Hutton Institute.

Who has been consulted in developing this proposal?: Relevant stakeholders, including SNH, Forestry Commission, SEPA and RSPB, have been consulted as part of a joint, concerted activity across WP 1.3 and Theme 1. The proposal has also been discussed with Scottish Government (Biodiversity and Land Use Team) and RESAS in spring and autumn 2015 and the Natural Heritage Management team (Natural Resources Division) at Scottish Government in September 2015.

Summary of the proposal:

This RD will improve our understanding of the applicability of existing biodiversity management measures and novel approaches, both in relation to 'on the ground' management practices and institutional settings to promote such practices. To this end, this RD will:

- review practical experience and synthesise existing ecological, socioeconomic and local knowledge on biodiversity management measures,
- assess the potential and feasibility of market and non-market based mechanisms to promote biodiversity management practices in full consultation with Scottish stakeholders,
- assess the development of new management options for agri-environment schemes,
- develop a working tool to account for habitat/species distributions and impacts of habitat loss and gain.

Based on these collective aims, the RD has the following Objectives (O):

O1: Synthesis and assessment of stakeholder attitudes toward different biodiversity management options:

O1.1. Synthesis & assessment of current biodiversity management measures: The initial focus will be an interdisciplinary review and synthesis of both the theory and practice of existing biodiversity management measures. For this purpose, O1.1 will focus on the one hand on policy tools and, on the other hand, on management actions on the ground. The review of policy tools will cover a broad range of measures which have been used in Scotland or other countries to promote the conservation and promotion of biodiversity, including payments for ecosystem services, offsetting schemes and agri-environment measures. The review will focus on the performance of different tools in relation to the protection of biodiversity and the supply of a range of public goods and ecosystem services and the way spatial and temporal trade-offs among different services and stakeholders are handled. In addition, O1.1 will include a structured consultation with policy makers and other key stakeholders involved in the implementation of mechanisms not currently widely employed in Scotland to understand the factors influencing uptake and implementation of novel approaches.

In parallel to the focus on policy tools, O1.1 will also develop a synthesis of specific 'on-the-ground' management measures to promote biodiversity outside protected areas. Through a review of literature and current schemes we will identify how well current measures deliver desired outcomes, potential management options that could be implemented in Scotland, and gaps in the suite of options that need addressing. Given the known shortage of options available to hill and upland farmers, particular emphasis will be given to assessing the efficacy of upland management, including muirburn, grazing and other activities covered by the current SRDP actions for biodiversity conservation, with a particular focus on upland wading

birds and raptors. This will cover the benefits, uptake and geographic distribution of current SRDP actions, and assess whether SRDP or alternative actions have wider landscape level effects on biodiversity. This specific alignment is in line with the development of the Farmland Biodiversity Initiative (integrated via 1.4.3).

Objective 1.2. Assessment of the degree of support and acceptability for different types of biodiversity management in Scotland: The knowledge developed during the first year of O1.1 will be used to explore the potential for using different market and non-market based mechanisms for the improved conservation and management of biodiversity in Scotland. Which mechanisms will be the focus of this part of the research will be decided in consultation with Scottish Government and other key stakeholders. The research will assess Scottish stakeholders' attitudes to and support for different types of mechanisms, and their design, implementation, and metrics for measuring the 'value' of biodiversity and ecosystem services. Differences consist, for example, in who is deemed responsible for implementing, controlling and paying for different measures, whether measures are voluntary or compulsory, whether or not mechanisms require the existence of private property rights and whether a monetary value can be assigned.

Objective 2: Assessment of new management options for agri-environment schemes: The review under Objective 1.1 will be used to identify research gaps in the development of novel biodiversity management practices on the ground. In consultation with stakeholders (policy, agency, NGO and land managers) we will select potential measures to be tested in years 2-5 of this RD. At least part of the work on developing new agri-environment measures in this RD will focus on upland habitats. This will support the development of the Farmland Biodiversity Initiative (1.4.3) and it will also complement the work on the impact of management on ecosystem services under RD 1.3.2.

Objective 3: Development of a working tool to account for habitat/species distributions and impacts of habitat loss and gain: This objective will consider both habitats at risk from different types of development (identified at local and national levels) and where habitats might be created (e.g. green infrastructure investments such as in the Central Scotland Green Network). The biodiversity and ecosystem services associated with these habitat changes will be characterised. Models will be used to analyse the potential effects that habitat change might have in their spatial context. By modelling population dynamics, these models will provide insights into threshold effects and time lags in relation to biodiversity valuation studies. Results from O1 and O2 along with preliminary work in O3 will be also used to develop a decision tool to inform and support the applicability of biodiversity offsetting in practice.

Key deliverables and milestones:

O1: Synthesis and assessment of stakeholder attitudes toward different biodiversity management options:

O1.1: Synthesis & assessment of current biodiversity management measures:

D 1.1i, Year 1 – Output: Report reviewing current literature and experiences with different biodiversity management mechanisms in Scotland.

D 1.1ii, Year 1 – Output: Interview guide to explore attitudes toward new biodiversity management measures not widely used in Scotland.

D.1.1iii, Year 1 – Output: Policy brief outlining potential management options that

could be implemented under SRDP and research gaps for biodiversity management.
D 1.1iv, Year 2 – Output: Report on stakeholder attitudes towards new biodiversity management measures (based on interviews).
D 1.1v, Year 3 – Output: Research paper on experiences with existing biodiversity management mechanisms based on review and stakeholder interviews.
KE event, Years 1 & 2 – Policy meetings to discuss main results from fieldwork on biodiversity management options.
KE event, Years 1 & 2 – Participation in and dissemination through ESCom.
O1.2: Assessment of the degree of support and acceptability for different types of biodiversity management in Scotland:
D 1.2i, Year 2 – Output: Interview guide for stakeholder interviews.
D 1.2ii, Year 2 – Output: Stakeholder workshops on perceptions of biodiversity management measures.
D 1.2iii, Year 2 – Output: Report based on the interviews and workshops with Scottish stakeholders and members of the public on their perceptions and attitudes regarding different options for biodiversity management.
D 1.2iv, Year 3 – Output: Conference paper on perceptions of biodiversity management measures.
D 1.2v, Years 4 & 5 – Output: Research papers (2) on the acceptability of different types of biodiversity management schemes.
KE event, Years 2 & 3 – Policy meeting to inform and discuss fieldwork.
KE event, Years 2-5 – Participation in and dissemination through ESCom.

Objective 2: Assessment of new management options for agri-environment schemes:
D 2i, Year 1 – Output: Policy brief written with stakeholders, identifying novel measures to be tested in the field.
D 2ii, Years 2-5 – Output: Experimental investigation of novel management methods.
D 2iii, Year 5 – Output: Research papers (2-3) on the impacts of novel management options on biodiversity.
KE event, Year 1 – Stakeholder consultation on novel measures.
KE event, Years 2-5 – Annual farm demonstration days held on each farm.

Objective 3: Development of a working tool to account for habitat/species distributions and impacts of habitat loss and gain:
D 3i, Year 1 – Output: Maps on development pressures and habitats.
D 3ii, Year 2 – Output: Maps and paper on integrating biodiversity and ecosystem service delivery with habitat types (with RD1.4.1).
D 3iii, Year 2 – Output: Incidence-based metapopulation model accounting for offsetting.
D 3iv, Year 2 – Output: Development of specific test cases (upland birchwoods) to examine the feasibility of offsetting for woodlands.
D 3v, Year 3 – Output: Paper on the valuation of key ecosystem services (with RD 1.4.1).
D 3vi, Year 3 – Output: Paper on the potential impact of offsetting on species functional types.
D 3vii, Year 4 – Output: Report on the risks and limits to biodiversity offsetting in relation to the trade-offs between space for different habitat types or ecosystem services.
D 3viii, Year 5 – Output: Develop and test a trading approach for estimating compensation requirements for habitat loss.

KE event, Year 1 – 'Groundtruthing' maps with stakeholders.
KE events, Years 2-5 – Stakeholder consultation on tool development.
KE event, Year 3 – Modelling results on CKEI web site.

Technical approach:

Objective 1: Synthesis and assessment of stakeholder attitudes toward different biodiversity management options

Objective 1.1: Synthesis and assessment of current biodiversity management measures: The first phase of work will be to review and evaluate current biodiversity management experiences with a focus on the degree to which these would be feasible and appropriate to help Scotland meet its biodiversity targets. The review will cover two strands of issues. Firstly, it will consider how different interventions handle uncertainty and time scales, as well as the role of stakeholders, their values and perceptions, including risk and economic performance. In the case of biodiversity offsetting measures, the review will focus on how the concept of 'no net loss' is put into practice. In this respect, the review will assess offsetting schemes involving habitat improvement using the '4-level approach on ecosystem restoration' (Lammerant et al. 2013 Report to European Commission. ARCADIS) to categorise the types of offsetting actions employed. Participants in England and Scottish Borders will be interviewed about their experiences with different biodiversity management measures in order to explore opportunities and barriers for the implementation of novel management measures. Stakeholders will include representatives from government, agencies, developers, consultants, local communities and NGOs. The review will also cover the costs and transaction costs of different measures and the short- and potential long-term effectiveness of actions taken (this will complement work in RD 1.3.2 on restoration effectiveness).

Secondly, the review will cover the specific management options available to land managers to benefit biodiversity. We will review the existing literature and results from agri-environment monitoring to assess the efficacy of current SRDP and Greening options for biodiversity to highlight potential options that are not cost-effective in Scotland. We will complement this by examining management options in other environment schemes in other countries that are not currently employed in Scotland to assess if any of these could potentially be employed here and whether they would be cost-effective. The selection of such measures will happen in consultation with key stakeholders. In addition, a gap analysis will be carried out to assess habitats and species that are poorly covered by current SRDP and Greening measures. This will make use of the matrices of species/habitat × measure used in the development of the current SRDP targeting.

Objective 1.2 Assessment of the degree of support and acceptability for different types of biodiversity management in Scotland: The research will assess Scottish stakeholders' attitudes to existing as well as currently not practised biodiversity management approaches, such as biodiversity offsetting, existing landfill tax schemes, branding and marketing schemes and the measures under the new Scottish Rural Development Programme (links to RD 1.4.3). Research under O1.2 will investigate stakeholders' perceptions of the pros and cons of different types of design and implementation across different habitats. It will also investigate the acceptability of different ways of measuring the 'value' of biodiversity and ecosystem services which are pre-requisites for some of these measures. These may be monetary or non-monetary, but must be translatable into a common metric. The

research will also identify which benefits and services cannot be captured using this approach. This will help to gauge the social acceptability along with potential gaps, barriers to uptake, trade-offs, inequities and conflicts in relation to different approaches to biodiversity management. This will be done using qualitative research methods such as interviews and focus groups with different stakeholders (e.g. policy makers, on the ground managers, developers, environmental and other interest organisations, general public, etc.).

Objective 2: Assessment of new management options for agri-environment schemes: The initial phase of this work will be to take the analysis of potential agri-environment measures employed outside Scotland and the gap analysis from O1.1 and collaborate with stakeholders (policy, agency, NGO and land manager) to identify priorities for the development of research and demonstration activities. This prioritisation will form the basis for new experiments that will be put in place from Year 2. We envisage an emphasis on measures that could benefit grassland and upland habitat, but this will be decided with stakeholders. It is also envisaged that we will focus monitoring on key groups such as pollinators, seed eating and insectivorous birds, bats and plants. Implementation, maintenance and loss of output costs will be monitored in addition to the biodiversity monitoring.

Objective 3: Development of a working tool to account for habitat/species distributions and impacts of habitat loss and gain: Research under O3 will identify the types of development likely to impact on habitat extent and the typical locations of impact in Scotland. O3 will examine Local Authority development plans and the Scottish Government's Infrastructure Investment Plan to determine the types and extent of habitat that are likely to be lost as a result of development. The research will quantify the need to highlight areas of the landscape that, although not formally protected, may have important ecological functions, such as enhancing landscape connectivity, not accounted for by plans. Thus, with a view to either find alternatives to their development or to assess offsetting potential of other sites (under like-for-like and under transferability rules) and the different stakeholders who could potentially be involved in these schemes (links to RD 1.4.3), meta-population models and metrics will be developed for the comparison of siting offsetting to minimise the disruption to existing habitat networks and to reduce overall habitat fragmentation. In addition, based on the identified habitat types, and locations and the work on acceptability of different metrics in O1, the types of biodiversity and ecosystem services delivered will be quantified (this may draw directly on mapping work in the current RESAS programme and work in RDs 1.3.2 and 1.4.1). Primary valuation work planned for RD1.4.1 is intended to inform both the development of natural capital accounts and the needs of wider environmental management. The RD1.4.1 valuation work is intended to cover 'generic' ecosystem services but will be designed in such a way as to allow identification of values for services in peri-urban settings this will be important for identifying values relevant for offsetting.
Linking to the assessment of woodland ecosystem services in RD 1.3.2, woodland ecosystems and their biodiversity will form an 'outer-envelope' in the assessment of offsetting options, to complement the work on managed agricultural systems in O2. The exploration of biodiversity offsetting for woodland systems is aligned with and helps navigate trade-offs in carbon management that are explored in the CXC-Woodland project. This work takes into account the slow temporal development of Scotland's semi-natural woodlands, by using chronosequence studies, also linking to

chronosequence work on soils in Theme 1. Research by the Royal Botanic Garden Edinburgh will quantify the accumulation of biodiversity in woodland habitat over time, and so investigate the temporal dimension to offsetting for woodland ecosystems.

A tool for estimating compensation requirements for habitat loss will be developed based on information from other processes, the preferences of Scottish stakeholders, the international Business and Biodiversity Offsets Programme (BBOP) principles and information on different habitats in order to assess which habitats could be incorporated into an offset scheme, and to identify which should not be. For this purpose, close engagement with stakeholders at different policy and user levels will be essential. This stage will develop a model to account for local/habitat species distributions and the spatial impacts of habitat loss and gain using a meta-population theory framework. The framework will be tested to determine offsetting potential and limitations, taking into consideration stakeholder preferences and values. Specific case study areas will be selected jointly with stakeholders.

Detailed work plan - See Summary, Technical approach and Gantt charts .

Expertise: The work on market and non-market mechanisms will draw on the existing expertise of the researchers in natural resource management and local perceptions of environmental issues, in spatial analysis and in restoration and habitat management.

Hutton's social sciences team has experience in analysing nature-human relationships through multiple economic and social angles both in the Scottish context under the cSRP (e.g. WP 1.2/WP 1.3) and in the context of developing countries (e.g. ALTER project, ESPA funded). The Hutton's ecological team has extensive expertise in the management of habitats for biodiversity conservation, in the analysis of biodiversity policy and in the assessment of connectivity in landscapes.

SRUC's team of environmental economists has long-standing experience in applied non-market valuation and policy assessment. This work has been for a wide range of clients including the Scottish Government (study into the Cost-Effectiveness of Biodiversity Measures in the SRDP); UK government (e.g. valuations supporting the UK Marine and Coastal Access Act); UK Research Council projects Valuing Nature Network, UK NEA and Follow-on; EU funded studies on Natural Water Retention Measures and management soil carbon (FP7 SmartSOIL) and the TEEB.

RBGE's research team has long-standing experience in understanding how landscape dynamics control biodiversity and species interactions. This includes the use of historical mapping to understand the effects of past landscapes on present-day biodiversity.

Key linkages, interdisciplinarity & collaboration:

Links with other research deliverables: The research in this RD has strong links to other RDs in the research programme, while also developing stand-alone research. Primary valuation of ecosystem services and the natural asset register developed in RD 1.4.1 will be used for the characterisation of ecosystem services and to identify values that will be relevant for the development of a working tool to account for habitat/species distributions and impacts of habitat loss and gain. In addition, the research on the development of new options and approaches for SRDP will be linked to Objective 1.4.3b in RD 1.4.3. Both RDs will share case studies and coordinate the development of new management options. The research on woodland ecosystems

and their biodiversity will be linked to woodlands research in RD 1.3.2 and to the CXC-Woodlands project. Time-lines for the accumulation of biodiversity, including the continuity required for protected species, will feed into the CXC programme. This will be achieved by identifying the most suitable sites for biodiversity protection, transitional areas of continuous-cover low-rotational forestry, and areas appropriate for more intensive management systems. The review of biodiversity management measures will also link with the comparative policy analysis in RD1.4.2 and to Objectives 1 and 2 in RD1.2.4, regarding the research on good international practice and PES schemes. In addition, the RD2.3.8 research on agroecological approaches in the lowlands will complement the research conducted in this RD regarding the development of new agri-environment options in different agro-ecological contexts.

Links with other, international research within the MRPs: This work will draw on insights from a Horizon 2020 project (2015-2018) 'Providing smart delivery of public goods by EU agriculture and forestry' (PROVIDE). This project includes mapping of hotspots in terms of public goods, primary monetary and non-monetary valuation and scoping of policy mechanisms for the provision of public goods and ecosystem services. In addition, some of the researchers in this RD have been involved a recent bid on woodland expansion and the values and trade-offs between various woodland characteristics and are also collaborating with researchers at the University of Leeds and Mexico in order to understand better the 'commoditization' effect of market instruments for managing the environment. These projects will add value to the research conducted in this RD by providing a theoretical and empirical grounding to the work proposed here.

Interdisciplinarity: The proposed work on biodiversity management mechanisms integrates economic, social science and ecological expertise. Most of the Objectives in this RD will be delivered by interdisciplinary teams to ensure that the outcomes integrate multiple areas of knowledge and address relevant policy questions.

Collaboration: Researchers from Hutton, SRUC and RBGE will collaborate in this RD. Social scientists and ecologists from Hutton will collaborate in O1 and O3, while social scientists from Hutton and SRUC will jointly deliver O3. In addition, O3 will involve collaboration between SRUC economists, Hutton social scientists and ecologists and RBGE ecologists.

Added scientific value:

This research will contribute to fill some of the existing gaps in the literature and policy arena, by providing a systematic overview of the strengths, weaknesses and potential of different measures to promote and safeguard biodiversity outside protected areas in a Scottish context. The research in this RD will be particularly relevant to Step 5 Priority Project 11 (Sustainable land management) and Step 2 with Priority Project 4 (Securing economic and social benefits from, and investment in, natural capital) as defined in the Scotland's Biodiversity - A Route Map to 2020. Research in this RD will investigate attitudes toward the adoption of novel biodiversity management approaches that could be appropriate for the Scottish context but are not currently implemented. Research in this RD will combine knowledge on the ecological and socio-economic aspects of biodiversity management with reference to actions under the SRDP and both gains and losses of habitats in non-protected areas. The combination of spatial models and values for biodiversity and ecosystem services will provide a novel understanding of what the

full impacts of changing habitats will be. In turn, this will inform better spatial targeting of responses such as offsetting and SRDP measures to meet biodiversity targets. Our approach to offsetting goes beyond current models and practice by expanding the metrics used for compensatory action. Our research into attitudes towards different management options will also inform the potential for implementation and indicate where different approaches may be required.

KE, audiences and impact:

KE: At the national level, work in this RD will be directly relevant for the UK's and Scotland's efforts towards the 2020 Aichi targets. The "Biodiversity and Land Use Policy Unit" (BLUPU) approach and the WP 1.3 Working Group (see WP 1.3. for a description) will be employed to make the research in this RD useful for reporting towards these targets (with interim reports for the CBD due in 2017), and also in relation to the SBS Route Map. In addition, via the WP Management Group (see WP 1.3 description) our KE activities will be integrated with those of the Centre for Knowledge Exchange and Impact (CKEI). We plan to contribute to CKEI Activities such as the cross-theme signature events and links to external projects. Specifically for this RD, we will hold regular formal meetings (see KE deliverables) as well as informal meetings with stakeholders to consult and co-develop the research on biodiversity management measures. In addition, the research will also include stakeholders in the form of interviews, focus groups and workshops regarding perceptions, barriers and preferences in O1 and O2 and will guide the development of the working tool in O3. The development of the decision support tool will be done in full with these bodies involving, primarily, face-to-face meetings to discuss research outputs and design. In addition, findings will be presented at ESCom meetings, national and international conferences, and reports and scientific journal papers will be produced to cover the key research questions.

Audiences: KE will focus on two key audiences: those involved in governance of biodiversity management schemes; and potential users of such schemes. Audiences at the national level will be policy teams responsible for strategic issues requiring understanding of biodiversity management options. Policy teams for which work is anticipated to be of most direct relevance are those in Land Use and Biodiversity guiding the Land Use Strategy 2, and Scottish Biodiversity Strategy, Scottish Planning Policy and Forestry Strategy and government agencies such as SEPA and SNH. Audiences at the regional and local level will be land managers, such as land planners, the Central Scotland Green Network, local authorities, land owners (public and private), developers (wind energy, housing and industrial) and conservation NGOs. A diverse set of activities and outputs (see deliverables) will ensure that we engage with the right audiences at the right time. For example, at an early stage the research will engage with key stakeholders (e.g. policy makers, NGOs, NFUS) to explore the uptake of novel biodiversity management approaches. Scientific audiences will be reached through publications in international journals, presentations at national and international conferences and other scientific meetings. We will also actively participate in ESCom conferences and working groups.

Pathways to Impact:

The proposed research responds to some of the challenges raised by the Aichi targets, the EU Biodiversity Strategy and Scotland's Biodiversity Strategy, including the recently published Scotland's Biodiversity – A Route Map to 2020 and the CAP and Scottish Rural Development Programme. The research will support SG policy

advisors in ENFOR and ARD during the mid-term CAP review starting in 2017. By reviewing a broad range of biodiversity management measures and testing some of them on the ground, the project will help both policy makers and land managers to address biodiversity loss in a social, economic and environmental feasible and acceptable way. This will be of relevance to the Scottish Government's RAFE (Rural Affairs Food & Environment) Delivery Board and we would be able to contribute through RD1.4.3. The researchers in this RD have actively engaged during the current RESAS programme with SG policy makers and stakeholders on the ground so we are well placed to develop research that is relevant and practical for end-users. We also anticipate that the results will provide useful insights into biodiversity management approaches that can inform the Scottish Government's contribution to the UK delegation to CBD COP 14 at the end of 2018, where the Aichi targets will be discussed, and the re-negotiations of SRDP starting in 2017.

RESEARCH DELIVERABLE NUMBER: 1.3.4

Work planning and timetable for Year 1 (O=Objective, D=Deliverable, M=Milestone, R=Report to RESAS; for RD contributions to KE at WP level see WP1.3 description)

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1 Report reviewing current literature and experiences with different biodiversity management mechanisms in Scotland. ***M1.i: report complete.***												D1.1i M1.i
O1.1. Interview guide to explore attitudes toward new biodiversity management measures not widely used in Scotland**.** ***M1.ii: interview guide finished.***					D1.1i M1.ii							
O1.1. Policy brief outlining potential management options that could be implemented under SRDP and research gaps for biodiversity management. ***M1.iii: policy brief complete.***							D1.1iii M1.iii					
KE event: Policy meetings to discuss main results from fieldwork on biodiversity management options										KE1.i		
KE event: Participation and dissemination through ESCom.												KE 1.ii
O2. Policy brief written with stakeholders identifying novel measures to be tested in the field**.** ***M2.i: Policy brief complete***.												D2.i M2.i
KE event: Stakeholder consultation on novel measures.												KE 2.i
O3. Maps on development pressures and habitats. ***M3.i: Maps complete***.									D3.i M3.i			
KE event: 'Groundtruthing' maps with stakeholders.												KE 3.i
End of year reporting to RESAS (ALL OBJECTIVES)												R1

RESEARCH DELIVERABLE NUMBER: 1.3.4
Work planning and timetable for Year 2

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.1. Report on stakeholder attitudes towards new biodiversity management measures (based on interviews). ***M1.iv: report complete.***						D1.1iv M1.iv						
O1.2. Interview guide for stakeholder interviews. ***M1.v: guide finished.***					D1.2i M1.v							
O1.2. Stakeholder workshops on perceptions of biodiversity management measures. ***M1.vi: workshops complete.***									D1.2ii M1.vi			
O1.2. Report based on the interviews and workshops with stakeholders on their perceptions and attitudes regarding different options for biodiversity management. ***M1.vii: report complete.***												D1.2iii M1.vii
KE event: Policy meetings to discuss main results from fieldwork on biodiversity management options.												KE 1.iii
KE event: Participation and dissemination through ESCom.												KE 1.iv
O2. Experimental investigation of novel management options. ***M2.ii: experiment established.***												D2.ii M2.ii
KE event: Annual farm demonstration days held on each farm.												KE 2.ii
O3. Maps and paper on integrating biodiversity and ES delivery with habitat types. ***M3.ii: paper submitted.***												D3.ii M3.ii
O3. Incidence-based metapopulation model accounting for offsetting. ***M3.iii: model parametrised and simulations complete.***												D3.iii M3.iii
O3. Development of specific test cases (upland birchwoods) to examine the feasibility of offsetting for woodlands. ***M3.iv: data analysed.***								D3.iv M3.iv				
KE event: Stakeholder consultation on tool development.												KE 3.ii
End of year reporting to RESAS (ALL OBJECTIVES)												R2

Name of WP: 1.4 Integrated and Sustainable Management of Natural Assets

1. Work package overview

Our vision for 2021 is to provide the scientific capacity and knowledge brokerage to support Scottish Government (SG) and its agencies to achieve their Rural Affairs, Food and Environment (RAFE) outcomes, and through these, the UN Sustainable Development Goals. We will have illustrated how managing natural assets can achieve sustainable land use which is resilient to future pressures and contribute to sustainable growth of the Scottish economy, our health and well-being. Building on work on planetary limits and tipping points across the theme, we will have presented the trade-offs and synergies that may occur and demonstrated sustainable trajectories. We will have supported policy development and reviews, through for example, providing evidence for alternative logics of intervention when negotiating the next CAP and associated Rural Development Programme (SRDP); and influenced land managers' practices. The quality of our work will mean we are seen as both international experts and the practical 'go to' people for advice on sustainable integrated land and water management. We will act as Theme "champions" for land use research and policy, across the Programme (SRP) and the CKEI.

Natural assets are recognised in the SG Economic Strategy as an important component to achieving the SG's overall ambition to make Scotland a more successful country, with opportunities for all, through sustainable economic growth. Scotland is blessed with abundant natural assets, and our national identity, international exports (e.g. tourism or whisky), individual well-being and community cohesion are based on their quality and extent. However, we are already exceeding safe limits to their use with some natural assets in decline such as farmland biodiversity, water quality and soil nutrients, whilst other assets may be vulnerable to future environmental, land-use or land management changes. Sustainable trajectories must be socially acceptable and support land-based livelihoods. These aspirations are evident in the SG RAFE outcomes: 'Scotland's nature is resilient and flourishing'; 'Scotland's natural environment is valued at home and internationally'; 'Scotland's land and other natural assets are managed in the public interest'; and 'Scotland uses resources efficiently and sustains them for the future'. The overall aim of WP1.4, therefore, is to illustrate the multiple benefits that natural assets provide to Scottish society and to use this understanding to support decision making on trade-offs and management at multiple scales. The WP objectives are: (a) to use a dynamic natural assets register (NAR) and natural capital accounts (NCA) to illustrate how assets contribute to Scotland's green growth aspiration; (b) identify and quantity trade-offs and impacts on multiple assets and ecosystem services (ESs) to illustrate where we are living beyond planetary limits; (c) support integrated decision-making and adaptive management to protect multiple natural assets and maximise benefits in socially acceptable ways; and (d) illustrate how existing and novel measures can deliver integrated delivery of benefits. This requires a comprehensive picture of the state of Scotland's natural assets (RD1.4.1); identification of the scope for delivering multiple benefits whilst ensuring the resilience of assets to change (RD1.4.2); and applied demonstration of how these benefits can be delivered in practice (RD1.4.3). The WP will synthesise data on specific natural assets (soils, water and biodiversity) and their function, resilience and management across settings as diverse as peatlands, woodlands, extensive/ intensive farming systems and peri-urban greenspace to act as an integration hub for Theme 1. It will also draw on data, tools and insights regarding agricultural systems and rural industries in

Theme 2; and regarding rural communities and health and wellbeing in Theme 3 (see Figure 1). The WP research will be delivered across a range of spatial scales from national through regional, catchment, holding and field scale; and will set the Scottish picture in the context of international trends. This will allow the WP to help answer the Theme's overall questions (see Theme Overview above) and support the programme's (SRP) focus on integration to make the best use of our land and natural assets.

The WP is structured through three Research Deliverables (RDs):

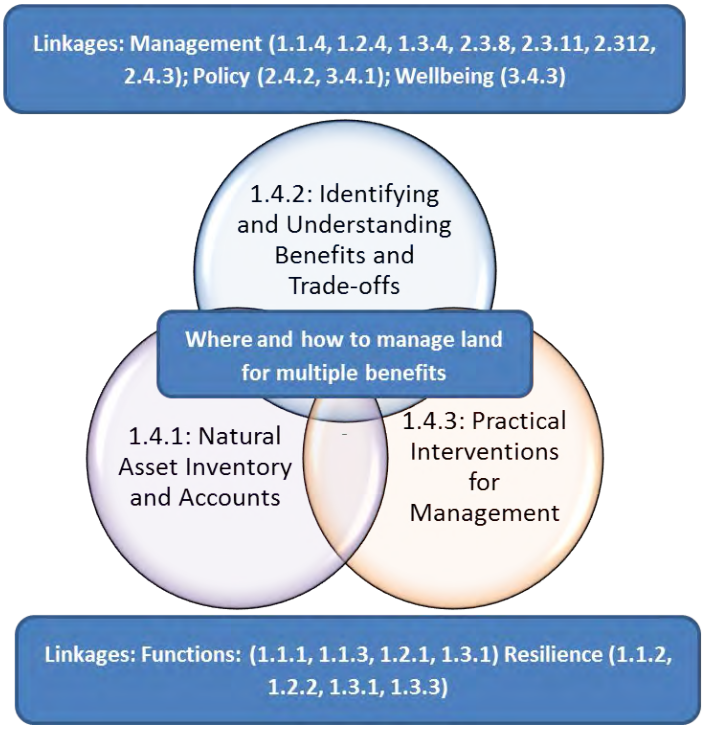


Figure 2: WP1.4 and interactions across the SRP

RD1.4.1: Natural asset inventory and accounts - How can we systematically account for ecosystem services in Scotland? This RD will develop a publicly accessible register of Scotland's natural assets, to improve our knowledge of how much of what is where, and which assets are at risk in particular places. Bundled ESs within specific habitats in the register can then be valued and act as a foundation for NCA. These data will be used by RD1.4.2, RD1.4.3 and elsewhere throughout the SRP.

RD1.4.2: Identifying and understanding multiple benefits and trade-offs - How can we identify resilient interventions for multiple benefits? This RD will analyse the trade-offs and synergies in terms of the ESs being delivered by existing patterns of land use, linking historic land use change with the current state of natural assets and exploring consequences of different drivers of land use change in the future. This will provide national and regional level evidence to support policy, particularly how new combinations of existing measures or new measures could deliver RAFE's objectives. This RD provides the tools and the institutional context for RD1.4.3.

RD1.4.3: Practical interventions to realise multiple benefits and manage trade-offs - How can we support delivery of multiple benefits in practice? Working with stakeholders at a landscape scale, this RD will support delivery of multiple benefits in intensive/extensive agricultural catchments; and woodland expansion in peri-urban and accessible-rural settings. A comparative research design, comparing different land use and land management choices will draw out what works where and why; and provide stakeholder feedback to RD1.4.1 (priority data gaps) and RD1.4.2 (local perceptions and management strategies) and across the SRP.

2. Coordination and management

2.1 Work package management and coordination within the Strategic Research Programme

Work Package-level management activities and structures: The WP coordinator (WPC) will report to the Natural Assets Theme Management Group. WP representatives from each of the MRPs (Hutton, RBGE, MRI, BioSS and SRUC) will be responsible for ensuring delivery within their own organisations. RD Coordinators (RDCs) will attend regular WP Management Group (WPMG) meetings (see Fig 2) to maintain cross-RD and MRP dialogue, whilst identifying opportunities for integration. The WPC and RDCs have been allocated additional time to cover these management activities (20% for the WPC). Strong working relationships have already been established, building on existing collaboration as WP/RDCs in the current RESAS 'Ecosystem Services' Theme (Hutton, BioSS and SRUC) and through collaborative development of this tender (RBGE and MRI). The WP/RDCs are experienced project managers, able to adapt research plans and take remedial actions where required. They have been carefully chosen to provide a mix of economic, natural and social scientists from across the MRPs; in order to maximise the opportunity for interdisciplinary insights and strengthen an integrated approach.
Managing the annual reporting cycle: The WPC will be responsible for setting out clear reporting milestones and setting up quarterly virtual meetings for the WPMG. This group will be used to check on performance against the Gantt charts, coded according to an agreed scheme (green – on schedule, amber – slightly delayed, red – significant delay), and identify research impacts. The group will collaborate on the material for reporting progress, findings and impact to the Theme Coordinator for annual reporting to RESAS and a six-monthly update in October of each year. The kick-off activities in April 2016 will ensure that common data collection processes are in place across the MRPs to allow efficient reporting; and compliance with the Programme's Data Management and Intellectual Property Plan. QA for the data underpinning narratives and metrics will be the responsibility of the RDCs. The WPC will be the main point of contact for RESAS and the SRP's integrative group.

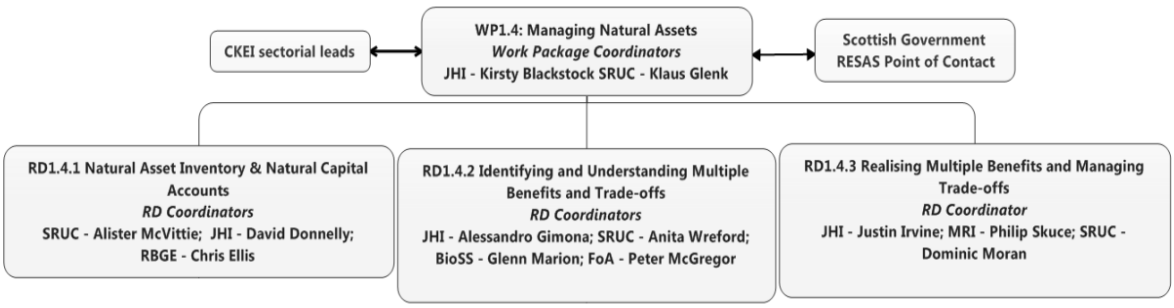


Figure 3: Management Structure for WP1.4

WP Change Management and Integration: The WP combines strategic research and scientific capacity building with some flexibility to respond to stakeholder requests as recommended in the Mid-Programme (2011-16) Review. The WPMG, working with stakeholders and the CKEI Think Tank (TT, see KE below), will horizon scan for opportunities for stakeholder and scientific collaboration. In addition, an annual internal meeting will be held to identify further integration opportunities, allowing us to refine data collection and analysis to answer new questions. The WP will share a common framework, building on and improving the EU conceptual framework for ecosystem assessments to coordinate these connections. Opportunities to combine insights on the same policies, from research undertaken at different spatial scales will be maximised.

Links within the SRP: We have selected common research platforms (for example, the MRP research farms) within the Theme to enable shared data collection, data

analysis and stakeholder engagement. Opportunities to link across the SRP will be a standing agenda item for the WPMG meetings and passed to the CKEI TT. The main linkages are identified in Figure 1 above. Research on ecosystem function will feed into RD1.4.1, resilience into RD1.4.2 and management into RD1.4.3. Achieving these linkages will be facilitated through shared staff. Collaborative activities between RDs will be prioritised where a specific linkage will benefit both RDs and maximise impact. More general exchanges of information or data will occur through joint WP or RD-level activities across the SRP to build on shared interests; e.g. a workshop on state-of-the-art research on land manager preferences and behaviours. We will combine the rural industry and communities perspectives with the natural assets perspective by working on integrative projects with WP2.4 and WP3.4 (e.g. O1.4.2ci). The KE Sectorial Leads (KESLs) and Programme Advisors will attend the annual research meetings to foster linkages across the SRP.

Centres of Expertise: Many of the researchers involved in WP1.4 will be also working with the Centres of Expertise (CoE) (Waters, Climate Change, Animal Disease Outbreaks and Plant Health). Their Coordinators will be invited to the annual internal research planning meeting to stay updated about the SRP's strategic capacity.

2.2 Mechanisms for networking and collaboration

In addition to the RD KE plans, there will be three main mechanisms for networking. We will support the Theme-level Biodiversity and Land Use Policy Unit (BLUPU) and Soils Stakeholder Group (SSG) to provide expert judgement and synthesis to multiple policy customers whilst identifying future opportunities. We will actively seek to sit on relevant stakeholder working groups e.g. greening of CAP working group. Working beyond CAMERAS, we will also set up a wider WP working group (WPWG) including the main end-users (practitioners and scientists) with an interest in land use and ESs. As there is a significant cross-over with the 'ESCom Scotland' network's annual event, we are exploring using this as our WP working group. Scientific networking is discussed in Section 2.4.

2.3 Interactions with Underpinning Capacity

The WP will connect Underpinning, particularly, to Service 3 (Maintenance of key long-term data sets of national significance) and Service 9 (Maintenance of national soil archive) for 1.4.1. Ongoing support from BioSS (Service 7) will be utilised to ensure that the experimental designs are statistically appropriate and that spatial and temporal modelling processes are statistically robust (RD1.4.1; RD1.4.2; RD1.4.3). These continue working relationships with BioSS staff (Brewer & Potts). In addition requests made through the Policy Support Service, particularly in light of greening of CAP or supporting the LUS delivery, will utilise resources and researchers from this WP. Potential PhD studentships funded through Underpinning Capacity Service 2 (Seedcorn), and participation in international projects supported through Service 11 (Platform) will add value to the research of WP1.4 and facilitate strong scientific networks between the MRPs and HEI sector.

2.4 Enhancing Additionality

The WP builds on the state of the art achieved by other integrated land or ecosystem based research programmes (such as the National Ecosystem Assessment, The Economics of the Environment and Biodiversity (TEEB) or the international Ecosystem Services Partnership (ESP). We link to ESs and land use research communities, in particular, the UK VNN and NERC BESS Programmes and

European platforms such as the proposed EUROPARC[1] research advisory group. We focus on finding solutions to the challenges identified by these international programmes. Examples include: considering the technical challenges of up-, down- and cross-scaling environmental, social and economic data to improve decision making, in order to cross-fertilise techniques across different disciplinary domains; or addressing uncertainty through different modelling and scenario approaches. To do this, PIs have been allocated resources to attend one conference/workshop a year to share our science. Furthermore, PIs will be encouraged to sit on international committees to help shape the scientific discussions (e.g. Intergovernmental Platform on Biodiversity & Ecosystem services (IPBES); and attend relevant 'sand-pit' events for RCUK funding calls, such that expertise from the MRPs is used to support scientific innovation in the relevant areas. Participating in the ESRC Centre for Complexity and NERC highlight topic on integrated dynamics of natural capital systems will add value to the focus on systems science in this WP. We are developing linkages with the H2020 PROVIDE and PEGASUS (2015-2018) projects. A proposed innovation partnership bid will link WP1.4 with Scottish Forum for Natural Capital (SFNC) and the Scottish Whisky industry. We will use the CKEI tool kit to promote research amongst scientific communities such as social media updates regarding publications or contribution to academic blogs. The WP will take the 'green' route to open access and has reserved a budget to publish each RD's most important papers per year as open access to increase the visibility of the research.

2.5 Work package risk management

The WP will comply with Theme-level risk management, including a risk register updated after WP management meetings. We have identified a number of risks and how WPMG will respond in Table 1.

Table 1: Projected key risks for WP1.4, where the overall risk status (likelihood x occurrence) is indicated in terms of Amber or Green, for medium and low risks, respectively.

Key Risks	Risk Assessmsnt	Impact	Controls	Risk Owner
Significant budget reductions	Medium	Medium-High	Work programmes renegotiated with SG, and impacts agreed with partners on cancelling work areas, or reorganising priorities.	DEC
Staff turnover	Medium	Low-High (post dependent)	Ensure early discussions with relevant project and management teams for new staff members to familiarise with the research.	RD, WP, Theme Coordinator
Divergence in priorities between Underpinning and SRP	Low	Low-Medium	Ensure communications between relevant Underpinning capacity and SRP activities. Accountability links through individual MRPs, with utilisation and issues arising in SRP identified at Theme Management meetings.	WP, Theme, MRP
Divergence in stakeholder and research priorities	Low - Medium	Medium	BLUPU, SFG and WPWG will be used to agree why and where priorities may need modified (e.g. changing in public sector priorities), or if findings conflict with stakeholder positions. Early identification of issues, monitored by theme management, actions taken to engage and resolve issues, and reported to DEC.	WP, Theme, DEC
Divergence in priorities between partner MRPs	Low	Medium-High	Regular WP and Theme Management meetings to ensure communication, early identification of potential for issues to arise. Reporting to DEC for resolution of prospective issues. Adherence to project plan and schedule of Deliverables, with alerts to RESAS via annual/six–monthly reporting.	RD, WP, Theme, Coordinator

[1] European Network of Protected Area Management organisations associated with the IUCN

3. Impact and KE

The WP will create better opportunities for co-construction of the research and to identify and sustain clear pathways to impact. The ITGF reflects the expressed interests of Scottish stakeholders as it was generated from an extensive consultation process. Stakeholders were consulted at a cross-MRP event held on 27th February 2015 followed up by further targeted discussions (meeting held 19th March, 2015, with representatives from SEPA [2], SNH, SG, FCS and NFUS) and bilateral discussions with SLE, SG BLUPU, NATRES, RDP and CNPA. The revision process has involved discussions with RESAS (Hinze), SG BLUPU (Gateley), NATRES (Turpie) and ARD (Struth) policy units, SEPA (Melville) and SNH (Christie). Use has been made of discussion notes from other stakeholder meetings e.g. Scottish Biodiversity Strategy (Bassett, SNH) and SG EQ (Ritchie). CAMERAS' evidence plans and RAFE outcomes have been consulted as expressions of stakeholder needs. Stakeholders can be categorised as follows: research collaborators; end-users/facilitators; and interested parties. End-users/facilitators will have the greatest role in co-construction.

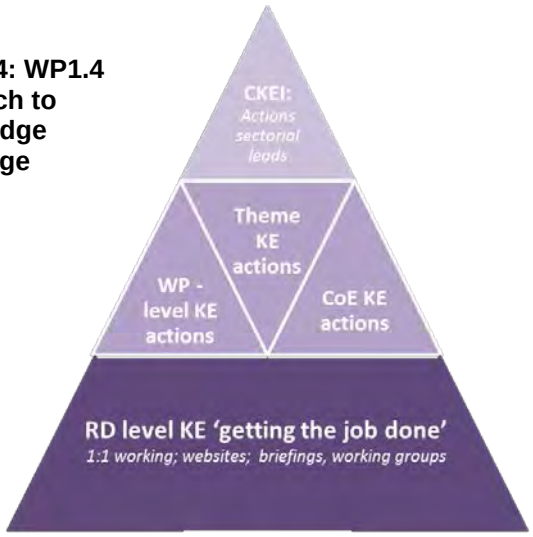
Research Collaborators	End-Users/ Facilitators	Interested Parties including Public
Specific non-academic individuals, organisations or communities providing data analysis or peer review of results.	Individuals representing organisations to ensure alignment with policy cycles, identify future stakeholder needs, facilitate data collection or data access, and comment on results.	Organisations and individuals who may have an interest in the research activities and the results.
RESAS analysts; CAMERAS partners (particularly SG, SEPA, SNH, NPA, RPID); local authorities; Office for National Statistics; Defra; Land & Riparian Managers; Beef producers and wholesalers, Community groups and Individuals participating in research activities	SG policy teams within ENFOR and ARFC; SNH; SEPA; FCS; NFUS; SLE; CNPA, QMS, Food and Drink Scotland, Land/ extension agencies, CSGN, RSPB, GWCT, SFNC, NCI, JNCC, land managers and all businesses dependent on natural assets (e.g. tourism).	Scottish Environment LINK; Members of the Public; MSPs, MPs, MEPs, councillors, European Commission, UNEP, EU Joint Research Centre; Scottish Crofters Federation; Tenant Farmers Forum, Environmental consultants, teachers

Both co-construction and impact pathways require a suite of mechanisms to engage multiple audiences. To maximise use of existing structures (e.g. CREW), new initiatives (e.g. CKEI) and collective WP- to Theme-level outputs; we have a tiered KE approach (Figure. 3). A measure of progress will be an increase in invitations to present at stakeholder meetings such that WP1.4's research becomes a valued part of the governance of Scotland's natural assets.

[2] Scottish Environment Protection Agency (SEPA); Scottish Natural Heritage (SNH); Forest Commission Scotland (FCS), National Farmers Union Scotland (NFUS); Scottish Land and Estates (SLE); Natural Resources (NATRES); Rural Development Policy (RDP); Cairngorms National Park Authority (CNPA); Rural and Environment Science and Analytical Services Division (RESAS); Agriculture and Rural Development (ARD); Environmental Equality (EQ). The Coordinated Agenda for Marine, Environment and Rural Affairs Science (CAMERAS); Rural Payments and Inspectorate Division (RPID); Office of National Statistics (ONS); Environment and Forestry (ENFOR); Agriculture, Food and Rural Communities (AFRC); Quality Meat Scotland (QMS); Central Scotland Green Networks (CSGN); Royal Society for the Protection of Birds (RSPB); Game and Wildlife Conservation Trust (GWCT); Scottish Forum for Natural Capital; Natural Capital Initiative (NCI); Joint Nature Conservation Council; United Nations Environment Programme (UNEP);

RD level KE: is described in each RD document. Each RD will collaborate with stakeholders on specific shared tasks (e.g. SEWeb); to work with end-users to ensure the findings are presented in suitable formats at suitable times to allow uptake; and to produce outputs to inform interested parties. *KE ACTIONS: (1) close working with collaborators; (2) populate and update web pages and social media to inform interested parties including plain English summaries of scientific papers; (3) co-author policy or practitioner briefings with collaborators for end-users; (4) sit on relevant end-user working groups (e.g. RAFE Digital Strategies Group).*

Figure 4: WP1.4 approach to Knowledge Exchange



WP level KE: A WPWG consisting of representatives from end-user organisations will meet every six months to discuss and interpret SRP research in light of their needs and to identify opportunities for research collaboration. As we build credibility through these group interactions, we anticipate an increase in informal individual telephone or face-to-face meetings to discuss specific opportunities or results that may be of particular interest. Additionally, the WP/RDCs will attend relevant stakeholder forums (e.g. potential subgroup on integrated land use reporting to the RAFE delivery board[3]). *KE ACTIONS: (5) set up WPWG to facilitate dialogue with end-users; (6) populate and update appropriate web pages and social media to inform interested parties including annual summary of research highlights (7) present at end-user conferences and/or write articles for end-users' publications; (8) sit on end-user national level steering or advisory groups; (9) respond to relevant statutory consultations.*

Centre of Expertise-enabled KE: We will work with the CoEs as conduits for co-construction, to advise on new pathways to impact, and act as a shop-front for research summaries. *KE Actions: (10) work with CoE teams to raise stakeholder awareness; (11) mobilise our researchers to respond to CoE responsive mode requests; (12) increase interactions of SRP staff with CoE staff who can advise on good practice in science communication to end-users and interested parties.*

Theme level KE: As WP1.4 is tasked with integrating inputs from across the SRP, we will support KE wherever possible. We will run the 'BLUPU' working group (with WP1.3) and the Soils stakeholder group (SSG) (with WP1.1). By embedding these within WP1.4, we will improve integration across the Theme and allow us to examine different mechanisms of policy engagement. The BLUPU will consist of the main SG policy units and their delivery partners from CAMERAS. The SSG will consist of stakeholders with broad soils interest, building on the working group for International Year of Soil 2015. We will work closely with SG to establish the engagement and to support the running of the group. Both groups will ensure research is aligned with specific policy needs and can deliver at the required period, thus they have a more

[3] We have been advised that the current governance review of LUS and SBS is likely to recommend setting up a new RAFE working group in this area

targeted remit than the WPWG. *KE Actions: (13) relaunch the BLUPU group; (14) launch the Soils Stakeholder Group in partnership with SG; (15) generate co-authored policy briefings with end-users; (16) identify new research collaborations and (17) publicise the map of proposed and actual outputs against policy timelines.*
CKEI: The WPC will liaise closely with the KE Sectorial Leads to ensure appropriate contributions to CKEI-led activities. Such activities will include contributing to: *the comms toolkit (CKEI Activity 2) – providing content for the website, e-zine for interested parties, ensuring that branding and presentational standards are adhered to; events (CKEI Activities 3 and 5) through providing material and skilled staff to support such events targeted at interested parties and end-users; annual campaigns (CKEI Activity 4), by providing suggestions and content of interest to interested parties and end-users; to the Think Tank (CKEI Activity 6) through sitting on the TT core group, refining the grand challenges and providing expertise on natural assets for outputs targeted at interested parties and academics; practitioner workshops (CKEI Activity 7), in particular, working with the Farmland Biodiversity Initiative to showcase synthesised results across the programme on management practices; and secondments, work shadowing and placements (CKEI Activity 9), by suggesting individuals who would benefit from close engagement with policy teams, particularly in ENFOR, ARD, SEPA or SNH.*

Pathways to impact: Impact requires flexibility on the behalf of the researchers and the end users to believe the research is credible, relevant and properly delivered in a transparent way that treats stakeholders with respect. Experience from the current SRP has taught us that time invested in interpreting scientific results in terms of what they mean for policy is the best way to support policy development and implementation, hence investment in BLUPU, SFG and WPWG. We seek the following types of impact: **Instrumental** – the WP contributes to policy (e.g. SRDP, greening of CAP and LUS) and practice (e.g. methods to identify, map and account for ESs) (see Table 1 below). **Conceptual** – the WP will raise awareness of the importance of natural assets and adaptive management, drawing attention to threats and opportunities involved in managing for multiple benefits, helping end-users to look at policy and practice in a new light. **Culture** – the WP will encourage research collaborators and end-users to invest more time into co-construction and constructive criticism to help research maximise its relevance and credibility. **Enduring Connectivity** – the WP will work with networks beyond Scotland as part of the drive to internationalise the SRP (e.g. Ecosystem Services Partnership). **Capacity-Building** – the WP will leverage existing capacity through research proposals from other funders and invest in the strategic capacity needed.

4. Quality assurance (QA)

The MRPs contributing to WP 1.4 will maintain the highest possible standards to meet the requirements and the needs of their 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,which is systematically reviewed and revised for continuous improvement and ensures:
    - Understanding of specific quality objectives and targets by 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/targets
- Obtain and act upon feedback from key stakeholders and the Scottish Government
- Develop and maintain competency of all staff through the provision of tailored training and the clear communication of quality assurance requirements

Table 1. Summary policy timeline for key stakeholders of WP1.4

Policy priorities	Impact routes	Audience	Timeline	RDs		
				1	2	3
RAFE outcomes via improved metrics for decision making across multiple policies	Revised Natural Capital Asset Register	SNH	2018+	✓		
	Revised Ecosystem Health Indicators for SBS	CAMERAS	2017-2018	✓		
	Improved Natural Capital Accounts	Defra, ONS	2020+	✓		
	RAFE subgroup on digital services	CAMERAS and Scottish Government	2016-2018	✓		
	Adjusted GDP taking account of natural assets in agricultural sector	ONS, RESAS analysts	2019+	✓	✓	
RAFE outcomes via evidence regarding policy implementation	Proposed RAFE land use and biodiversity delivery sub-group	CAMERAS and Scottish Government (NATRES)	2016-2018		✓	✓
Report on Policy and Practice (RPP4) – agriculture and other land uses	Indicative maps of prime land expansion taking account of multiple benefits	Scottish Government ARD –CAP reform	2017-2019+			
	Indicative woodland Strategies taking account of multiple benefits	Forestry Commission; Local Authorities	2017-2019+		✓	✓
	Indicative peatland restoration plans taking account of multiple benefits	SG Environmental Quality; SNH; RSPB	2017-2019+		✓	✓
Land Use Strategy	Advice on existing and potential delivery mechanisms	Scottish Government (NATRES)	2017+		✓	✓
Scottish Rural Development Plan	National targeting of existing AECS measures	Scottish Government (NATRES)	2017-2018	✓		
	Support for ECAF implementation	Scottish Government (NATRES)	2018+			✓
	New measures or combinations of measures for SRDP 2021+	Scottish Government (NATRES)	2017-2018		✓	
Common Agricultural Policy	Review of LFASS or appraisal of ANC methodologies	Scottish Government (ARD CAP reform and EU Rural development policy)	2018+		✓	
Cairngorms National Park Development Plan; CSGN plans; Tweed Catchment Management Plan Capercaillie Action Plan; Strategic and Environmental Impact Assessments	Advice on overcoming conflicts in land management and use between housing/infrastructure, forestry/farming, recreation and conservation	Scottish Government (NATRES, Environmental quality, Planning); SEPA, SNH; CNPA, CSGN, Tweed Forum	2018+			✓
Results also fed to relevant impact pathways in WP1.1, 1.2 and 1.3						

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 by Scottish Government Survey Control Unit. RESAS have been informed of potential use of these approvals.

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

Not applicable to research within this work package.

7. Sustainable development

The MRPs contributing to WP 1.4 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. Through these the MRPs:

- Regularly assess and review environmental aspects and impacts of their operation
- Implement operational control procedures and monitor environmental performance through management reviews of environmental issues, meetings and audits
- Comply with all relevant environmental legislation and other requirements
- Operate an environmental management system which is systematically maintained, reviewed and revised to ensure continuous improvement. Some institutes currently operate to the ISO 14001 standard
- Set environmental objectives and target, including CO_2 emissions reduction.
- Allocate sufficient resources to achieve its environmental objectives and targets within budgetary constraints
- Ensure that energy consumption is monitored to explore potential for reduction.
- Minimise waste, promote re-use of materials and maximise recycling
- Minimise the use of chemicals, radioisotopes and other toxic materials and to adhere to statutory regulations relating to their storage, handling, use and disposal
- To protect and promote biodiversity on the “campus”
- Exploring alternative technologies to improve environmental performance
- Senior management within the MRPs receive advice from Environment Committees or their equivalent
- Ensure competency through provision of training and communication.

RD 1.4.1 Natural Asset Inventory and Natural Capital Accounts
Research aim and key drivers: To understand if we are operating within safe limits for our natural assets, it is necessary to know first what their state is. The aim of this Research Deliverable, therefore, is to develop a spatially-referenced register of Scotland's natural assets. The Natural Assets Register (NAR) will include assessments of the condition of the assets, their role in providing ES benefits to society, and their contribution to Scotland's green growth aspiration as recognised in Scotland's Economic Strategy. In addition to this overarching strategy and the Scottish Government's Strategic Objectives the RD's policy drivers include: LUS, Scotland's Environmental Monitoring Strategy (EMS), National Peatland Plan, SBS, SRDP, Climate Change Act, Floods Directive and Scottish Forest Strategy and food security. The RD is aligned to the Theme 1 vision through assessing Scotland's natural assets in the context of planetary boundaries and the extent to which our use of natural assets can achieve environmental and social objectives within our ecological limits. This contributes to Theme 1's RQ1 (How do Scotland's natural assets function, how healthy are they, what are their trends, and what are 'safe' limits to their sustainable use?). The NAR will integrate data from across Theme 1 and will be used to inform existing efforts to assess the state of Scotland's natural assets, e.g. SNH's Natural Capital Assets Index (NCAI), and to support better decision making, e.g. targeting of SRDP measures. We will develop ways to share information in the NAR across a wide range of public and private sector stakeholders. The NAR will be combined with socio-economic approaches to develop natural capital accounts (NCA) for Scotland. The NCA will apply valuation information including where possible non-monetary values such as health/wellbeing outcomes. The NCA will be tested over a range of scales, and together, by 2021, the NAR and NCA will provide the biophysical and socio-economic evidence base to support RAFE outcomes and other policy objectives. *Who has been consulted in developing this proposal?:* The RD has been developed in consultation with Scottish Government, SNH, SEPA, FCS, SEWeb and NFUS. Specific elements of the work, e.g. refinement of the NCAI and NAR accessibility, have involved direct contact with the relevant staff of SNH and SEPA respectively.
Summary of the proposal: Using the asset and service flow inventory, the RD will examine relationships between assets, functions and service delivery, and explore NCA and ESs valuation methods to support decision processes (e.g. water management choices, including how NCA informs business decisions) from national to local scale. The RD will also help to improve existing SRDP agri-environment climate option targeting maps for RESAS and the SNH NCAI. Research in this RD will make use of legacy data where appropriate and develop novel methods of linking legacy datasets with recent national observations, for example using remote sensing (RS). A key question is the translation from ecosystem character to functions and services. Existing frameworks for this kind of work will be calibrated using Scottish data. This RD benefits from findings and expertise gathered in external research contracts that have built on cWP 1.1 and cWP 1.2, e.g. links between biodiversity and ESs delivery (Eastwood *et al*., 2013); and interdisciplinary research on ESs, e.g. NERC Valuing Nature Network (see Martin-Ortega *et al.,* 2014; McVittie *et al.,* 2015). Linkages to CXC are relevant, including the development of approaches for assessing risk to Notifiable Features (a key component of biodiversity reporting) from climate change. This underlines the intention to produce information in the NAR not just on current condition, but also on trajectories and sensitivities to drivers of change. With respect to the NCAI, this offers the opportunity to use it for scenario analysis e.g. in RD1.4.2.

Our work addresses three main objectives.

Objective O1.4.1a Development of a Natural Asset Register

This Objective will develop a comprehensive, national, spatially-explicit NAR, which will allow the identification of assets "at risk" and include an inventory of ES flows from the assets. This work will be relevant to SG and agencies by acting as a key resource in terms of monitoring change in environmental health and service delivery, assessing the value of Scotland's natural assets, and targeting action and preventing deterioration, e.g. through SRDP, in order to maintain/restore those assets.

The design of the NAR will be informed by and will build on the ESs Indicator database from the current Theme 1, and Natural Capital Committee's metrics and risk register approaches, spatially extrapolating these where appropriate. These data will be supplemented as new information becomes available across the SRP. This will support maps and models of relationships between terrestrial and water-based assets. The data created will be used for ES flows and process modelling. Activities in this RD will include the development of a framework for representing different maps of natural assets alongside one another in a compatible manner (i.e. issues of scale, uncertainty, resolution, etc. will be addressed). In addition we will take the concept of a 'database of maps' further by: (a) identifying specific stakeholder requirements and synthesising the spatial data into suitable formats; and (b) generating new information, going beyond basic biophysical and socioeconomic parameters, to ease interpretation of the relationships between environmental functions, drivers, ESs and stakeholder perceptions/goals.The proposed Ecosystem Services Data Management section of Scotland's Environment Web (SEWeb) may be a suitable means of providing access to the NAR while also enhancing the usefulness and impact of SEWeb. We will collaborate with SEWeb on the development of the site and any relevant KE events. Should SEWeb not be chosen, we will ensure that the means chosen will permit full integration with existing sites through the use of web services and consultation with the relevant bodies. Access through mobile platforms, e.g. UK Soil Observatory's (UKSO) mobile app, will be investigated to increase user access to data and expand the awareness of the NAR to a wider audience.

O1.4.1a Development of a Natural Asset Register	
O1.4.1ai Preparation and building asset register M1:Review of natural asset registers (m4) M2: Launch of 1st version of asset register (m12) M4: Ongoing population with data sets (y3-5)	D1: Asset registers review (m4) D2: Draft NAR (m12) KE1: NAR launch (m12) D3: Recurring updated NARs (y3-5)
O1.4.1aii Make the NAR publicly accessible M1: Consultation on accessibility (m12) M2: Draft websites put online (m18) M3: Launch of site (m24) M4: Review of mobile device access (y3) M5: Development of apps (y3-4)	D1: Consultation report (m12) D2: NAR website (m24) KE1: Website launch (m24) D3: Review of value of mobile device access (y3) D4: Apps for testing (y3-4) D5: Apps freely available (y4)

Objective O1.4.1b Assessing ecosystem service delivery and interactions

The 2014 -2021 SRDP introduces agri-environment-climate options that are location specific. Drawing together a wide range of data, the NAR will enable the selection of priority areas for action to be refined. It will also provide an invaluable dataset for the analysis of ES relationships and trade-offs, and their links to asset state and system function. To improve spatial targeting, an analysis will be undertaken of how species

distributions correspond with likely impacts of management options. Various data including species rarity/rate of decline will be tested for incorporation to target resources to areas where support will have the most positive impact, and targeting maps will be integrated with the NAR to assess if payments focused on conservation can benefit other assets. A review of the NCAI undertaken by Hutton (cWP 1.1; 2014) assessed the robustness of the different components of the index. Revision of the NCAI will replace less robust components of the index with new data and will incorporate new elements to reflect stakeholder policy needs. In particular there is a desire to incorporate new ecosystem health indicator data (drawing on work in RD1.3.1 and 1.3.3) into the NCAI to enhance its policy responsiveness. Existing information on Scotland's cultural ecosystem services (CES), developed using the CICES classification (cWP1.1), will be refined and extended to reflect Scottish contexts. Emphasis will be on the more challenging aspects of CES (e.g. spiritual, symbolic). Innovative methods and engagement with a range of stakeholders will generate deeper understanding of the links and mechanisms between CES and decision making at various scales. Linkages with RD3.4.3 and RD1.4.3 will improve understanding of the relationship between CES and wellbeing.

O1.4.1b Assessing ecosystem service delivery and interactions	
O1.4.1bi: Data collation M1: Methods and data assimilated for use (m12) M2: Analysis of Earth Observatory (EO) data in biodiversity modelling (m22) M3:Draft maps of climate change impacts (m23) M4:Comparison of multi-tiered ES mapping methodologies (y3) M5:Spatial relations between environmental justice measures and ESs analysed (y4) M6:Impact of climate change on selected ESs: sensitivity to methods analysed (y5)	D1: Methodology report (m12) KE1:Stakeholder workshop (m24) D2:Research brief on EO to model condition changes (m24[4]) D3:Research brief on multi-tiered mapping (y3) D4:Research brief on - environmental justice (y4) D5:Research brief on climate change impacts (y5)
O1.4.1bii ES Flows and Inventory Assets M1:Improved resolution of ES models (m11) M2:Preliminary assimilation of RS data into ES models (m12) M3:Preliminary habitat maps (m18) M4: Integration of EO and ES data(m24) M5: Assessment of use of radar images in ES models (y3-4) M6: Assessment of EO data in ES models (y5)	D1: Report on improved ES models (m11) D2: Habitat Maps (m18) D3:Research brief on integrating EO & ES data (m24) D4:Research brief on use of Sentinel data (y3-4) D5:Research brief on use of satellite data (y5)
O1.4.1biii Natural Capital Asset Index M1:Proposed refinements to NCAI (m12) M2:Further NCAI refinement (m24) M3:Identification of additional data and refinements to NCAI (y3-5)	KE1: SNH consultation & D1:Report on consultation (m6) D2/ 3: Provide options for new NCAI data – report (m12, 24) KE2: SNH consultation (m17) D4:Update options for NCAI (y3-5)
O1.4.1biv Linking peatland restoration project data to a model of peat depth and condition M1:Acquisition and integration of restoration project data with spatial covariates (m12)	D1: Survey data and spatial covariate database – report (m12) D2:Peat depth model and

[4] All research briefs or papers will also be turned into policy briefings if requested by BLUPU or SFG.

M2: Development of model for estimating organic horizon depth. (m24) M3:Image analysis for peatland vegetation and site condition from smartphone imagery (y3-5) M4:Development of smartphone app for local peat depth and condition estimation (y3-5)	mapping – report (m24) D3:Image analysis methodology for site condition assessment – report (y3-5) D4:Mobile app for peat characterisation (y3-5)
O1.4.1bv Targeting SRDP Payments M1:Assessment & collation of species & habitat data (m6) M2:Scoring system for spatial targeting (m23) M3:Targeting methodology including ESs and habitat map (y4)	KE1: Consultation on data for refining SRDP targeting (m12) D1:Paper detailing the impact of different prioritisation methods on Scottish farmland biodiversity (m23) D2:Provisional targeting maps for SRDP 2021 options (y4)
O1.4.1bvi Cultural Ecosystem Services indicators and mapping M1:Data collation and gap analysis (m8) M2:Research methods confirmed (m10) M3:Draft 'maps' for CICES CES classes (m20) M4:Complete draft set of CES proxies/indicators for selected CES (y3) M5:Draft 'maps' for CICES CES classes (y4) M6: Recommendations on using CES indicators and maps provided (y5)	KE1:Stakeholder consultation (m4) D1:Data inventory report (m8) D2: Internal report on social science methods (m10) D3:Prototype maps (m20) D4:Research brief on social science data collection (m22) D4:Paper and research brief on CES (y3) D5:Improved CES maps (y4) D6: Paper and research brief on CES proxies (y5)

Objective O1.4.1c Natural capital accounts

Valuation and the development of NCA will be closely integrated with development of the NAR. Key to this will be determining the most appropriate ESs values (monetary and non-monetary) and the identification of gaps in existing ES valuation data. Much of the existing valuation evidence has been produced without reference to a systematic classification of ESs or the means by which they are quantified. It is necessary to develop a new and consistent set of values for natural capital accounting and other uses in Scotland. The research will refine an existing approach (2011a, 2011b) through integration with the modelling of ES delivery within this RD. The approach is flexible and could be used to apply ES values to the NAR maps to form the NCA. Testing the transferability of these values for accounting will be an important research activity. The approaches will need to be applicable across different resolutions: broad-scale, low resolution values suitable for national level analysis (e.g. SG) to fine resolution for companies and land managers.

O1.4.1c Natural capital accounts	
O1.4.1ci Identifying ES values for natural capital accounts M1:Initial data collection and gap analysis (m7) M2:Primary valuation survey implemented (m18)	D1:Gap analysis of ESs values – report (m7) D2:ES valuation papers (m19) KE1: Valuation seminar (m24)
O1.4.1cii Developing case study accounting frameworks M1:Year 1 and 2 accounting case studies selected (m8) M2:Ongoing selection of accounting case	D1:Initial shortlist (m7) KE1:Stakeholder consultation (m8) D2:Reports/briefings on initial case studies (y3)

studies reflecting stakeholder inputs and data availability within the SRP (y3-5)	D3:Reports/briefing on further case studies (y4-5)
O1.4.1ciii Developing the transferability of ES values M1:Key contextual factors influencing ES value transferability identified (m12) M2:Value transfer approach applied valuation data (initial case studies) (m24) M3:Ongoing development of transfer approaches to accounting case studies (y3-5)	D1:Draft value transfer approach – report (m12) D2:Papers on ES value adjustments (m24) KE1:See O1.4.1ci (m24) D3:Papers on further value adjustments (y4-5)

Technical approach: The work planned under this RD will be organised into three concurrent sections that interact in order to ensure the cross-compatibility of data structures, data collection and outputs.

O1.4.1a Development of an Asset Register: This objective will be responsible for collating the data to be included in the NAR and the development of appropriate structures for data management, display and dissemination of the NAR. Activities will address issues such as the treatment of features and indicators that are difficult to map (e.g. cultural services). The data and indicators included in the NAR may represent measures of the stock of natural capital. Whilst this is important, for effective policy and management it is also necessary to understand how ESs arise from the natural assets. Creation and harmonisation of objects that form the NAR will include identifying areas where ecosystems are most/least resilient/healthy (building on typologies and assessment processes from RDs1.1.2, 1.2.2, 1.3.1 and 1.3.3). This work will:

- Identify the most appropriate geographic data model for a NAR that satisfies a portfolio of requirements across a wide range of spatial scales
- Determine how to represent multiple and spatially non-congruent criteria
- Develop ways to store and display 'difficult to map' indicators, e.g. CES and spatially extensive features stored as points (e.g. the raised bog inventory)
- Identify the best way to make the NAR accessible

Detailed work plan:

Review existing natural asset inventories and literature, liaise with likely consumers of maps/data e.g. SEWeb, CAMERAS partners, app designers etc. Develop a formal specification that implements the chosen data model and feature/attribute specification.

- Build the NAR. The register will be developed with guidance from MAES (EU, 2014), benefitting from its pilot studies and recommendations and using the CICES classification. Relevant data will be identified from discussions with appropriate organisations and from existing reviews of ESs data and research undertaken in the current programme and in response to SG requests.
- Provision of Digital Soil Maps and enhanced data availability/functionality from the Scottish Soils Database.
- Assessment of the contribution of remote sensing to the NAR and its periodical updating. In particular the work will focus on the use of existing and new technologies e.g. the ESA Sentinel and soil moisture sensors (SMOS/SMAP) to contribute to modelling and mapping assets and their conditions. The feasibility of using the new technologies for modelling of change in condition will be assessed. The sensors will be integrated in a nested approach for modelling and monitoring at different resolutions. Where required datasets will be downscaled to the resolution relevant for the application. High performance computing will be used to create the capability to process high amounts of (satellite) data.

- Investigate indicators for CES. Produce an inventory of existing in-house and partner (SNH, SEPA, Scottish Water etc.) data needed to populate the NAR. Develop innovative methods (combining biophysical, social science and cartographic expertise) to create and map CES indicators that are difficult to spatially locate such as the symbolic or spiritual. This will include participatory research to both inform and critique development of proxy indicators (years 1-2) and subsequent refinement and integration (years 3-5; in collaboration with RD3.4.3).
- Investigate and implement options for making the NAR accessible including site within SEWeb, an independent website, part of the CKEI web presence and/or the ESCom Scotland website. The option will be chosen in consultation with key stakeholders and include an interactive viewer facilitating the display of NAR maps. In years 3-5 of the programme access to the NAR through mobile device applications will be developed. Relevant outputs from the SRP will be incorporated into the NAR as they become available. The NAR and its chosen accessibility option will be updated to react to data sharing and publishing initiatives (in Scotland and elsewhere) and milestones and deliverables will be generated collaboratively with stakeholders to reflect such developments.

O1.4.1b Assessing ecosystem service delivery and interactions: This objective will use a variety of modelling approaches to link the data and indicators in the NAR to the flow of ESs; this will draw on spatial analysis within the RD and modelling work undertaken across Theme 1. This understanding of the flow of ESs from natural assets will be used in particular to inform refinements to the NCAI and SRDP targeting maps. It will also be used within continuing research in the RD to use the NAR to identify areas for priority action in terms of ecosystem management and restoration and use the NAR to develop new methodological approaches to understanding the relationships between natural assets, ecosystem functioning, and service delivery.

Detailed work plan: The main goal for the first three activities in this section is the development and application of methods to link the character of the natural asset, its condition, its functioning and ES delivery including interactions between ESs. We will describe how ESs flow originate from the assets in the inventory and identify important landscape areas for delivery of multiple benefits and corresponding gaps. The RS data in the register will be used to refine existing ES models (nutrients, sediments, carbon, pollination, food production).
- Spatial modelling of natural assets and climate change impacts with characterisation of spatial uncertainty in models at appropriate scales. This will be based on acquisition and use of improved datasets to be applied in refined spatial models. The uncertainty of the modelling will be explicitly assessed and mapped. The identified (RS) data coupled with climate downscaled data (linking to RD1.4.2) and land use data will be used for preliminary models of direct and indirect climate change impacts on selected natural assets (soil moisture, carbon stocks, biodiversity). Spatial uncertainties will be assessed to identify hotspots of uncertainty. In years 3-5 we will expand on the modelling and mapping taking into account new case studies (agreed with stakeholders) and methods integrating RS with ESs for biodiversity and soil functions mapping. We will focus particularly on extended assimilation of RS data into ES models and modelling of climate change impacts.
- From year 3 on we will investigate the usefulness of SENTINEL radar data and of sub-meter sensors for ESs mapping (i.e. modelling beyond habitat classification), and for targeting incentives; we will compare different existing methodologies to assess the same services, to establish their strength and weaknesses, and trade-offs between comparability (e.g. with other EU countries) and accuracy, and investigate how the assessment of the impact of climate and land use change depends on the

method used. We will also investigate the relationships between ESs and indices of deprivation and investigate whether ESs supply data could inform such indices.

- Use the NAR to examine the relationship between physical assets and cultural values (e.g. health/wellbeing) attributed to the landscape. This will be carried out through community-level engagement using visual methodology (e.g. participatory mapping, Touch Table) within case studies (links with RD3.4.3 in years 3-5). Case study sites will be selected in consultation with partners and 1.3.2 and 1.4.3 as well as findings from and gaps from years 1-2. Development of spatial datasets on biophysical parameters will inform the development of maps of ecosystem functions and services (through links with RD1.1.4 and RD1.1.1).
- Restoration project data from peat soils collated by the Peatland Action Plan (PAP) will be used to develop models of peat depth and site condition score. The PAP data will be linked to existing data (Scottish Soils Database) to allow spatial modelling and mapping of peat depth/condition. It will also provide improved information for SRDP and PAP decision making. Linkages with the Crichton Carbon Centre will be utilised to disseminate outputs to land managers and policy makers.
- Refinement of methods for targeting SRDP payments for use in the next SRDP (2021 onwards): various data will be incorporated to target resources to areas to maximise the benefits; targeting maps will be integrated with the NAR to assess if payments for conservation benefit other assets. NAR and the SRDP targeting will be informed by soil hydrology outputs (RD1.1.4). In later years the SNH habitat map and natural asset/ ESs maps will be integrated with the spatial targeting approach.
- Use the NAR to deliver refinements to the NCAI. The work will be undertaken in close collaboration with SNH and SG, in particular staff tasked with biodiversity monitoring. This will be done through a rolling programme, incorporating new data sets as they become available.
- We will explore how a register of water body assets could be used to map relationships between water availability/use/quality/quantity and associated ESs (with WP1.2.2 and CEH, HEI project 8).

O1.4.1c Natural capital accounts*:* The objective of the RD will use the NAR to develop NCA. These will combine the biophysical data in the NAR with ESs flows and economic valuation data to develop a spatial NCA framework. The NAR will be used to 1) develop the NCA from the NAR, and 2) apply the NCA across a range of scales and end-users (Government, agencies, specific sectors or industries, and business). The NCA will build on existing work in the current programme (cWP1.3) and approaches developed by the Office for National Statistics (ONS) at UK level. However, our proposed integration of the NCA with the NAR represents an innovative development as the NCA will have a spatial basis. This offers the potential to explore how well the demand and supply for ESs are matched across Scotland. In addition this RD will address identified gaps in the monetary valuation of natural capital and ESs. Regarding valuation of natural assets, some of the issues for exploration include the extent to which the type of habitat providing ESs contributes to the values, and the role of socio-economic and spatial factors in determining values.

Detailed work plan:

- Develop a valuation framework that integrates information about environmental (soil, topography, climate, geology etc.) factors, the ES flows they produce with the benefits they provide. Use this methodology to map functions and services and to identify knowledge gaps and uncertainties.

o Test the approach to valuation and natural capital accounting across a number of case studies (land-use sectors considering different bundles of ESs and habitats, scales and end-users, including corporate sector). Case study selection and timing

will reflect data availability (NAR and linked RDs) with case study applications and refinement continuing throughout the programme. Examples include: Agriculture, including the potential to map and value genetic diversity in production systems (link to RD2.3.2); Forests and woodlands (link to RD1.3.2); Water ESs, including peatland restoration (linking to the Peatland code). This links to work under RD1.1.4 and activities in RD1.2.1; Urban/rural greenspaces (including health/wellbeing values; link to RD3.4.3) and pollination services (link to RD1.4.2) including the mapping of ESs provision by linear features and ecological focus areas (EFAs).

- Alternative metrics and models for assessing natural capital benefits will be explored through interaction with activities in RD2.4.3 and O1.4.2biv. By considering similar case studies we expect to identify areas of convergence and/or divergence across the different approaches and to assess their relative merits. Interaction of circular economy models with the spatial aspects of the NAR and NCA may offer insights into the barriers or opportunities for achieving circularity.
- Developing robust estimates of ESs values to inform the NCA and environmental management. Research will use stated preference (choice experiment) surveys to refine approaches to ES valuation to explore the role of context in forming ES values and the impact on the transferability and scalability of values; e.g. how does the type of habitat providing ESs contribute to the values held?. It will explore the role of socio-economic and spatial factors in determining values; with RD3.4.3 on how objective and subjective qualities of landscape affect well-being and influence values. The spatial emphasis within this RD underlines the importance of understanding spatial relationships (e.g. distance decay) between ES provision and values. Existing valuation evidence will be used, e.g. the TEEB Valuation Database and related outputs (e.g. Hussain et al., 2012), to refine the spatial analysis of ESs values. The spatial elements of the ESs valuation will further inform the targeting of SRDP measures and research into biodiversity offsetting (RDs 1.3.4).

Expertise: The expertise of the PIs is provided in their associated CVs. Hutton and SRUC have the relevant technical systems and support staff to deliver this RD.

Key linkages, interdisciplinarity & collaboration:

Linkages within the Natural Assets Theme: The descriptions of the linkages are included in *Technical Approach.* This RD draws on and will feed into work across a number of RDs in the Natural Assets theme, and the NAR will be used throughout the Theme. Linkages include: relationships between natural assets, ecosystem functions, ESs delivery (RDs 1.1.2, 1.3.1, 1.3.2, 1.4.2, 1.2.1), digital soil mapping (1.1.4); research on integration of environmental factors into assessment of ESs, linking with RD1.1.1; collaboration with SNH to refine the NCAI linking to research on ecosystem health indicators under RD1.3.1 and 1.3.3 to incorporate new measures of ecosystem health; NCA and valuation research links to peatland valuation work in RD1.1.4; biodiversity valuation also links to habitat creation and biodiversity offsetting research planned in RD1.3.4.

Linkages across the Strategic Research Programme and associated activities: The NCA and valuation research links to circular economy modelling in RD2.4.3, landscape and well-being in RD3.4.3 and to CXC and CREW. This RD is involved in the Whisky Nexus innovation bid in collaboration with WP2.4. CES research will link to RD3.4.3 on environmental and landscape qualities, use and enjoyment of landscape and wellbeing. This RD links to RD2.3.2 in mapping genetic diversity in production systems. The potential role of the NAR as part of a baseline assessment of the status of environmental public goods will be explored in RD3.4.1.

Collaboration with external organisations: 1.4.1 aligns closely with priorities of CAMERAS partners. Work with SNH on NCAI will be closely integrated with the

development of the NAR. The NAR will be integrated with the UKSO app. UKSO (a joint initiative including Hutton, Centre for Ecology and Hydrology (CEH), BGS and Cranfield University) has expanded to other organisations with EU Joint Research Centre (JRC) looking to use the approach across Europe. We have links with HEIs and other research bodies (University of Edinburgh, CEH, Forest Research) through ESCom Scotland. Hutton and SRUC co-funded the ESCom Scotland website; this will form a key KE conduit to the stakeholder community and potential public engagement. ESCom Scotland and the Scottish Forum on Natural Capital (SFNC) provide connections to the NGO and business sectors. We will align to SFNC's project groups through activities related to peatland, greenspace and links to circular economy work (RD2.4.3). SEWeb is a key KE resource; we will collaborate to make best use of outputs from this RD, including potentially State of the Environment reporting. We will collaborate with CAMERAS to develop case studies in modelling and mapping (including participatory mapping) in years 3-5. International linkages include engagement with the Ecosystem Services Partnership (ESP) where we are active in its thematic and sectoral working groups. The RD is active in international research consortia through EU funding which we would seek to align with RESAS funded research. We anticipate involvement in the *TEEB for Agriculture and Food* sectoral study.

Interdisciplinarity: Research in 1.4.1 is strongly interdisciplinary both with respect to the three objectives and multiple links across the research programme. This includes the integration of innovative methods for public engagement in identification of difficult to quantify CES, technical knowledge on mapping and data structures with modelling of biophysical assets to determine the flow of ESs they provide, and economic and social-science approaches to evaluating benefits. RD Coordinators will use WPMG and research plans to identify further opportunities for integration.

Added scientific value: Our approach to developing the NAR, understanding ESs flows and developing the NCA is innovative and ambitious both in terms of the strong spatial element to these activities and our interdisciplinary integration in developing the necessary data and structures. The NAR will add value to the current SRP and UK programmes such as BESS through mapping assets and flows by developing an understanding of how to scale-up knowledge of ES flows. This development in the understanding of flows will then inform the refinement of the NCAI and SRDP targeting maps. The SRDP targeting work will develop new methods to integrate species distribution and habitat data to target conservation resources. It will analyse the consequences of this for ESs supply. It builds on our involvement in previous studies into NCA (e.g. agriculture, and potential soil accounts), and developing understanding of linking biophysical and socio-economic approaches (VNN projects on agriculture and peatland). The spatial approaches across the RD can add value to ongoing activities at the ONS. We are involved in a number of international initiatives such as the Valuing Nature programme and the Ecosystem Services Partnership. These will provide the opportunity for wider scientific collaboration.

KE, audiences and impact: The initial limited access NAR launch will be in early 2017. There will be full public access when the supporting mechanism (possibly a SEWeb site) is launched in March 2018. This website will be an important KE pathway for the NAR and will also link to the Atlas of Living Scotland. The RD is represented on the RAFE subgroup on Digital Strategies and SEWeb management group so that we can be informed by their priorities and developments. RD researchers are involved in a number of working groups that offer direct KE opportunities into policy development (e.g. Science and Technical Group for the SBS). JHI and SRUC are represented on ESCom's governance board offering potential for impact through the 'ESCom Series' seminars which reach a wide

stakeholder audience. The RD will also contribute to the WP stakeholder working group, WP and theme level KE and fully support the activities of the CKEI, such as providing materials to support annual campaigns or showcase events and using the comms tool kit. **Audiences and Engagement:** The primary audiences for the NAR will be policymakers, land managers and agencies; accessibility via SEWeb will allow use by a wider audience. Work on improving the SRDP targeting maps would be in collaboration with SG Policy teams, plus stakeholders such as RSPB, SLE and NFUS. The NCA case studies will involve the business sector (via the SFNC) and agencies (SEPA, SNH). The audiences for the accounts will be the corporate sector, Defra and the ONS (e.g. the proposed Whisky Nexus Innovation project). **Pathways to Impact:** The NAR will provide accessible information on the status of Scottish ecosystems for policymakers, land managers, agencies and other interested parties from 2018 onwards to inform decisions about the sustainable use of natural assets and ESs. Work on SRDP targeting will have a direct impact through developing targeting mechanisms for biodiversity measures in 2021-27 SRDP. We will participate in the ongoing SNH led discussion forum on the framework for CES indicators to improve understanding of the role of landscape character in the context of ESs and the ecosystem approach. The NCA will inform decision making on from multiple perspectives and assist SNH in reporting to the SBS natural capital group.

RD1.4.1: NATURAL ASSET INVENTORY AND NATURAL CAPITAL ACCOUNTS
Work planning and timetable for Year 1

Year 1: 2016/17 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.4.1ai Building a NAR. Review and report on existing NARs; design and construction of the NAR database and populating with ESs data sets. ***M1:Review of natural asset registers.M2: Launch of 1st version of asset register***				**M1 D1**								**M2 D2 KE1**
O1.4.1ai Make the NAR Accessible. Investigate and consult on accessibility options (informed by consultation with SEWeb ESs technical and user group). ***M1:Consultation on accessibility***												**M1 D1**
O1.4.1bi Data collation, spatial model. Review and collate existing data. ***M1: Methods and data assimilated for use***												**M1 D1**
O1.4.1bii ES Flows and Inventory Assets. Improved spatial thematic resolution of ESs models. ***M1: Improved resolution of ESs models. M2:Preliminary assimilation of RS data into ESs models***											**M1 D1**	**M2**
O1.4.1biii Natural Capital Asset Index. Develop options for NCAI refinement, and proposed refinements. ***M1:Proposed refinements to NCAI***						**KE D1**						**M1 D2**
O1.4.1biv Linking peatland restoration data to peat model. Acquisition and integration of restoration project data with spatial covariates ***M1: Acquisition and integration of restoration project data with spatial covariates***.												**M1 D1**
O1.4.1bv Targeting SRDP Payments. Assessment and collation of relevant species/habitat data; on-going consultation on refinement of SRDP targeting; consultation on species responses. ***M1:Assessment & collation of species & habitat data completed***						**M1**						**KE1**
O1.4.1bvi Cultural Ecosystem Services indicators and mapping. Data collation and gap analysis to guide research operationalising CICES CES classification. ***M1:Data collation and gap analysis, M2: Research methods confirmed***				**KE 1**				**M1 D1**		**M2 D2**		
O1.4.1ci Identifying ESs Values for NCA. Valuation data collection and gap analysis. ***M1:Initial data collection and gap***						**M1**						

analysis						**D1**						
O1.4.1cii Developing case study accounting frameworks. Selection of year 1 and 2 accounting case studies and delivery of initial case study shortlist and stakeholder engagement. ***M1:Year 1 and 2 accounting case studies selected***							**M1 D1**	**KE 1**				
O1.4.1ciii Developing the transferability of ESs values. Identification of key contextual factors influencing ESs value transferability. ***M1:Key contextual factors influencing ESs value transferability identified***												**M1 D1**
Annual report to RESAS (all objectives)												**R1**

RD1.4.1: NATURAL ASSET INVENTORY AND NATURAL CAPITAL ACCOUNTS
Work planning and timetable for Year 2

Year 2: 2017/18 Activity	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.4.1.aii Make the NAR Accessible. Continue with implementing the approach to NAR accessibility; draft and launch of the website. ***M2: Draft websites put online, M3:Launch of site***						**M2**						**M3 D2 KE1**
O1.4.1.bi Data collation, spatial modelling. Earth Observatory and digital surface model data assimilation, stakeholder validation and preliminary mapping. ***M2:Analysis of EO data in biodiversity modelling complete***										**M2**		**KE1 D2**
O1.4.1.bii ESs Flows and Inventory Assets. Improved spatial ESs modelling by EO data assimilation. ***M3: Preliminary habitat maps. M4: Integrated EO and ESs data***						**M3 D2**						**M4 D3**
O1.4.1.biii Natural Capital Asset Index. Further development of NCAI . KE Consultation with SNH and provide options for new NCAI data to SNH. ***M2: NCAI further refined***					**KE 2**							**M2 D3**
O1.4.1.biv Linking peatland restoration project data to a model of peat depth and condition. Development of model for estimating organic horizon depth. ***M2: Model for estimating organic horizon depth developed***												**M2 D2**
O1.4.1.bv Targeting SRDP Payments. Development of scoring system for spatial targeting; impact analysis of prioritisation methods on farmland biodiversity. ***M2:Scoring system for spatial targeting available***											**M2 D1**	
O1.4.1bvi CES – Synthesis. Develop prototype maps of selected CICES CES classes for Scotland based on Year 1. ***M3:Draft maps for CICES CES classes***								**M3 D3**				
O1.4.1.c1i Identifying ESs Values for NCA. Primary valuation survey implementation and stakeholder engagement. ***M2:Primary valuation survey implemented***						**M2**	**D2**					**KE1**
O1.4.1.ciii Developing the transferability of ESs values. Application of transfer approach to primary and secondary											**M2**	**D2**

valuation data. ***M2:Value transfer approach applied valuation data (initial case studies)***												
Annual report to RESAS (all objectives)												**R1**

RD 1.4.2: Identifying and understanding multiple benefits and trade-offs - How can we identify resilient interventions for multiple benefits?

Research aim and key drivers: Managing ecosystems to avoid exceeding planetary boundaries will inevitably involve trade-offs and synergies between different ecosystem services. Maximising one benefit (e.g. provision of food) may be traded-off against another (e.g. carbon storage), resulting in some difficult decisions, due to competing demands and pressures. These trade-offs will only be exacerbated by drivers of change. The Scottish Government's Economic Strategy highlights the importance of investing in natural capital to deliver opportunities for all, but whilst Scotland has plentiful natural resources, we are exceeding planetary limits for some. To reach a situation where Scotland's natural assets are enhanced, we need all sectors of society to contribute to the protection of ESs for multiple benefits. To achieve this aim, communities must work with land-based businesses to get more value from existing incentives, regulation and advice. Fulfilling societal demand for multiple benefits from land requires a change from the current focus on single assets. To achieve food, environment, energy and water security, integrated, cross-scale and spatially explicit policy options need to be developed that consider and connect multiple objectives and interests. This reflects the Land Use Strategy (LUS) principles and the mainstreaming of an ecosystem approach within SEPA, SNH and the National Park Authorities. Provision of new scientific evidence gives an opportunity for SG and CAMERAS partners to align delivery of several policies including SRDP, Scottish Biodiversity Strategy (SBS), Water Framework Directive (WFD) and Peatland Strategy to deliver multiple benefits. In turn, this will contribute to Scotland's ability to meet its UN Sustainable Development Goals (Agenda for 2030), and to the Aichi Targets (CBD). Our vision for 2021 is to have developed approaches that will support integrated decision-making to protect multiple natural assets and maximise benefits in socially acceptable ways. We will have identified and quantified impacts on and trade-offs among multiple ecosystem services (ESs) generated by land use and land management change across spatial scales. As such it will contribute to the Theme's RQ3 on the key ecosystem benefits derived from Scotland's natural assets, their distribution, relationships and trade-offs.

Who has been consulted in developing this proposal: During Sept-Oct 2015, we consulted with the Land Use and Biodiversity Team, the Natural Heritage team, RESAS, SNH, SEPA, FCS and Agriculture and Climate Change. We have built on consultations carried out by WPCs from WP1.1, 1.2, 1.3, 2.4 and 3.4.

Summary of the proposal: The RD will refine tools developed in SRP (2011-16) to deliver a more comprehensive analysis of the current state of ESs delivery at national, regional and catchment scales as well as a dynamic assessment of trends and resilience under drivers of change. Developing socio-ecological modelling approaches will help us understand the relationships between the demands of society and the supply of ESs. This will provide the strategic capacity to learn from the existing distributions of 'hot' (many ESs being delivered) and 'cool' (ESs in competition or decline) spots. This will support decision making at the national scale by Scottish Government or their agencies, regional scale by local authorities or national parks, or catchment/landscape scale by catchment management or other partnerships. Solutions or trends that look promising at one scale may not be socially acceptable or desirable when analysed at a different scale. The RD has three main objectives covering the opportunities and trade-offs for the sustainable delivery of ESs, opportunities to improve sustainability and the resilience of our socio-ecological

systems to change.

Objective 1.4.2a: Identification of gaps in the current delivery of multiple benefits: This will analyse, at national and regional scales, the current spatial gaps in the delivery of ESs and benefits that society desires (as expressed in policy goals identified in O1.4.2bi). We will analyse historical pathways of land use and land management change to better understand the present provision of ESs that results in trade-offs between provisioning (e.g. food production), regulating (pollination, nutrients and sediment retention) and cultural ESs (landscape character). The focus will be on interpreting and improving the maps generated in the current SRP in light of policy questions. O1.4.2a will run for up to two years in order to support cultural ES science contributing to RD1.4.1's NAR; and provide material to inform case studies in 1.4.3. Desired Outcomes: O1.4.2a will develop an evidence base to illustrate the uneven delivery of ESs and the divergence from policy goals; providing a baseline for policy appraisal in O1.4.2c.

O1.4.2a Identification of gaps in the current delivery of multiple benefits	
M1: Trade-off mapping completed and used to inform policy (m20)	KE1: presentation at BLUPU & soils stakeholder groups (m12) D1: research brief and maps from ESs trade-off analysis (m20)

Objective 1.4.2b Identification of opportunities to increase multiple benefits through policy and industry delivery mechanisms. O1.4.2a will illustrate where we have a 'gap' between what society desires from our environment and what is currently delivered. The ability to close this gap, and to turn trade-offs into synergies, often comes down to how land is governed and managed. Whilst RD1.4.3 will look at how to deliver practical management on the ground, this objective will tackle national and regional level governance approaches. This objective will assess four ways in which delivery of multiple benefits can be increased: O1.4.2bi) improved policy and institutional alignment; O1.4.2bii) opportunities to use monitoring and evaluation to deliver multiple benefits; O1.4.2biii) the role of social innovation and O.1.2biv) sustainable supply chains. We will draw on policy, institutional, governance and uptake of best practice research across the programme (RDs 1.1.4, 1.2.4, 1.3.4, 2.3.12, 2.4.2) and support the delivery of adaptive management in RD1.4.3. Outputs from years 1-2 will feed into the option appraisals in O1.4.2c and we will integrate the learning within the objective from years 3-5 onwards. Desired Outcomes: the resulting evidence will support SG in their quest to deliver RAFE outcomes in an integrated fashion, and will illustrate how to deliver LUS2 which draws together a range of land and water policies. It will support improving environmental performance of food supply chains relevant to QMS (Quality Meat Scotland), Scotland Food and Drink, and the SRDP Beef Efficiency Scheme (BES).

1.4.2bi: Aligning existing and new delivery mechanisms

M1: Opportunities for better alignment of policy delivery identified (m24) M2: Recommendations for using new instruments to deliver multiple benefits in Scotland (m50)	KE1: Stakeholder /BLUPU presentation (m10) D1: Report from stakeholder meeting (m18) D2: Journal paper on aligning delivery mechanisms[5] (m24). D3: Research briefing on new instruments (m26). KE2: Stakeholder workshop: using new instruments to deliver multiple benefits (m28) D4: Stakeholder workshop report (m30) D5: Journal paper on innovative instruments (m50).
1.4.2bii: Using M&E to deliver multiple benefits	
M1: Existing sources of data collated and analysed (m24) M2: Recommendations on using existing sources of knowledge to support adaptive management (m56)	D1: Good practice summary report (m24). D2: Journal paper on how M&E shapes delivery of multiple benefits (m28). KE1: BLUPU & SFG presentation (m30). D3: Journal paper on how M&E processes can deliver multiple benefits (m54).
1.4.2biii: Using social innovation to deliver multiple benefits.	
M1: Role of social innovation in sustainable land use identified (m24) M2: Role of social innovation in sustainable land use demonstrated (m56)	KE1: BLUPU & SFG presentation (m12). D1: Journal paper on social innovation (m24). KE2: Stakeholder workshop to scope applications in Scotland (m 26). D2: Journal paper on application(s) (m38). D3: Journal paper on prospects for social innovation (m56).
O1.4.2biv: Improving the environmental performance of supply chains	
M1: Conceptual framework for analysis of trade-offs in supply chains developed(m12) M2: Impacts represented spatially - beef (m24) M3: Impacts represented spatially – other commodities (yr3/4) M4: Prospects for spatial supply chain analysis identified (yr 5)	D1: Research briefing note on methodology to assess and map impacts of beef supply chain (m12). KE1: Stakeholder workshop (m14). D2: Spatial database of material flows arising along beef supply chains (m24). D3: Journal paper on trade-offs and synergies between improving environmental performance and food security goals in beef supply chains (m26). D4: Journal paper on synergies between improving environmental performance and food security goals in dairy supply chains (m36-m48). D5: Synthesis report on spatial analysis of resource efficiency, illustrated with case studies (m60).

Objective 1.4.2c Option appraisals to demonstrate resilience of natural assets under different trajectories. This objective will contribute to the SRP's integrative 'land use' project, and aims to be responsive and open-ended to allow us to use our

[5] All journal papers will be accompanied by a policy briefing if requested by BLUPU and SFG.

science to respond to the most salient policy requests. We will use a number of modelling approaches to explore options for sustainable land use under multiple drivers of change impacting multiple ESs. ES resilience to change is still poorly understood but we know that the future is uncertain and Scotland should prepare for change across a range of drivers (social, technological, environmental, economic and political). We will run parameterised models under a range of scenarios to identify vulnerabilities, tipping points and sustainable pathways into the future, looking both near-term (up to 5 years, and medium term to 2050). We will build on the analysis of the current situation in O1.4.2a and use insights from 1.4.2b to develop storylines in years 3-5. The objective has three components: O1.4.2ci: Policy option appraisal for delivery of multiple benefits; O1.4.2cii: Climate adaptation and mitigation impacts on multiple benefits, and O1.4.2iii: Assessing the economic impacts of changes in ecosystem services. Desired Outcomes: Evidence used for policy options appraisal supporting the CAP review. Recommendations incorporated in national and local forest strategies and Woodland Grant Scheme; evidence used in the CNP Forest and Woodland Framework and by the CSGN partnership (via 1.4.3). Support to RPP4 fed to SG via CXC. Methods used by ONS in to develop adjusted GDP measures.

O1.4.2ci: Policy option appraisal for delivery of multiple benefits	
M1: Quantify ESs delivery linked to potential agricultural, woodland and peatland management changes (m28)	KE1: Select options with stakeholders (m4) KE2: Discuss draft results at BLUPU and SSG (m18) D1: Maps illustrating ESS delivery from policy scenarios (m18) (with WPs 2.4 & 3.4) D2: Policy briefing on impacts of land use change on ESS (with WPs 2.4 & 3.4) (m20) D3: Journal paper on viability of RS to monitor land use intensity (m24) D4: Journal paper on ESs impacts from policy drivers on land (m26) D5: Further briefing(s) based on re-analysis requested by stakeholders (m28)
O1.4.2cii: Climate adaptation and mitigation impacts on multiple benefits	
M1: ESs impacts of trading off agriculture against woodland expansion and peatland restoration illustrated (m20) M2: Integration of MCA tool with WISE model (with CXC–Peatlands, m22) M3: Completed MCA of impacts of woodland expansion, peatland restoration and prime land on ESs (yr3) M4: Full ESs models embedded into the online MCA tool (yr 5)	KE1 Stakeholder workshops for multi-criteria mapping (m6) D1: Woodland & ESs opportunity maps (Scotland, CSGN and CNP) (m20, yr4) D2: Peatland restoration & ESs opportunity maps (m22, yr4) D3: Policy briefings summarising opportunity mapping results (m24) KE2: Web-hosted interactive video on woodland expansion, peatland restoration and expansion of prime agricultural land and impacts on ESs (m24) D4: MCA web based tool (yr3) D5: Apps to improve the MCA tool (yr 3). D6: Research briefings on preferred sustainable pathways (yr 3, 4) D7: Journal paper on MCA and model integration methodologies (yr 4)

	D8: Revised online MCA tool (yr5)
O1.4.2ciii: Assessing economic impacts of changes in ecosystem services	
M1: Agreed route map for integrating service flows through modelling (m9) M2: Complete initial case study (m18) M3: Agreed subsequent case study (m20) M4: Complete subsequent case study (m36) Years 3-5 completion of 3rd case study	KE1: Stakeholder meeting on economy-wide modelling and the integration of environmental values (m3) KE2: Workshop with Office of the Chief Economic Advisor (OCEA) staff (m13) D1: Technical report (m18) D2 Journal paper 1st integrative case study (m18) D3 Journal paper from 2nd integrative case study (m36) Further journal paper from 3rd case study (m50)

Technical approach:

Objective 1.4.2a: Identification of gaps in the current delivery of multiple benefits: We will use GIS and spatial statistical analysis and geo-statistics methods to refine the pattern of relationships between the provision of different ESs and land management/use. A variety of models, such as the InVEST suite, will be used for refining trends in ESs, mainly process based models of nutrient sediment and carbon retention, pollination, and habitat provision, building on existing datasets and model outputs from the SRP (2011-16), and extending these to include ESs most pertinent to stakeholders (via BLUPU and SFG) such that O1.4.2c can proceed from a strong baseline. The maps will be assessed against policy goals summarised in O1.4.2bi. The focus of this sub-objective will be on discussing the mapped model outputs and gap analysis with policy-makers and other stakeholders, to inform 2016-18 policy discussions whilst the NAR is being developed in RD1.4.1. The spatial analysis on 'neglected' CES includes refining landscape character models that draw on spatial data. This work will support the research to fill CES gaps in the NAR (RD1.4.1).

***Objective 1.4.2b Identification of opportunities to increase multiple benefits through new and existing delivery mechanisms*.** 1.4.2bi: Aligning existing and new delivery mechanisms: A comparative analysis of institutions and processes to deliver soil, water and biodiversity policy goals will identify opportunities for improving alignment/integration, to support delivery of multiple benefits in peatland, forestry and agricultural settings. Yrs 1-2 involve analysis of primary (interviews) and secondary (policy documents and reports) data on decision-making processes. Our analysis will connect existing policy goals for biodiversity, water, and soils, with interaction of their different institutions across scales. The analysis will also focus on how trade-offs are managed in peatland, forestry and agricultural settings, enriched by insights from policy makers (KE1) and from O1.4.2a. These insights will inform the identification of innovative mechanisms for policy delivery, using international best practice to identify those mechanisms that enable delivery of multiple benefits, and suit Scotland's existing institutions. Examples include Payments for Ecosystem Services, certification and social impact bonds. Yrs 1-2 focus on establishing the methods for evaluating the new instruments because there is no existing guidance on how to compare differing instruments for multiple benefits. The analysis of existing applications using primary (interviews, stakeholder workshops) and secondary (reports) data occurs in years 3-5. O1.4.2bii: Using Monitoring & Evaluation (M&E) to deliver multiple benefits. M&E processes support adaptive management, therefore it is important to understand how M&E processes utilise

existing sources of knowledge about multiple benefits and trade-offs for decision-making in peatland, forestry and agricultural settings. In years 1-2, we will use document analysis to identify sources of expertise that are relevant to understanding multiple benefits, combined with an analysis of good practice tools that will aid synthesis of such knowledge. The analysis will consider the potential challenges to using these sources in peatland, forestry and agricultural settings at different scales. Later work (yrs 3-5) will use these insights to help us understand how and why different sources of knowledge are used in M&E, based on interviews with practitioners. In parallel, we will develop recommendations for improving knowledge used in decision making – e.g. which presentation tools, datasets, and social processes aid learning - to encourage delivery of multiple benefits via M&E. In yrs 1-2, we will synthesise recommendations about good practice in M&E. In yrs 3-5, we will identify how and when datasets, including RD1.4.1's NAR and NCA, might influence decision-making on trade-offs and multiple benefits. Using decision making contexts selected with stakeholders, we will analyse primary data (interviews) and secondary data (document analysis) to compare how decisions are made and could be made differently with new combinations of knowledge. O1.4.2biii: Using social innovation to deliver multiple benefits. There is a knowledge gap in understanding how to boost social innovation in agriculture, forestry and rural development. We will categorise social innovation in years 1-2, and operationalise social innovation in decision-making for delivery of multiple benefits in different/selected settings and scales by years 3- 5. Improved knowledge of social innovation focused on maximising multiple benefits delivery will be developed using quantitative-based (e.g. indicators), qualitative-based (interviews, focus groups, etc.) and mixed methods (e.g. Multi-Criteria Analysis, MCA) to measure impacts of and influences on social innovation. The current institutional conditions (see O1.4.2bi), will be used to analyse how far and in which way they support or hinder social innovation. O1.4.2.biv: Sustainable Supply Chains: A supply chain perspective will help mitigate trade-offs between food production and provision of other multiple benefits. The research will start to identify how different actors in the supply chain could reduce trade-offs between natural capital depreciation and commodity production in agriculture, working closely with RD2.4.3. Mapping the supply chain's associated impacts on ESs provides information on the spatial scale at which supply chain interventions are most effective (regional/national/international) to inform the design of appropriate delivery mechanisms to facilitate change. The research will focus on beef supply chains in years 1-2. The beef sector is economically the biggest agricultural sub-sector (by gross-value-added) and is the largest source of agricultural GHG emissions. We will first classify the main beef production systems in Scotland and estimate their output. Quantitative models of the main supply chains will be developed and will enable quantification of the main material/energy flows along the supply chains, e.g. energy consumption, water consumption, GHG emissions and nutrient use efficiency (N and P). The models will be used to identify hotspots, i.e. points in the supply chains and geographical locations where there is potential to improve delivery of multiple benefits and reduce environmental impacts. As such it provides a strong link to the work in 1.4.1 on the NAR and the NCA; and could help support case studies in 1.4.2ciii. An initial list of measures for improving performance, and potential barriers to uptake, will be developed and discussed with a range of industry and policy stakeholders. A short list of the measures will be established and their technical feasibility, cost effectiveness and public acceptability investigated, potentially as part of 1.4.3b's demonstration days. In yrs 3-5, the same

methodology will be applied to other commodities e.g. agroforestry systems.

Objective 1.4.2c Option appraisals to demonstrate resilience of natural assets under different trajectories. O1.2.4ci: Policy option appraisal for agricultural, woodland and peatland management. This work will use study short term change (up to 5 years), to assess the impacts of probable land use change on ESs (linking with RD2.3.11). To examine pathways of ESs delivery, we will use IACS data and time series of MODIS and LANDSAT. For present-day images we will experiment with SENTINEL products. We will then use space-time statistical methods to relate the land management change data to satellite and other covariates (e.g. soil) that might explain the observed ESs patterns. Bayesian Belief Network (BBN) models will be used to link biodiversity to land use intensity (e.g. stocking rates). We will relate changes in grazing intensity to changes in spectral response, using generalised additive models to identify areas of interest, and will model impacts on ESs and biodiversity in these areas. This will provide the ESs consequences layer to a shared policy option analysis at national scale. Guided by policy makers, we could consider options for different combinations of greening, SRDP and RBMP measures, woodland expansion and peatland restoration to map the opportunities to deliver multiple benefits. In collaboration with WP2.4.1/2 and WP3.4.1 we will explore the relationships between trends in farm viability, socio-demographic profile and ESs delivery across rural Scotland. O1.4.2cii: Climate adaptation and mitigation impacts on multiple benefits: To model the distribution of native woodlands and their key species we will use National Forest Inventory, the (downscaled) Atlas of the British Flora, and Countryside Survey data, together with, soil hydrology, climatic and terrain data, and the FC scenarios used in CXC-Woodlands, to produce a woodland distribution model obtained using statistical spatial methods (e.g. space-time generalised additive models). For climate proofing we will use downscaled projections of climatic variables and model niche shifts. A similar approach will be adopted for key peatland species. The climatic niche of peatlands and their species will be modelled using downscaled data at 1km (UKCIP projections). Changes in woodland over time and their impacts on cultural services will be visualised. The relevance of different geographic scales will be tested as part of stakeholder engagement materials. The imagery will use interactive mapping and visualisation tools with multiple layers of information to aid explanations of links between past and present capturing of stakeholder opinions on implications of changes on landscape resilience. MCA analysis will build on further development of tools constructed for the Aberdeenshire LUS pilot project and on the WISE tool for peatlands. Having unified the two approaches, we will use apps, based on open source tools, such as geoODK, to allow users to submit feed-back. This work will collaborate with 1.1.2 (soil resilience), 1.1.4 (soil hydrology), 1.3.3 (peatlands, species shifts) CXC (woodlands and peatlands). Climate adaptation and mitigation impacts work will use a rule based model of land use change with a time horizon of 20+ years and the resulting spatially explicit land use changes will illustrate potential changes to ESs for each set of storylines. In years 3-5, the model will become more dynamic to account for feed-back between ESs and individual-based land use decisions, with a longer time horizon to investigate resilience of multiple ESs to environmental change. Broad storylines will be translated into time series of important drivers and use with tools, such as LANDSFACT and DynaCLUE, to project plausible land use change. Using cluster analysis we will define region of Scotland from their biophysical and farm type characteristics. For each scenario, we will model the trajectories of change in ESs from the baseline across both space and time for each land use and climatic region

combination. We will examine the scales of perturbation and speed of return to pre-disturbance conditions as measures of resilience. By modelling transition probabilities, we will examine how different policy measures might create different trajectories affecting the quantity and location of ESs trade-offs. O1.4.2ciii Assessing economic impacts of changes in ecosystem services. This work is based on collaboration with the Fraser of Allander Institute (FAI), University of Strathclyde. Agriculture and wider land use make a modest contribution to conventionally measured Scottish GDP, but this would be more significant if other assets and service flows were better recorded. We wish to understand what might happen to growth if there were fundamental changes in delivery of ESs through changes to land use. We will investigate the contribution of ESs values/flows to economic growth, by investigating how market and non-market values (with 1.4.1) can be reconciled with general or partial equilibrium modelling. A meeting on economy-wide modelling and the integration of environmental values will develop a route map for integrating service flows (e.g. landscape values and improved water quality) through partial and general equilibrium modelling. A workshop with Office of Chief Economic Advisors staff on Scotland's natural capital, growth and wellbeing will inform further analyses in year 2 onwards. We will support scientific integration across the SRP using a variety of statistical, econometric and agent-based modelling approaches to combine qualitative and quantitative data to deliver policy-relevant information (i.e. costs and benefits) for key integrated storylines. We will develop an empirical study for a number of storylines to be agreed with RESAS. The current options are:1) biofuels and land use change; 2) Sustainable intensification and livestock production and consumption; 3) Global food security and food policy in Scotland; and 4) Modelling livestock movements and disease transmission.

Expertise of the PIs can be found via the web-links. The remaining un-named staff have a range of support skills and several years' experience supporting integrated modelling projects and facilitating stakeholder engagement. A post-doctoral research fellow will be supervised by at Fraser of Allander Institute, HEI project 6). SRUC will be providing two new posts: an integrated systems modeller and an agri-environmental modeller.

Key linkages, interdisciplinarity & collaboration:

Linkages within the Natural Assets Theme: We will interact with 1.4.1 by using the NAR and NCA in models (O1.4.2a & c); using the NAR for spatial representation of beef supply chains (O1.4.2.biv). We will contribute to 1.4.1's targeting SRDP incentives (also 1.3.1 and 1.4.3). Outputs will be used in 1.4.3's case studies (upland and lowland agriculture, woodland expansion, natural flood management) to inform their adaptive management approaches. They will also support work on woodland expansion (1.3.2), ecosystem resilience (1.3.3), peatland restoration (1.1.4, 1.3.3), and water management (1.2.4). Whilst most of the research on ecosystem function leading to ESs delivery across 1.1, 1.2 and 1.3 feeds into 1.4.1, some work e.g. soil hydrology (1.1.4) will directly support modelling in O1.4.2a and c. O1.4.2b will work in partnership with 1.1.4, 1.2.4 and 1.3.4 sharing knowledge around potential of new instruments, non-scientific sources of knowledge and collective action to support delivery of policy goals. **Linkages across the Programme:** O1.4.2ci will work with 2.4.1/2.4.2 and 3.4.1 to explore opportunities to develop a triple bottom line (environment, business and community) policy option analyses e.g. CAP (ANC) impact analysis. O1.4.2biv will draw on the findings of WP2.1 WP2.2 and WP 2.3 to evaluate circularity measures identified in RD 2.4.3 as a means of improving beef supply chains. O1.4.2a and 1.4.2ci will exchange methods, approaches and, when

appropriate, data with RD 2.3.11 to investigate trade-offs between provisioning and regulating ESs. **Collaboration with external organisations:** We will work with the Fraser of Allander Institute (FAI) in O1.42ciii; U. of Reading co-supervising a PhD student in O1.4.3cii,; ESCom: with U. of Edinburgh (Metzger group) and Forest Research (D. Mosley) on scenario work in O1.4.2cii; IVM, U. of Amsterdam (Peter Verburg group) on land use change impacts on ESs in O1.4.2cii; Natural Capital Group (Stanford University) on further testing of InVEST modules in O1.4.2a; ESP partnership (e.g. Joachim Maes, JRC) on comparison of Scottish and EU results (O1.4.2a,ci and ii); and IRSTEA methods for land use time series analysis (O1.4.2a,ci, ii). The work in O1.4.2ciii will liaise with ONS and Natural Capital Committee, WAVES and TEEB. We will organise national and international events e.g. via ESCom and ESP (Ecosystem Services Partnership) and disseminate work to our partners through the web site. **Interdisciplinarity:** This RD is highly interdisciplinary involving soil science, hydrology, ecology, modelling, software engineering, earth observation, economics, rural sociology, geography, and statistics. This RD will increase the strategic capability to assess consequences of policy choices more holistically, integrating economic and an environmental stand points.

Added scientific value: O1.4.2a and c builds on the NEA, MAES and CICES frameworks to produce detailed comprehensive and systemic national scale dynamic pathways integrating land use, changes in climate and land capability, ESs and biodiversity for Scotland. We will be building on our international reputation for linking land capability to ESs delivery and leading the way on refining these methodologies. Our approach to couple detailed land use statistics with time-series of satellite images is novel, and exploits the UK's data-rich research environment. Providing interactive multi-criteria tools to record stakeholder preferences for managing ESs is novel, when using process models indicating the consequences of their choices. Coupling land use change decisions with impacts on ESs under climate change scenarios will contribute to global partnerships methods e.g. Ecosystem Service Partnership, Global Land Project, working on these knowledge gaps. O1.4.2b contributes to environmental policy integration such as undertaken in FP7 OPERAs but extends this by linking with new delivery mechanisms, including supply chains and social innovation, which engage the private sector.

KE, audiences and impact. Audiences and Engagement: We will utilise the thematic level Soils Stakeholder and BLUPU groups to align the work with the needs of the ENFOR and ARD directorates; as well as more informal 1:1 communication with stakeholders. We will also use regular ESCOM events and conferences to reach an audience of CAMERAs partners, eNGOs, NFUS and SLE (e.g. planned seminar on woodland expansion 2016; SRUC-SEPA conference 2018). We also seek to present at events such as the NFUS farming and environment forum and SLE annual conference. We will interact with CXC, CREW, EPIC and Plant CoEs to share results and support their events. We will co-organise meetings with spatial planning teams in local authorities, e.g. Aberdeenshire, Perth and Kinross, CNPA and Planning Aid Scotland. We will support, with 1.4.3 and 1.3.2, stakeholder events in the CSGN and the CNP. We will co-organise events with QMS (Quality Meat Scotland) on beef supply chains. We will co-organise events with SFNC, Natural Capital Initiative and TEEB, and contribute to Fraser Economic Commentaries. We will support WP and theme level KE including populating webpages and writing briefings, using the CKEI comms toolkit; as well as providing expertise to CKEI events and campaigns – these will reach the majority of our interested parties

including the public. The RD will support the CKEI Think-Tank activities. Pathways to **Impact:** The analysis of the hotspots and historical trajectories of multiple assets currently in decline and vulnerable to future change will support SG policy advisors in ENFOR and ARD during the mid-term CAP review starting 2017, providing evidence for improved design of instruments and the need of spatially targeted incentive schemes. Understanding how to identify trade-offs and deliver multiple benefits will provide evidence for the Scottish Government's RAFE Delivery Board as they seek to identify opportunities that will efficiently deliver to more than one RAFE outcome, whilst avoiding unintended consequences: we understand an advisory group will be set up to support the board and we would seek a place upon this. SG Natural Heritage Management Team, Natural Resources Division are interested to learn more about the potential of new delivery mechanisms to work alongside existing incentives. We anticipate that our work on M&E will provide early insights that can inform the SBS route map and the Scottish Government's contribution to the CBD COP 14 in 2018, where the Aichi targets will be discussed. The modelling and the governance strategic capacity could explore responsible stewardship, if such analyses were useful to supporting delivery of the Land Reform (Scotland) Act.

RD 1.4.2: IDENTIFYING AND UNDERSTANDING MULTIPLE BENEFITS AND TRADE-OFFS.

Work planning and timetable for Year 1

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.4.2a Identification of gaps in the current delivery of multiple benefits. Identify current status and historic trends associated with delivery of ESs to inform policy-making												KE1
O1.4.2bi: Aligning existing and new delivery mechanisms. Comparative analysis of data on policies associated with soils, water, biodiversity, agricultural, forestry, peatland and peri-urban land use.										KE1		
1.4.2bii: Using M&E to deliver multiple benefits. Collating existing data sets for M&E associated with soils, water, biodiversity, agricultural, forestry, peatland and peri-urban land use.												
1.4.2biii: Using social innovation to deliver multiple benefits. Developing typology of social innovation.												KE1
O1.4.2biv: Improving the environmental performance of supply chains. Classify production systems and design conceptual model for quantitative modelling. ***M1 conceptual framework for analysis of trade-offs in supply chains developed***												M1 D1
O1.4.2ci: Policy option appraisal for delivery of multiple benefits. Collating and improving data, building BBN.				KE1								
O1.4.2cii: Climate adaptation and mitigation impacts on multiple benefits. Collating data and refining models based on stakeholder feedback						KE1						
O1.4.2ciii: Assessing economic impacts of changes in Ecosystem Services. Agree and apply modelling approach. ***M1: Agreed route map for integrating service flows through modelling***			KE1						M1			

End of year reporting to RESAS (ALL OBJECTIVES)												**R1**

RD 1.4.2: IDENTIFYING AND UNDERSTANDING MULTIPLE BENEFITS AND TRADE-OFFS.
Work planning and timetable for Year 2

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.4.2a Identification of gaps in the current delivery of multiple benefits. Overlaying maps with policy goals from O1.4.2bi ***M1: Trade-off mapping and interpretation completed***								M1 D1				
O1.4.2bi: Aligning existing and new delivery mechanisms. Finalise comparative institutional analysis.***M1 Opportunities for better alignment of policy delivery identified***						D1						M1 D2
1.4.2bii: Using M&E to deliver multiple benefits. Collate existing data sets and analyse against international good practice for using M&E data for AM of land use. ***M1 Existing sources of data collated and analysed***												M1 D1
1.4.2biii: Using social innovation to deliver multiple benefits. Finish classification and identify opportunities for social innovation in Scottish context**.** ***M1: Role of social innovation in sustainable land use identified***												M1 D1
O1.4.2biv: Improving the environmental performance of supply chains. Apply quantitative modelling to illustrate spatial 'hotspots'. ***M2 Impacts represented spatially - beef***		KE1										M2 D2
O1.4.2ci: Policy option appraisal for delivery of multiple benefits. Applying BBN to explain impacts on ESS for policy options chosen by stakeholders. ***M1: Quantify ESs delivery linked to historic and potential agricultural, woodland and peatland management changes***						D1 KE2		D2				D3
O1.4.2cii: Climate adaptation and mitigation impacts on multiple benefits. Refined tools from yr1 applied to generate maps of impacts of ESS from land use change, including further								M1 D1		M2 D2		KE2 D3

model integration. ***M1: ESS impacts of trading off agriculture against woodland expansion and peatland restoration illustrated. M2: Integration of MCA tool with WISE model (with CXC – peatlands)***												
O1.4.2ciii: Assessing economic impacts of changes in Ecosystem Services. Carry out agreed case study analysis using partial and full CGE modelling. ***M2: Complete initial case study*** Design next case study. ***M3: Agreed subsequent case study.***	**KE2**					**M2** **D1** **D2**		**M3**				
End of year reporting to RESAS (ALL OBJECTIVES)												**R1**

RD 1.4.3: Practical interventions to realise multiple benefits and manage trade-offs.

Research aim and key drivers: Our vision for 2021 is to have provided practical guidance for the landscape-scale application of agri-environment and woodland expansion schemes that supports adaptive management of our natural assets. We will have illustrated how existing and novel policy measures can deliver integrated delivery of benefits supporting inclusive growth that respects our planetary boundaries. As such we will have contributed to answering Theme 1's RQ4: "How can we improve the management of our natural assets to support sustainable land-based industries and vibrant communities, how can we improve existing instruments, and what other instruments could be applied to support social and economic entitlements and a just distribution of outcomes?"

Land management and land-use change has consequences for natural assets as well as the viability of land based businesses, and managing them requires cooperation and collaboration across a landscape. Benefits from natural assets include not only soil, water and biodiversity management but also agricultural production, disease control, and human well-being (Fig 1). Support for land managers to deliver benefits is available through incentives such as the Ecological Focus Areas (EFA, Pillar 1), Agri-Environment Climate Scheme (AECS) and the Woodland Grant Scheme (WGS) (Pillar 2). Uptake of these measures across the landscape is also supported by the Environmental Cooperation Action Fund (ECAF, Pillar 2). The aims are to focus on practical examples to provide insights regarding: i) how to implement current and novel agri-environment measures to achieve multiple benefits and ii) how cooperation can deliver landscape-scale sustainable management of our natural assets. We will use Adaptive Management (AM), which iteratively uses evidence from monitoring interventions, to evaluate the effectiveness of these schemes and inform the design of more effective alternatives. We will collaborate with researchers, government agencies, local authorities, land managers and the public. We will communicate the results to practitioners (via Farmland Biodiversity Initiative (FBI) demonstrations days) and help inform the review of polices such as the SRDP and the Land Use Strategy (LUS) in order to improve our capacity to reduce trade-offs between the public interest and individual land manager objectives.

Who has been consulted in developing this proposal: Our focus on SRDP was discussed with SG NATRES and the Farmland Biodiversity Initiative with RESAS and BLUPU. The delivery of multiple benefits has been discussed with BLUPU, SNH and SEPA. The main case study stakeholders have been consulted including the MRP farm managers; CNPA, RSPB, SNH, CGGN and FCS. We used information from 1.2.4 regarding research desired by the Tweed Forum.

Summary of the proposal: This RD will support integrated land and water decision making to protect the multiple benefits we derive from natural assets by focussing on a range of practical case studies that are representative of the major land uses in Scotland. We will identify and promote best practice in AM to help land managers deliver these benefits whilst maintaining viable land based businesses. This will include investigating how novel approaches can reduce barriers to this delivery. We will focus on case studies to show how an AM approach can deliver integrated land management in practice. We will develop key partnerships between agencies and land managers in the case studies to evaluate existing and novel management actions at both the holding and landscape scale. First we will explore the barriers and opportunities for delivering landscape scale multiple benefits incentivised by

EFAs, AECS and ECAF in both an intensive arable and grass system and in an extensive upland grass system. This will use farms managed by JHI and SRUC (Balruddery, Glensaugh, Hartwood and Kirkton), nested in their surrounding catchments. Second, we will explore multiple benefits from woodland expansion incentivised by the WGS in both peri-urban contexts (CSGN) and in rural areas (Cairngorms). In years 3-5, we will apply our approach in other contexts (e.g. the Tweed catchment) to evaluate how integrated land and water management can deliver multiple benefits. We will use an RD-level AM framework to facilitate a comparative analysis of the case studies to identify common factors across systems and scales. This will allow us to learn about barriers and opportunities and to suggest innovations that can support practical delivery of wider landscape-scale benefits. The work in this RD is organised under four linked Objectives drawing on work across the Programme (see Fig 1).

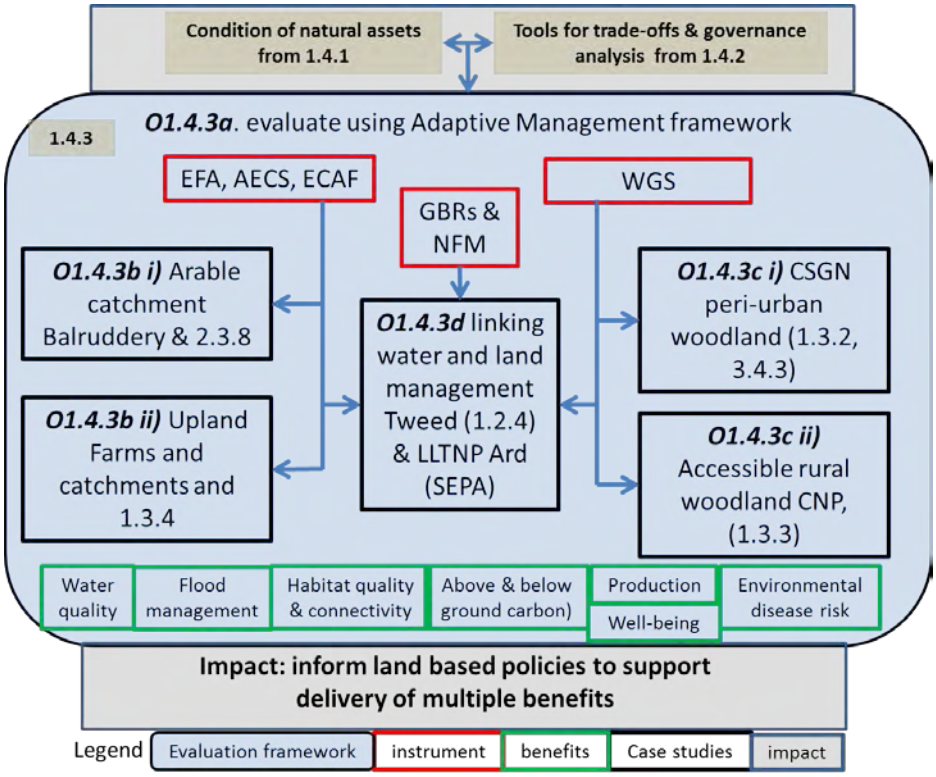


Figure 1. The practical case studies under investigation in this RD showing the structure and linkages to other work in the SRP proposal.

<u>Objective 1.4.3a: Set up and use an AM framework to facilitate the evaluation and coordination of measures to deliver multiple benefits</u>: Here we will choose from existing AM methods to determine an approach that fits best with the institutional arrangements for managing a range of natural assets in Scotland. We will use this approach to evaluate how the actions can deliver multiple benefits. We will apply and adapt our tailored AM approach across the five years of the SRP in the case studies selected for O1.4.3b, c & d to develop guidance for other contexts.

M1: AM approaches reviewed (m7)	D1: Report on relevant AM approach for Scotland (m7)
M2: AM evaluation framework	KE1: Workshop with WGWG to discuss

developed (m9)	framework (m8) D2: Workshop summary (m9)
M3: AM utility tested in case studies (m32)	KE2: SNH Sharing Good Practice Event (m23) D3: Research brief: comparing effectiveness of achieving multiple benefits in case studies using AM framework (m32)
M4: AM application for evaluating effectiveness of agri-environment and woodland schemes assessed (m57)	D4: International conference presentation " Using AM for evaluating interventions" (m28) D5: Technical guide on applications of AM framework in different contexts for decision makers (m32) D4.3: Journal paper (and policy brief if requested[6]) on the practical application of AM (m57).

Objective 1.4.3b: To assess the potential for EFAs, AECS and ECAF to deliver multiple benefits at a landscape scale: We will work with two case study catchments: i) an intensive arable and grass system and ii) an extensive upland grazed system (described in the 'Technical Approach'). We will investigate a) whether the SRDP schemes can reconfigure the landscape to deliver wider benefits and b) the barriers to uptake of the ECAF across these landscapes. In years 4-5, we will contribute to the development of these farms as platforms for demonstrating best practice in the delivery of multiple benefits as part of the Farmland Biodiversity Initiative.

M.1: Research agenda co-constructed with stakeholders (m8)	KE1: Initiation meetings with stakeholders in each case study to discuss AM framework (m7) D1: Workshop summaries (m8)
M2: Annual demonstration days held (m12)	KE2: Demonstration days held annually (m12) and then each year thereafter D2: Demonstration day reports (m12 and annually)
M3: Ecosystem services (ESs) and benefits delivery mapped (m21)	D3: Maps of ESs and benefits delivered from current land use and management actions (m21)
M4: Analysis of attitudes and barriers to cooperation completed: (m28)	D4: Technical report on barriers to uptake of AECS options and ECAF(m11) D5: Conference paper on innovations to overcome barriers(m13) KE3: presentation to BLUPU and SFG (m22) D6: Journal paper on potential approaches to

[6] All journal papers will be accompanied by a policy briefing if requested by BLUPU and SFG.

	cooperative landscape scale incentives (m28)
M5: Options for land use change in catchment modelled, mapped and evaluated (m33)	D7: Maps and visualisations of consequences for benefits from implementing EFA and AECS options at a landscape scale (m24) KE4: MCDA workshops to evaluate benefits delivery from current/potential land-use change (m31) D8: Reports on stakeholder evaluation of options (m33)
M6: Cost effectiveness analysis of landscape scale interventions completed (m37)	KE5: Presentation to BLUPU and SFG on factors affecting cost-effectiveness of landscape scale interventions in delivering multiple benefits (m27) KE6: Present findings at demonstration days (m36) D6.1: Report outlining how to compare the cost of land use options against benefits arising (m37).
M7: (Potential) uptake at catchment scale and the multiple benefits evaluated (m48).	D7.1: Maps of potential uptake of wider benefits (m48) KE7: Presentation of findings at Farm Biodiversity Initiative demonstration days (m48)

Objective 1.4.3c: To develop approaches that reconcile woodland expansion with other land use priorities. We will investigate the trade-offs and multiple benefits from woodland expansion in two case studies: i) a peri-urban system and ii) accessible rural woodland (described in the 'Technical Approach'). We will consider how woodland expansion constrains or provides opportunities to enhance well-being, flood risk, water quality, carbon sequestration, biodiversity and local development plans (LUS: Objective 3, Proposal 11). In years 4-5 we will apply lessons learned in new areas or in the proposals for Objective 1.4.3d.

M1: Research issues and agenda co-constructed with stakeholders (m3)	KE1: Initiation meetings with stakeholders in each case study to discuss AM framework (m3) D1: Workshop summaries (m4)
M2: Interview/focus groups in communities completed (m33).	D2: Report on benefits derived by communities from case study areas identifying main trade-offs (m9) D3: Report on innovative digital storytelling methods for AM (m14) D4: Conference and journal paper on mobile ethnography (m33)
M3: Evaluation of woodland expansion options completed (m34)	D5: Maps of woodland expansion options and consequences for ESs and biodiversity (m12) KE2: Participatory mapping workshops to assess social impacts of woodland expansion (m18) D6: Workshop reports(m21) KE3: Presentation to BLUPU on impact of woodland expansion on social, economic and ecological aspects of the case studies (m35)

M4: Assessment of governance mechanisms for stakeholder participations in decision making completed (m36)	D7: Technical guidance on good practice for stakeholder participation in AM for realising multiple land use benefits (m33) D8: Video podcast (m33) D9: Journal paper (m36)
M5: Recommendations developed for applying AM to other case studies (m36)	D10: Report synthesising how AM can be applied in other contexts where there are conflicts between the public interest and private objectives (m36)

Objective 1.4.3d: To use AM to integrate SRDP interventions with Natural Flood Management (NFM) and General Binding Rules (GBR) for the delivery of multiple benefits. We plan to phase-in this work in this case study building on the O1.4.3a, b and c with most work in yrs 3-5. Our plans are indicative and will be confirmed with the WP Working Group (WPWG) but we aim to work with ongoing initiatives in the Tweed catchment as well as collaborating with the ENFOR Strathard project. We will evaluate the effectiveness of interventions (incentivised by SRDP funding, designed to achieve NFM and to comply with GBR), to deliver multiple policy goals (see O1.4.2bi) whilst maintaining viable land based businesses. In years 1-2 we will contribute to stakeholder workshops run by Tweed Forum and the Strathard project group. In years 3-5 we will integrate activities with RD1.2.4 by combining our research to improve landscape-scale cooperation for the delivery of multiple benefits.

M1: Research agenda co-constructed with stakeholders (m9).	KE1: Meetings with local stakeholders (m7) D1: Workshop summaries (m9)
M2: Contribution to1.2.4's guidance completed (m12)	D2: Technical report on applying AM for integrated land management (m12)
M3: Data on ESs and benefits in new case study mapped (m33)	D3: Maps of current delivery of ecosystem services to identify gaps in delivery (with O1.4.2a) (m33)
M4: Potential land use change possible under NFM, GBRs and AECS modelled and evaluated (m58)	D4: Maps of land-use change options and consequences for multiple benefits (m39) D5: Report on the impacts of preferred land-use and management changes for multiple benefits: (m58)
M5: Impacts of implementing land use change to deliver NFM and SRDP for multiple benefits quantified (m58)	D6: Report on effect of interventions on farm economics and management practices (m33) KE2: Presentations to case study consultative groups(m48) D7: Journal paper (m58)

Technical approach: The RD builds on work in the SRP (2011-16) drawing on established stakeholder relationships and study sites as well as building on existing data in relation to multiple benefits. We will draw on the spatial planning tools developed as part of the Aberdeenshire RLUP (cWP1.3) and visualisation methods (cWP3.5 and cWP3.8). Feedback from our case studies will guide the development of tools in RD1.4.2. O1.4.3a provides a framework that will be applied to O1.4.3b-d to allow us to apply the learning to other settings.

Objective 1.4.3a: Set up and use an AM framework to facilitate the evaluation and coordination of measures to deliver multiple benefits. AM is an iterative, ongoing learning cycle that can provide a framework to integrate different knowledge systems and facilitate power sharing. AM can increase the capacity of managers to adapt to change and safeguard natural assets whilst allowing economic development, through the process of reflection and learning. We will develop an AM framework that can be used to support the goals of the LUS by evaluating land-use and management changes such as those promoted by Pillar 1 and Pillar 2 CAP support.

Work plan: We will explore examples of AM in action from the UK and internationally to select the most appropriate approach for the Scottish institutional context. This will consider how we can monitor uncertainty in terms of sensitivity to changes in the ESs and benefits. We will develop an evaluation framework to assess delivery and effectiveness across the case studies building on the report to SNH reviewing AM. Consistent with the AM theory, we will revisit the framework annually and refine it as results and insights become available. We will test this approach in O1.4.3b, c & d in terms of its ability to evaluate the effectiveness of interventions and understand how to best manage trade-offs among ESs delivery. We will monitor the process to evaluate: (i) the inclusiveness for all relevant stakeholders in order to build consensus; (ii) tools for integrating scientific and expert knowledge; (iii) how uncertainty is addressed and reduced as a result of management actions; and (iv) testing alternative management and governance options of land-use drawing on RD1.4.2 tools and testing the value of Multi-Criteria Decision Analysis (MCDA).

Objective 1.4.3b: To assess the potential for EFAs, AECS and ECAF to deliver multiple benefits at a landscape scale. We will work with case study catchments based around i) the arable Balruddery Centre for Sustainable Cropping and ii) the three MRP grassland research farms (Glensaugh, Hartwood and Kirkton/ Auchentyre) to demonstrate the effectiveness of EFAs and AECS management options in delivering multiple benefits across their catchments. Central to this is early engagement with stakeholders in the catchments to identify the issues. We will focus on exploring two main areas: i) whether the agri-environmental management actions can reconfigure the landscape to deliver multiple benefits and ii) the socio-cultural barriers to cooperation.

Work plan: We will establish local stakeholder groups comprising land managers, community representatives, local agency and environmental NGO staff. We will use existing data on land cover (LCM), land use (IACS), NAR data on soils, water and biodiversity supplemented with information from high resolution satellite images (WorldView3) trained on detailed vegetation maps available for the MRP research farms to predict the delivery of key ESs from current management in these catchments (working with RD1.4.1's NAR and RD1.4.2). Given the current land use and land cover, we will produce a series of options to explore where changes could occur in these catchments if schemes such as EFAs and AECS were taken up. The consequences for the delivery of multiple benefits across the catchment will be analysed to illustrate the potential added value that cooperation could have. Linking with work in RD2.3.8 and RD1.4.2, empirical and process based models will be used to estimate productivity and ESs outcomes (e.g. the dynamics of pollinators, and pests using the AgBioscape platform) resulting from proposed changes in cropping patterns under EFAs, scaled up to the catchment. This will be integrated with land use change models developed in RD1.4.2 that account for potential AECS

uptake to predict catchment scale changes in ESs relating to water quality, flooding, carbon stocks and disease risk. For the upland catchments we will draw on baseline data available for ESs under current management on the MRP farms linking with reviews of appropriate measures in RD1.3.4. For example, Kirkton is applying for funding for wader management (linked to RD1.3.2), is implementing new grassland management options (RD1.3.4) and neighbours a LEADER biodiversity recovery programme in the catchment. In addition to the existing data from RD1.4.2 on ESs, colleagues in MRI will provide input to models to predict how options (e.g. riparian strips and rewetting) will change the risk of diseases (e.g. fluke and cryptosporidiosis) based on risk factors such as terrain/soil type, climatic conditions, density of livestock/wildlife and grazing management (augmented by sampling, where feasible).The land use change options and the predicted effects on multiple benefits will be discussed with local stakeholders, aided by visualisation tools. We will utilise approaches such as MCDA to explore the acceptability of different options against economic, social and ecological criteria. The barriers to land manager uptake of these options and the extent to which ECAF is affected by these barriers will be identified using interviews and focus groups. This work will link with studies of farm management choices being conducted in RD2.3.12. Consultation on governance mechanisms to improve landscape scale cooperation with wider stakeholders at Farmland Biodiversity Initiative (FBI) demonstration days will further inform this analysis. Our approach will contribute to FBI demonstrating existing best practice on the four research farms in delivering multiple benefits and addressing trade-offs, as well as illustrating options for the future. We will explore the opportunity to link with other demonstration farms (e.g. Farming for a Better Climate farms, Game & Wildlife Conservation Trust Auchneran farm).

Objective 1.4.3c: To develop approaches that reconcile woodland expansion with other land use priorities. We will address benefits and trade-offs from woodland expansion, incentivised by the WGS using paired case studies: i) in the peri-urban sites in the Central Scotland Green Network (e.g. around Hartwood) linking with work on biodiversity and ESs in RD1.3.2 and on well-being in RD3.4.3 and ii) in accessible rural woodland around settlements in the Cairngorms National Park (CNP) linking to biodiversity resilience research in RD1.3.3. We will assess which types of land are best for new woodland in the context of other societal objectives. In both cases we will investigate how to secure multiple benefits and manage trade-offs between the woodland expansion and local development plans, recreation and biodiversity objectives, making use of insights from O1.4.2bi and cii) and data from the NAR in RD1.4.1. We will draw on evidence for how land use change can affect key biodiversity objectives (e.g. the Capercaillie Framework) and influence disease risk (e.g. woodland has abundant ticks that harbour Lyme disease). We will identify a) the barriers and opportunities for achieving collaborative decision making over woodland expansion and b) the social and institutional circumstances under which collaborative decision making can be supported.
Work Plan: We will establish local stakeholder groups comprising land managers, community representatives, local agency and environmental NGO staff. Research will be co-constructed through community workshops (organised with the CSGN & CNPA). We will use qualitative and mixed methods (e.g. desk-based research, semi-structured interviews, targeted focus groups and/or Q-methods) to understand motivations and barriers for woodland expansion. We will also conduct in-depth interviews and use videoed observation (at meetings or during field visits) to have

participants analyse psychological processes (working towards citizen social science). Minicam video ethnography will allow the hard-to-capture values such as spiritual and symbolic attributes (linking to RD1.4.1) associated with woodland and its ESs to be assessed. Methods may include social network analysis, which would then be integrated into the participatory maps. Participatory mapping in workshops using a touch-table will be employed to connect the social knowledge from interviews, observation and video ethnography with ecological knowledge on habitat quality and connectivity (drawing on work in RD1.3.3 (Objective 2bii). It will explore how woodland expansion options affect other benefits using tools developed in RD1.4.2.

Participants will include: the public, land managers, NGOs, agency staff, natural and social scientists. We will investigate the consequences for well-being by drawing on work in RD3.4.3 in the CSGN case study. This work will support community involvement in land use decisions as well as raising awareness about multiple benefits to develop more effective approaches to reconciling different land use objectives. In years 4-5 we will apply lessons learned in new areas e.g. O1.4.3d.

Objective 1.4.3d: To use AM to integrate SRDP interventions with Natural Flood Management (NFM) and General Binding Rules (GBR) for the delivery of multiple benefits. We plan to phase in this work building on the objectives above. Initially, we will collaborate with ongoing initiatives in the Tweed catchment linking to RD1.2.4 and the Tweed Forum. The contrasting Eddleston and Bowmont sub-catchments provide a gradient of land use from upland sheep and commercial forestry to peri-urban contexts. We will use an AM approach to evaluate the effectiveness of SRDP measures to deliver multiple policy goals whilst maintaining viable land based businesses. We will also share our insights with the ENFOR Strathard project.

Work Plan: In Years 1-2 we will support RD1.4.2's KE activities and contribute to their technical guidance on the use of AM in decision-making on land use and management changes to address multiple benefits and trade-offs. For example, how re-wetting and riparian strips for NFM will change the risk of diseases such as fluke, para-tuberculosis and cryptosporidiosis. The research needs identified as part of this process will be the focus for work in years 3-5 where we will work closely with RD1.2.4. We anticipate bringing together the biophysical data, stakeholder knowledge (e.g. SEPA "catchment walks" data on farmers' perceptions of acceptable and effective measures) with recommendations for improving cooperation across landscapes. This evidence base, together with the insights O1.4.3b &c, will be refined and tested to explore how to deliver multiple benefits and address trade-offs using a combination of SRDP schemes, NFM and GBRs.

Expertise: Expertise is outline in hyperlinked CVs. Further support staff will provide the technical expertise in GIS, database management and stakeholder facilitation.

Key linkages, interdisciplinarity & collaboration:

Linkages within the Natural Assets Theme: O1.4.3a will draw on the work to integrate adaptive management and spatial targeting for multiple benefits in RD1.2.3 Objective 3. In Objective 1.4.3b we will work with RD 1.3.2 the using Kirkton/Auchentyre catchment as one of the upland case studies. In addition, O1.4.3c will draw on the benefits of woodland expansion work in the CSGN in RD1.3.2. O1.4.3c will also draw on species habitat suitability modelling under land use change approaches developed in RD 1.3.3 and the spatial land-use change ESs modelling in RD1.4.2. The proposed work in the Tweed catchment will be a

collaboration with Objective 4 in RD 1.2.4 where we will evaluate how incentives can be used to support NFM as well as other ESs. Insights on new delivery mechanisms will be utilised from RD1.4.2, which in turn builds on insights from RDs 1.1.4, 1.2.4 and 1.3.4. O1.4.3b-d will draw on data within the NAR on function and resilience from across the Theme as well as values supporting the NCA in RD1.4.1.

Linkages across the Strategic Research Programme: The arable and intensive grass case study in O1.4.3b will be carried out in conjunction with RD2.3.8 (Hawes) to draw on their ESs data and make use of AgBioscape to analyse crops systems and their trade-offs (RD2.3.11, Begg). We will link to work in in RD2.3.12 (Objective 2.4) on understanding the drivers behind farmer motivations for choices relating to intensive and extensive farming system. The activities in the woodland expansion case study in the CSGN and the CNP will collaborate with RD3.4.3 to incorporate knowledge about benefits to health and wellbeing. We will also collaborate with the CXC-Woodland project.

Collaboration with external organisations: We will initiate collaborations with a) LEAF who hold events at Balruddery; b) the Farming for a better Climate and the QMS monitor farms c) SG's programme on SRDP monitoring and evaluation and d) GWCT via our Farmland Biodiversity Initiative. We will work with FCS, CSGN and Cairngorms Nature Partnership to support their woodland demonstration days. We will work with ENFOR's Strathard project and the Tweed Forum. We will run a session with our stakeholder research collaborators at an international conference on the practical application of AM (e.g. Resilience Alliance Conference, 2018). We will also utilise ESCom to engage with related research such as the FP7 OPERAs and OPENESS projects, as well as the H2020 PROVIDE project (led by University of Bologna) and the PEGASUS project (led by IEEP).

Interdisciplinarity: Activities and outputs will be a result of applying social scientific and ecological methodologies to develop and utilise a shared knowledge base and understanding of how these socioecological systems respond to drivers of change.

Added scientific value. The work will in this RD represents a systematic and comparative analysis of AM in practice, providing new examples to our ESCom partners and the Ecosystem Knowledge Network. This focus on AM complements the ESs assessment approaches in OPENESS and OPERAS by showing how things can be done in practice. It also complements the theoretical approaches to achieving adaptive management developed at CECHR, University of Dundee and across the world, e.g. the Resilience Alliance, and within CSIRO's programme on adaptive regional development. The integration of discursive and visual social data with ecological data in a spatially-explicit tool will complement RCUK programmes such as Valuing Nature Networks and BESS. Our focus on landscape scale cooperation builds on the FP7 PROAKIS project on farmer advice and knowledge systems, but connects it to a specific policy implementation process (ECAF).

KE, audiences and impact:

Audiences and Engagement: The RDC will attend the WP working group to discuss findings with national level stakeholders. The RD will initiate formal local level stakeholder meetings in the case study catchments as well as informal discussions with research collaborators. Progress, results and findings will be made available through a web presence provisionally called "Adaptive Management in Practice". We will utilise insights from the CKEI comms toolkit to:-

- Host best practice guidance (links to in RD2.3.12),and technical guidance on natural flood management (developed with RD1.2.4)
- Host technical guides, reports and plain English summaries of peer reviewed

papers as they become available (subject to RESAS approval)

- Provide a feedback link for stakeholders to engage with the research team.

The project will collaborate with SNH to run a Sharing Good Practice event on using AM towards the end of year 2. We will contribute to annual demonstration days using materials from O1.4.3b. These demonstration days will draw on other land management option work in the SRP, the SRDP monitoring and evaluation project and from the monitor farms as part of the Farmland Biodiversity Initiative. The RD will take advantage of regional events (e.g. agricultural shows, game fairs, CNPA research seminars, Cairngorms Nature Partnership events, CSGN Forum events, Tweed Forum events) to discuss the research. We will work with the Strathard Community Group to communicate approaches, lessons learned and insights relating to adaptive management that may be relevant to their activities. We will also contribute to CKEI activities where appropriate.

Pathways to Impact: Research plans and findings will be discussed with BLUPU and SFG to ensure timely and relevant policy engagement, particularly in supporting the RAFE outcomes. The AM evaluation of EFAs and AECS in case study catchments will inform Scottish Government (e.g. Susie Turpie and Anna Murray) on the design of future SRDP schemes, particularly how to delivery multiple benefits and tackle trade-offs in time for the review in 2018. In particular, the RD can help to inform how ECAF can be more effectively implemented across a landscape or catchment. The assessment of the cost effectiveness of Pillar 1 and Pillar 2 will help to inform SG ENFOR and AFRC on the benefits derived from the allocation of resources to these agri-environment schemes and demonstrate how Scotland's natural assets can benefit from CAP's agri-environment measures. The work on trade-offs and delivery of multiple benefits from woodland expansion, particularly the perspectives of local communities, will support the review of the WGS and provide evidence to help target future measures. The AM evaluation of integrated land and water management will help to inform agencies embedding an ecosystem approach to their work (e.g. SEPA and SNH); as well as supporting the use RBMPs to deliver wider ESs, providing evidence for the 2018 review of measures. The integrated assessment of how land can be configured to benefit ESs will help with practical guidance on dealing with the pressures affecting biodiversity outlined in the SBS2020 route map and support the CBD COP 14. The AM approach will provide guidance on collaboration between the private land management sector (e.g. Scottish Land and Estates, National Farmers Union of Scotland), environmental NGOs (SE Link), public bodies (National Park Authorities & Local Authorities) and agencies (SNH, SEPA) to reduce conflict over decision and deliver the public interest as well as private objectives.

RD 1.4.3: PRACTICAL INTERVENTIONS TO REALISE MULTIPLE BENEFITS AND MANAGE TRADE-OFFS.
Work planning and timetable for Year 1

Year 1: 2016/17	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.4.3a: Set up AM framework. Review approaches to AM and select appropriate ones for Scottish context. ***M1: AM approaches reviewed***							**M1 D1**					
O1.4.3a: Set up AM framework. Develop framework for ongoing evaluation. ***M2: AM evaluation framework developed***								**KE1**	**M2 D2**			
O1.4.3a: Set up AM framework. Apply framework to case studies in O1.4.3b, c and d.												
Objective 1.4.3b: Assess the potential for EFAs, AECS and ECAF to deliver multiple benefits. Stakeholder engagement ***M1: Research agenda co-constructed with stakeholders:***								**KE1**	**M1 D1**			
Objective 1.4.3b: Assess the potential for EFAs, AECS and ECAF to deliver multiple benefits. Synthesis of data and good practice to share with local stakeholders. ***M2: Annual demonstration day held (with FBI)***											**KE2**	**M2 D2**
Objective 1.4.3b: Assess the potential for EFAs, AECS and ECAF to deliver multiple benefits. Catchment scale mapping multiple benefits from existing management												
Objective 1.4.3b: Assess the potential for EFAs, AECS and ECAF to deliver multiple benefits Researching attitudes to uptake of cooperation action funds											**D4**	
Objective 1.4.3c: Reconciling woodland expansion with other land use priorities Stakeholder engagement.***M1: Research agenda co-constructed with stakeholders***			**M1 KE1**	**D1**								
Objective 1.4.3c: Reconciling woodland expansion with other land use priorities Interviews and focus groups with communities to identify benefits and trade-offs.									**D2**			
Objective 1.4.3c: Reconciling woodland expansion with other land use priorities Mapping woodland expansion and consequences for ESs and Biodiversity.												**D3**
Objective 1.4.3d: integrating SRDP with NFM and GBRs Stakeholder engagement ***M1: Research agenda co-constructed with stakeholders***							**KE1**		**M1 D1**			
Objective 1.4.3d: integrating SRDP with NFM and GBRs Contribute a section on AM to 1.2.4's technical guidance. ***M2: 1.2.4's guidance integrated land management completed***												**M2 D2**
End of year reporting to RESAS (ALL OBJECTIVES)												**R1**

RD 1.4.3: PRACTICAL INTERVENTIONS TO REALISE MULTIPLE BENEFITS AND MANAGE TRADE-OFFS.
Work planning and timetable for Year 2

Year 2: 2017/18	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
O1.4.3a: Set up AM framework. Apply framework to case studies in O1.4.3b, c and d.											KE2	
Objective 1.4.3b: Assess the potential for EFAs, AECS and ECAF to deliver multiple benefits. Synthesis of data and good practice to share with local stakeholders. ***M2: Annual demonstration day held (with FBI)***											KE2	M2 D2
Objective 1.4.3b: Assess the potential for EFAs, AECS and ECAF to deliver multiple benefits. Catchment scale mapping multiple benefits from existing management. ***M3: Ecosystem service and benefits delivery mapped in core landscapes***:									M3 D3			
Objective 1.4.3b: Assess the potential for EFAs, AECS and ECAF to deliver multiple benefits. Catchment scale mapping of benefits predicted from potential EFA and AEC uptake.												D4
Objective 1.4.3b: Assess the potential for EFAs, AECS and ECAF to deliver multiple benefits Researching attitudes to uptake of cooperation action funds	D5										KE3	
Objective 1.4.3c: Reconciling woodland expansion with other land use priorities Interviews and focus groups with communities to identify benefits and trade-offs.		D3										
Objective 1.4.3c: Reconciling woodland expansion with other land use priorities Mapping woodland expansion and consequences for ESs and Biodiversity						KE 2			D6			
Objective 1.4.3d: integrating SRDP with NFM and GBRs Collate scientific and local knowledge. ***M3: Data on ecosystem services and benefits in a new case study collated***												M3 D3
End of year reporting to RESAS (ALL OBJECTIVES)												R1