Developing a method to estimate the costs of soil erosion in high-risk Scottish catchments

Final Report

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List of abbreviations

CAP	Common Agricultural Policy
CIS	Countryside Information Service
DOC	Dissolved organic carbon
GAEC	Good Agricultural and Environmental Conditions
GHG	Greenhouse gas
HOST	Hydrology of Soil Types
IACS	Integrated Administration and Control System
JHI	James Hutton Institute
LCM	Land Cover Map
NFI	National Forestry Inventory
NSIS	National Soil Inventory of Scotland
POC	Particulate organic carbon
PSG	Project Steering Group
SFP	Single farm payment
SG	Scottish Government
SPR	Standard Percentage Runoff
SPS	Single Payment Scheme
SSKIB	Scottish Soils Knowledge and Information Base
SSSI	Sites of Special Scientific Interest
TOC	Total organic carbon

Glossary

Term	Definition
Agricultural land	The Scottish Government define this as land used for agriculture for the purposes of trade or business. Scottish National statistics (June 2018) state that the agricultural area in Scotland is around 80 %, which comprises 47% rough/common grazing,17% grass, 7% crops and fallow and 9% ‘other land uses’ (e.g. woodland, ponds or yards).
Accelerated rates of soil erosion	Rates of soil erosion (t ha^{-1} yr^{-1}) that exceed rates of soil formation by natural physical and chemical interactions (geomorphic processes) with the earth surface (Verheijen et al., 2009).
Biodiversity	The variety of plant and animal life in the world or in a particular habitat, a high level of which is usually considered to be important and desirable.
Buffer strips	Vegetated strips of land left uncultivated / ungrazed that control soil erosion by either reducing slope lengths, which reduces the ability of water flowing over the surface to carry soil particles and / or controlling the amount of eroded soil leaving the field by reducing energy to carry soil particles in flowing water resulting in soil particles being dropped within the buffer strip
Catchment	In this report is defined as an area where precipitation that falls inside its boundaries is either held within the area or flows (either overland or via drainage pathways) towards a single point or outlet. Also known as a hydrological area, drainage basin or river basin.
Cohesion	The force that holds together particles (mineral and/or organic) within a soil, which include electrostatic forces between particles and cementing by chemicals (e.g. iron oxide and calcium carbonate)
Cover cropping	Growing crops between main crops to maximise land cover and root development to protect soils
Cultivated land	Land that is worked by ploughing, sowing and raising crops (https://www.thefreedictionary.com)
Cultural services	The non-material benefits people obtain from ecosystems, including aesthetic inspiration, cultural identity, sense of home, and spiritual experience related to the natural environment.
Deposition	The laying down of sediment that has been eroded and transported (moved). It happens when the forces which transported the material

	become weaker and unable to support the weight of the sediment.
Diffuse pollution	Pollution occurring from multiple points that are often individually minor, but collectively can result in significant environmental damage. Diffuse water pollution is the release of potential pollutants from a range of activities that, individually, may have no effect on the water environment, but, at the scale of a catchment, can have a significant effect. https://www.sepa.org.uk/regulations/water/diffuse-pollution/
Ecosystems goods and services	The benefits arising to humans from the ecological functions of ecosystems. These include provisioning services such as food, water, timber and fibre; regulating services that affect climate, floods, and water quality; cultural services that provide recreational, aesthetic and spiritual benefits and supporting services such as soil formation, photosynthesis and nutrient cycling (Millennium Ecosystem Assessment, 2005)
Erosion event	In the context of this report, is a rainfall event (e.g. storm) of sufficient energy (intensity and duration) to cause soil erosion
Erosion Risk Classes	The risk of a soil being eroded by water under intense or prolonged rainfall. Class divisions are based on factors affecting erosion including soil texture, slope and runoff potential. In this report the erosion risk classes are used to modify the soil erosion rate from 10 simplified land use categories.
Erosive velocity	Water traveling at sufficient speed to detach and entrain soil particles and aggregates. Particle/aggregate size and cohesion determine the critical threshold (amount of energy related to speed of flowing water) at which flow becomes erosive.
Extensive arable	Arable system that uses inputs of herbicides, fertilisers and labour
Geomorph-ological processes	Natural processes of weathering, erosion and deposition that determine the nature and origin of landforms.
Georeferenced	Real world coordinates e.g. Ordinance Survey coordinates, that are used to locate items on a map.
Intensive arable	Arable system that maximises yields through the use of pesticides and fertilisers
Improved Grassland	Land used for grazing where over one third of the sward comprises, singly or in mixture, ryegrass, cocksfoot or timothy, or land that has been improved by management practices such as liming and top dressing, where there is not a significant presence of sensitive plant species indicative of native unimproved grassland https://www2.gov.scot/Topics/farmingrural/SRDP/RuralPriorities/Opti ons/Biodiversitycroppinginbye/DefinitionsofLandTypes

Humic soils	Humic soils are soils with a dark coloured, organic-rich topsoil (typically >7% organic carbon in the uncultivated state).
Land-based businesses	Relates to farming and industries connected to the land and environment, including horticulture, food production and forestry
Land use	The dominant activity taking place on an area of land. Within this report land use areas include arable and horticultural fields, grassland, forestry, woodland, wildscapes and urban
Mitigation measures	Measures to control soil erosion: grouped into agronomic (i.e. use of vegetation to control erosion), structural (e.g. use of field structures such as terraces and bunds) or soil management (e.g. reduced tillage) measures.
National Forest Inventory of Scotland	The National Forest Inventory (NFI) is a rolling programme designed to provide accurate information about the size, distribution, composition and condition of forests and woodlands within Great Britain. It is essential for developing and monitoring the policies and guidance that support the sustainable management of woodland (https://www.forestresearch.gov.uk/tools-and-resources/nationalforest-inventory/about-the-nfi/)
Natural capital	The world's stocks of assets from the natural environment, which include geology, soil, air, water and all living things. https://naturalcapitalforum.com/about/
Off-site impacts of soil erosion	The consequences of soil erosion that occur away from the site of the erosion event (e.g. dredging of eroded soil (sediment) from watercourses; water treatments needed to remove sediment from water for subsequent use such as for drinking water)
On-site impacts of soil erosion	The consequences of soil erosion where the erosion event occurs (e.g. loss in crop yield due to reduced soil depth or damage to the crop; the need to apply more fertiliser to compensate for nutrients lost in the eroded soil). Also includes the need for installation of mitigation measures.
Organic soils	Organic soils are formed under waterlogged conditions or where the natural decomposition rates of organic material are significantly slower than the rates of accumulation. These soils have more than 60% organic matter and exceed 50cm in thickness. (https://www.hutton.ac.uk/learning/soilshutton/soil-classification).
Organo-mineral soils	Soils with topsoil organic carbon concentrations greater than 35% and less than 50cm thick.

Organomineral and peat soils	A blanket term used in this report to include both organo-mineral (peaty and humic soils) and peat soils
Particle size	The size of soil particles (categorised as sands, silt and clays). This affects soil erodibility (susceptibility to detachment, transport and deposition), depending on the energy of the eroding agent. Particle size also affects specific surface area which determines the capacity of soil to adsorb nutrients, contaminants etc., which are eroded with the sediment.
Peat soils	Peat soils are formed under waterlogged conditions or where the natural decomposition rates of organic material are significantly slower than the rates of accumulation. These soils have more than 60% organic matter and exceed 50cm in thickness. (https://www.hutton.ac.uk/learning/soilshutton/soil-classification).
Provisioning services	Ecosystem services that provide materials or energy from the ecosystems (e.g., food, fibre, timber)
Reduced tillage	Cultivations that minimise soil disturbance. Usually non – inversion tillage with the use of shallow tines, chisels and discs
Regulating services	The benefits obtained from the regulation of ecosystem processes (e.g., climate regulation, water regulation, pest and disease regulation)
Rill erosion	Small eroded channels of intermittent, concentrated flow that can be removed by cultivations or the next rainfall event
Risk	A probability or threat of damage, injury, liability, loss, or any other negative occurrence that is caused by external or internal vulnerabilities, and that may be avoided through preemptive action (http://www.businessdictionary.com/definition/risk.html)
Rough grassland	(https://www2.gov.scot/Topics/farmingrural/SRDP/RuralPriorities/Opti ons/Biodiversitycroppinginbye/DefinitionsofLandTypes)

Rough grazing	Land that is either steep, very poorly drained, has very acid or shallow soils and occurs in wet, cool or cold climates zones. https://www.hutton.ac.uk/learning/exploringscotland/land-capabilityagriculture-scotland/rough-grazing
Sediment	Solid materials and particles that are detached, transported and deposited by the processes of erosion. Sediment may include mineral fractions (clays, silts, sands) and / or organo-mineral materials (e.g. peats).
Sediment concentration	The sediment load per unit of flow volume (e.g. mg l^{-1})
Sediment load	Solid particles (e.g. sands, silts and clays) produced by soil erosion processes that are part of the transport flow (e.g. by water).

Sediment transport	The movement of eroded material (sediment load) from the original site of the erosion event.
Sediment yield	The amount of sediment reaching or passing a point of interest in a given period of time
Soil degradation	The physical, chemical and biological decline in soil quality
Soil erosion	Detachment and transport of soil particles / aggregates by agents of erosion. These are rainfall; runoff; wind; co-extraction with harvested crops; adhesion to agricultural vehicles and implements. However, for this report the focus is on soil erosion by water. Units are usually tonnes per hectare per year (t ha^{-1} yr^{-1}) i.e. soil mass lost per unit area per unit time. Mass movements (e.g. deeper seated slope failures) are excluded from the analysis. (Morgan, 2005)
Soil erosion by coextraction on harvested crops, vehicles, farm machinery	Soil adhering on crop roots, tyres, tracks, vehicles, which then leaves the field, causing loss of soil.
Soil formation rate	The rate at which soil is formed naturally by biological, physical and chemical processes (Alexander, 1988; Verheijen *et al*., 2009; Egli *et al*., 2018)
Soil functions	Capabilities of soil (e.g. infiltration, carbon storage) associated with the delivery of a range of ecosystem goods and services (e.g. flood control, regulation of greenhouse gases)
Soil quality	"the capacity of soil to function, within natural or managed ecosystem boundaries, to sustain plant or animal productivity, maintain or enhance water quality, and support health and human habitation" ….or more simply "the capacity of soil to function" or "fitness for use". (Karlen et al., 1997)
Soil texture	Defined by the proportion of soil distributed over specified particle size ranges (categorised as sands, silt and clays) (Brady and Wyle, 1990)
Soil type	Soil type is based on soil properties (for example, colour, texture) and on the arrangement and nature of the different horizons (layers) within the soil. (https://soils.environment.gov.scot/maps/soil-maps/national-soil-mapof-scotland/)
Supporting services	Ecosystem services that are indirect services, as they are necessary for the production of provisioning, regulating or cultural services (e.g., soil formation, nutrient cycling, photosynthesis)

Tillage erosion	Movement of soil downslope, caused by preferential displacement of soil by tillage implements, both on the contour as well as up / downslope
Tolerable rate of soil erosion	Any actual soil erosion rate at which a deterioration or loss of one or more soil functions does not occur (Verheijen et al., 2009)
Topography	The shape and features of the land surface
Unimproved grassland	Land used for grazing or mowing which is not normally treated with mineral fertiliser or lime and does not constitute either improved grassland or rough grazings (https://www2.gov.scot/Topics/farmingrural/SRDP/RuralPriorities/Opti ons/Biodiversitycroppinginbye/DefinitionsofLandTypes)
Water quality	The physical, biological and chemical properties of waterbodies that determine its ecological status and treatment requirements (e.g. to meet drinking water standards).
Wildscape	Area of largely semi-natural landscape with minimal signs of human influence. (https://www.nature.scot/professional-advice/landscape/landscapepolicy-and-guidance/landscape-policy-wild-land)

Executive summary

The aim of this project is to estimate the financial costs of soil erosion in Scotland. These costs are incurred by land-based businesses where soil erosion occurs, and by society where soil is deposited ‘off-field’ or in-stream. Understanding the impacts and costs of soil erosion will inform policies designed to value the soil resource in delivering a range of ecosystem goods and services that support a broad spectrum of human activities and associated benefits.

Reviewing the current evidence base suggests that soil erosion by water is the dominant erosion process in Scotland. Land uses affected include forests and recently ploughed / seeded arable fields in winter cereals. Observed erosion rates in arable areas of Scotland range from 0.01 t ha^{-1} yr^{-1} to 23.0 t ha^{-1} yr^{-1}, compared to a tolerable limit of 1 t ha^{-1} yr^{-1} (Verheijen et al., 2009b). Off-site, soil erosion can diminish water quality and damage aquatic life, including salmon spawning ground and freshwater pearl mussel beds. In general, evidence of erosion rates, their impacts and mitigation in Scotland remains sparse, and tends to be anecdotal rather than quantitative.

To estimate the total on-site and off-site costs of soil erosion per annum in Scotland, an updated version of the ecosystem service framework approach used by Graves et al. (2011; 2015) was used. Here, the identified and quantifiable annual costs of soil erosion include: a) on-site costs (e.g. decline in agricultural and forestry yields caused by the reduction in soil depth, and the cost of replacing losses in soil-based C, N, P and K); and b) offsite costs (e.g. declines in water quality and greenhouse gas emissions).

A number of representative catchments were selected for the analysis: the Ugie; the Pow; the Girvan; the Esk and the lower Tweed catchment. Once the methodology was applied successfully at the catchment scale, it was then extrapolated to the national scale. Land use was simplified into 10 categories: Urban; Horticulture; Arable intensive; Arable extensive; Grassland improved; Grassland unimproved; Rough grassland; Forestry; Woodland; and Wildscape. The catchments were also classified into Soil Erosion Risk Classes: High, Moderate and Low for mineral soils, and one class for organo-mineral and peat soils.

The first step was to assess the degree and severity of soil erosion in the catchments. Given the lack of quantified erosion rates for Scotland, it was decided to use the most comprehensive database of soil erosion observations (the “National Erosion Survey”; Evans (2005), with over 1,680 field observations. This showed that soil erosion rates were largely driven by land use. The probability of erosion occurring was more related to Soil Erosion Risk Class.

The results are presented on a ‘per annum’ basis and can be used to justify the need for and expenditure on soil protection interventions that control soil erosion.

Currently, there is no policy related specifically to soil protection in Scotland (McKee, 2018). Most policy instruments are not explicitly designed to target soil, rather they view soil as an asset that underpins agricultural production, water quality or climate change mitigation (Prager et al., in press). Post-CAP, soil protection should be incorporated into national policies, although the efficacy of measures to prevent soil erosion should be reviewed. The question arises as to who should pay for implementation of mitigation measures, if deemed necessary (i.e. to reduce the costs of soil erosion), which has policy implications.

This assessment of the annual costs of soil degradation largely confirms the difficulties of deriving complete and reliable estimates of the benefits provided by soils and how these change according to soil condition. There are three aspects to this challenge (i) 'identifying' biophysical relationships between soil properties, soil functions and 'performance' of soils in particular applications (ii) 'valuing' the diverse range of market and non-market benefits and costs attributable to soils in different applications and (iii) assessing the 'dynamics' of soil properties, especially under conditions of climate change, as these affect changes in the supply and value of services.

Summary of on-site and off-site annual costs (£) for all catchments and for Scotland as a whole:

Catchment	**Area of catchment (ha)**	**On-site (£)**	**Off-site (without drinking water) (£)**	**Off-site (with drinking water) (£)**	**Total (without drinking water) (£)**	**Total (with drinking water) (£)**
Ugie	29,878	60,281	134,580	278,634	194,861	338,915
Pow	4,332	5,724	13,761	32,953	19,485	38,677
Girvan	23,393	34,939	78,421	168,882	113,360	203,821
Esk	51,763	74,343	175,760	354,603	250,103	428,946
Tweed	351,190	549,854	1,223,153	2,521,675	1,773,007	3,071,529
Scotland	7,108,057	9,695,133	21,277,022	39,803,328	30,972,155	49,498,461

The present study estimated that the total annual costs of soil erosion in Scotland are £49,498,461 (including drinking water treatment costs) or £30,972,155 (not including water treatment costs). Off-site costs of soil erosion always exceeded those associated with on-site costs for all the 5 study catchments. The same was true at the national scale.

Understanding the impacts and costs of soil erosion will inform national policies and local practices designed to value the soil resource in delivering a range of ecosystem goods and services that support a broad spectrum of human activities and associated benefits.

1. Introduction

Soil erosion is a natural process that is dependent on climate, topography, soil type, vegetation cover, land use and land management. Inappropriate land use and land management can trigger accelerated rates of soil erosion that have detrimental impacts both on-site (where the erosion takes place e.g. on agricultural fields) and off-site (away from the erosion site e.g. eroded soil / sediment entering watercourses).

Soil erosion was identified as one of the main threats to Scotland's soils in the comprehensive 'State of Scotland's Soil Report' (2011). The Scottish Government 'aims to promote the sustainable management and protection of soils, consistent with the economic, social and environmental needs of Scotland' (https://www.gov.scot/policies/biodiversity/soils/). The Scottish Soils Framework sets out a vision for soils to be "safeguarded for existing and future generations". It is recognised that soils provide a range of ecosystem goods and services that support a broad spectrum of human activities and associated benefits (Table 1). The continued provision of benefits from soil depends on successfully maintaining its physical, chemical and biological properties.

However, evidence suggests that the way soils are currently used degrades the resource (e.g. by soil erosion) resulting in loss of soil quantity and quality, along with the functions that soils support, and the ecosystem goods and services delivered by these functions. This can result in significant costs, not only to immediate users of soils but also to society as a whole. Climate change projections for Scotland indicate more heavy rainfall days and an increase in winter rainfall, leading to greater risks of soil erosion in the future, making the status of 'Soils and agriculture' in Scotland of 'high concern' (Committee on Climate Change, 2019).

Table 1. Millennium Ecosystem Assessment categories of ecosystem services and examples relating to soil (after Haygarth and Ritz, 2009).

Category	Examples of ecosystem services provided by soil
Provisioning services i.e. products obtained from ecosystems	Food Fibre and fuel Genetic resources
Regulating services i.e. benefits obtained from the regulation of ecosystem processes	Climate regulation Water regulation Water purification/detoxification Bioremediation of waste
Cultural services i.e. non-material benefits that people obtain through spiritual enrichment, cognitive development, recreation etc.	Spiritual and religious value Inspiration for art, folklore, architecture etc Social relations Aesthetic values Cultural heritage

	Recreation and ecotourism
Supporting services, necessary for the production of all other ecosystem services	Soil formation and retention Nutrient cycling Primary production Water cycling Provision of habitat

The aim of this project is to estimate the financial costs of soil erosion in Scotland. These costs are incurred by land-based businesses where soil erosion occurs, and by society where soil is deposited 'off-field' or in-stream. Understanding the impacts and costs of soil erosion will inform policies designed to value the soil resource.

1.1. Approach

A review of the literature was used in an attempt to identify soil erosion rates in Scotland, as well as the impacts of soil erosion and the associated costs of these impacts. At the same time, information on the costs and benefits (effectiveness) of soil erosion control measures was also gathered. A number of representative catchments were selected for the analysis. To estimate the total on-site and off-site costs of soil erosion per annum in those catchments, an updated version of the approach used by Graves et al. (2011; 2015) was used. Once the methodology was applied successfully at the catchment scale, it was then extrapolated to the national scale.

It was agreed that landslips / mass movements were out of scope for the project, as these are different geomorphological processes to those of soil erosion.

2. Literature review

The aim of the literature review was to determine the total annual costs of soil erosion in Scotland, based on the evidence of:

- The current soil erosion rates in Scotland;
- The on-site and off-site impacts of soil erosion in Scotland;
- The use of mitigation measures that are used to control soil erosion in Scotland.

The full literature review can be found in Appendix 1, but an updated form of the Executive Summary of the Literature Review is presented here.

2.1. Executive Summary of the Literature Review

It is recognised that soils provide a range of ecosystem goods and services that support a broad spectrum of human activities and associated benefits. The continued provision of benefits from soil depends on successfully maintaining its physical, chemical and biological properties. However, evidence suggests that the way soils are currently used degrades the resource (e.g. by soil erosion) resulting in loss of soil quantity and quality, along with the functions that soils support and the ecosystem goods and services delivered by these functions. This can result in significant costs, not only to immediate users of soils but also to society as a whole. Climate change projections for Scotland indicate more heavy rainfall days and an increase in winter rainfall, leading to greater risks of soil erosion in the future, making the status of ‘Soils and agriculture’ in Scotland of ‘high concern’ (Committee on Climate Change, 2019).

Soil erosion is a natural process that is dependent on climate, topography, soil type, vegetation cover, land use and land management. Inappropriate land use and land management can trigger accelerated rates of soil erosion that have both on-site (where the erosion takes place e.g. the field) and off-site (away from the erosion site e.g. road or river) impacts. Soil erosion was identified as one of the main threats to Scotland’s soils in the comprehensive ‘State of Scotland’s Soil Report’ (2011).

The literature review suggests that soil erosion by water is the dominant erosion process in Scotland. Notable soil erosion events are triggered by either high intensity rainfall; prolonged, low intensity rainfall; or rapid snowmelt. Land uses affected include forests and agriculture (especially bare, recently ploughed / seeded arable fields in winter cereals). Observed erosion rates in arable areas of Scotland range from 0.01 t ha^{-1} yr^{-1} to 23.0 t ha^{-1} yr^{-1}, which can exceed an identified tolerable limit of 1 t ha^{-1} yr^{-1} (Verheijen et al., 2009b). Limitations of the current evidence base include a tendency to focus on small areas of severe soil erosion, rather than a systematic approach to monitor and assess more insidious erosion. In general, quantified rates for all forms of soil erosion in Scotland remain sparse.

Regarding the on-site impacts of soil erosion, there is very little quantification of the reductions in crop yields due to soil erosion in Scotland. Single soil erosion events rarely cause significant problems for farmers, but over time may impact on the long-term sustainability of the land and can still result in loss of ecosystem goods and services such as crop production, but also carbon sequestration and water storage. These on-site impacts of soil erosion may take a long time to take effect, especially on deeper soils or where inputs of fertilisers can mask yield declines due to soil loss.

Off-site, soil erosion contributes to increased suspended sediments and turbidity in Scottish watercourses, which can diminish water quality and damage aquatic life, including salmon spawning ground and freshwater pearl mussel beds. In general, the greater the proportion of arable cropping in a catchment (and thus soil erosion risk), the greater the increase in suspended sediment load in waterways. However, the present review has found few quantified studies of the off-site impacts of soil erosion in Scotland.

There is some evidence on the use of erosion mitigation measures in Scotland: most was related to practices on forested land. However, monetary costs (and benefits) associated with measures to combat soil erosion and sediment transport are lacking for Scotland.

The 'on-site' and 'off-site' costs of soil erosion are incurred in many different ways, affecting a diverse range of ecosystems services and benefits to people, over a range of spatial and temporal scales. This makes estimating the costs of soil erosion particularly challenging and may explain the limited quantified evidence on the costs associated with soil erosion in Scotland.

The literature review demonstrates that evidence on soil erosion rates, impacts, mitigation and costs in Scotland tends to be anecdotal rather than quantitative. These estimates may have some uncertainty, given the paucity of data.

2.1.1. Update on the Literature Review

Extra references on forest haul roads and skid trails in newly planted / felled areas and the likely effect on soil erosion rates in forested areas have been added to the final Literature Review report. Evidence suggests that they are unlikely to contribute much soil erosion, as guidelines for soil protection in place should be properly implemented. A method of calculating the density of forest roads was found, but as this is likely to be very low, forest roads will not be considered as a separate land use in the analysis.

3. The case study catchments

An existing soil erosion risk map (Lilly et al., 2002; Lilly and Baggaley, 2014), covering about 95% of cultivated land in Scotland was used to identify representative catchments to take forward as case studies (Figure 1). The inherent erosion risk is related to slope gradient, soil texture and the ability of the soil to absorb rainfall (thus reducing the likelihood of runoff generation). The latter is based on the HOST (Hydrology of Soil Types) classification (Boorman et al. 1995).

A description of the erosion risk classes (and the map) can be found on Scotland's soils website (https://soils.environment.gov.scot/maps/risk-maps/map-of-soil-erosion-risk-partialcover/). For soils with mineral topsoils, the risk of soil erosion is classified into 3 main classes: Low, Moderate or High. Each main class is then divided into 3 subclasses (L1-3, M1-3 and H1-3). The higher the number in each class indicates a greater risk of erosion within that class. This is dependent on slope gradient, soil texture and the ability of the soil to absorb rainfall (thus reducing the risk of generating potentially erosive runoff). Organo-mineral and peat soils are also divided into 3 classes: Low, Moderate or High. The Low and Moderate classes are then subdivided into subclasses (Li-iii and Mi–iv), again with the higher the number in each risk class indicating a greater risk of erosion within that class (Figure 2).

If available, data on erosion rates, impacts, mitigation and costs were sourced from the literature review. Examples of the datasets available are shown in Figure 3. These observations were captured in a GIS and plotted onto the map (Figure 3). The aim was to relate the observed rates to soil type and land use (and other characteristics if known) to allow ‘extrapolation’ to other areas with similar site characteristics. However, it should be noted that only a very few of these sites have quantified data.

A long list of 55 potential catchments with information regarding their size, soil types, land uses (based on the Land Cover of Scotland (1988) classes (i.e. arable, moorland, improved grassland etc.) and soil erosion risks (classified as high, moderate or low) was presented to the Steering Group (Table 2). The location, land cover, Soil Series and soil erosion risk were sourced from relevant datasets (Figure 3).

A selection of 10 catchments (Table 2; Figure 1) was made to reflect a broad and representative range of soil types, land covers (including different proportions of different land covers in each catchment) and erosion risks, ideally accompanied with observations and surveys. For example, the Coyle (NS395214) in Ayrshire and the East Pow (NO069256) in Perthshire are contrasting catchments, representative of differing land use, soils and water quality issues. They were used in a pilot study to develop and demonstrate the soil erosion risk classes based on existing 1:25,000 scale soil maps (see https://soils.environment.gov.scot/maps/). They are both sub-catchments of SEPA’s priority catchments (http://www.sepa.org.uk/water/river_basin_planning/dp_priority catchments.aspx).

Geographical spread was also considered in the selection process, to reflect climate variability. The locations of the catchments are shown in Figure 1. Considering the resolution of data available in these catchments (Table 2), the area covered by the current 1:25,000 soil erosion risk maps is shown on the top left map (in darker grey) in Figure 1. Six of the 10 catchments lie wholly within the detailed Soil Map of Scotland (partial cover), while the others have some areas currently not mapped at that scale. Even so, it is still possible to apply the methodology (see Section 6) to these areas, with the proviso that this would be at a lower resolution and with increased uncertainty, as it would be based on the National Soil Map of Scotland soils data.

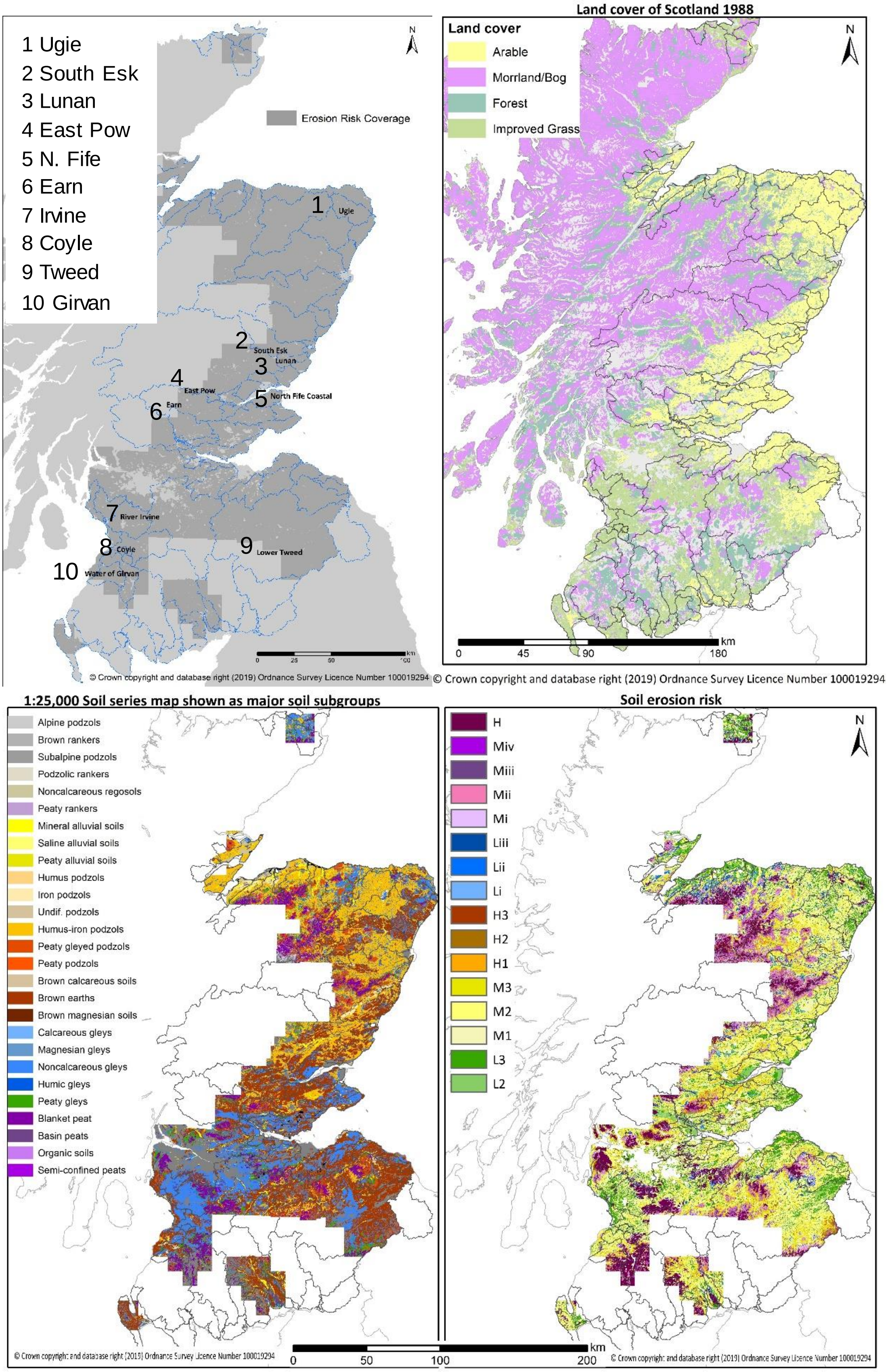


Figure 1. Location, land cover (top); Soil Series and soil erosion risk (bottom) of the catchments of interest (see Figure 2 for map legend).

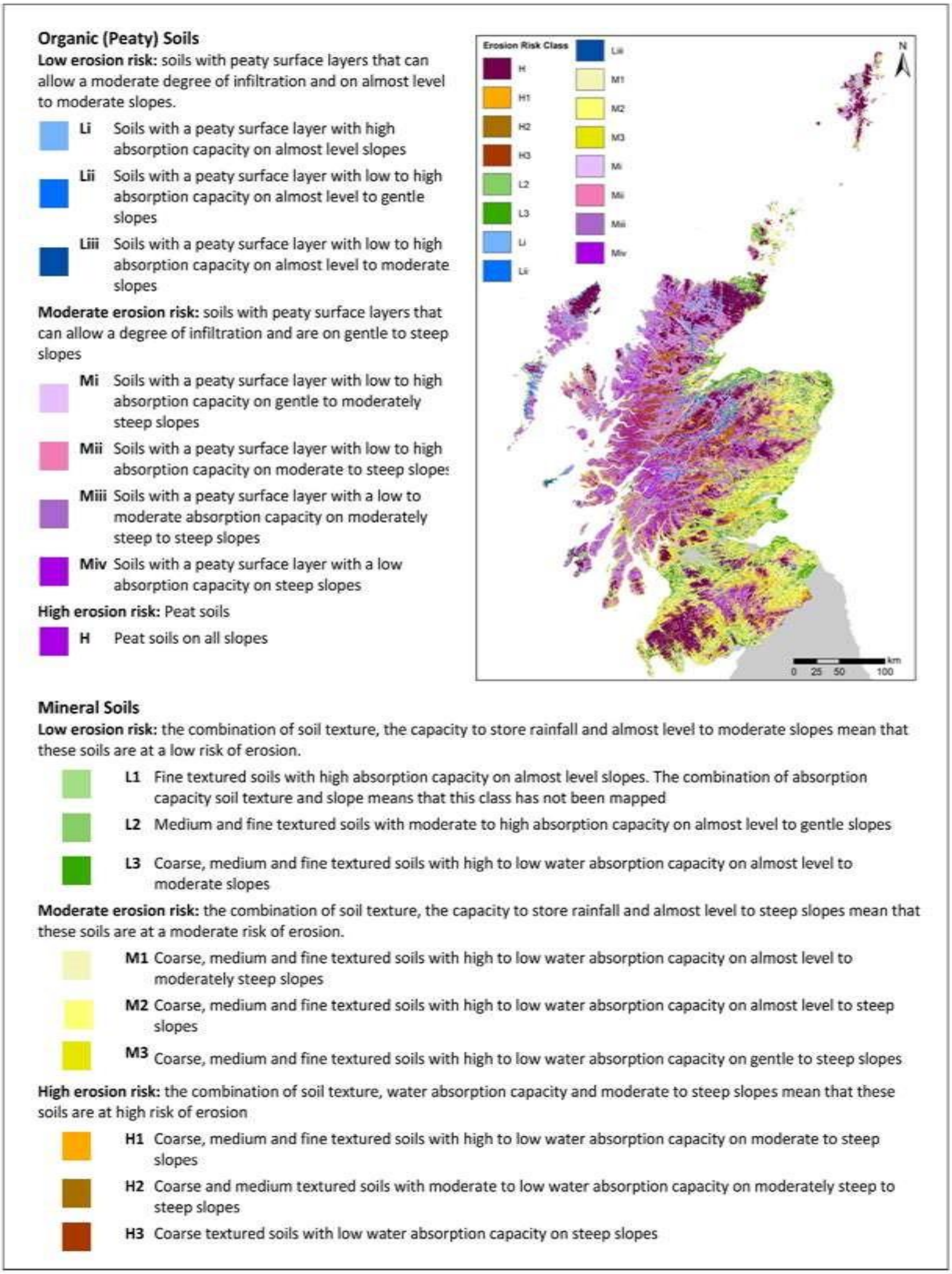
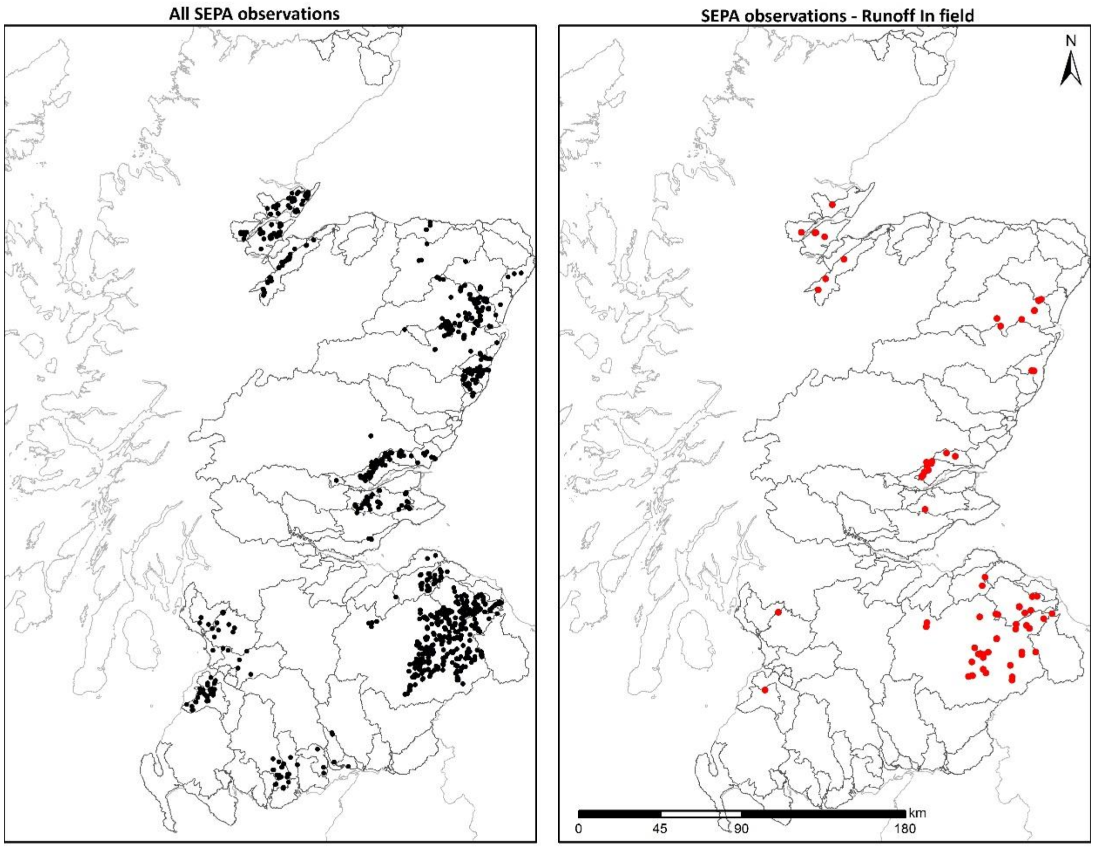


Figure 2: Map legend for mineral soils, and for organo-mineral and peat soils



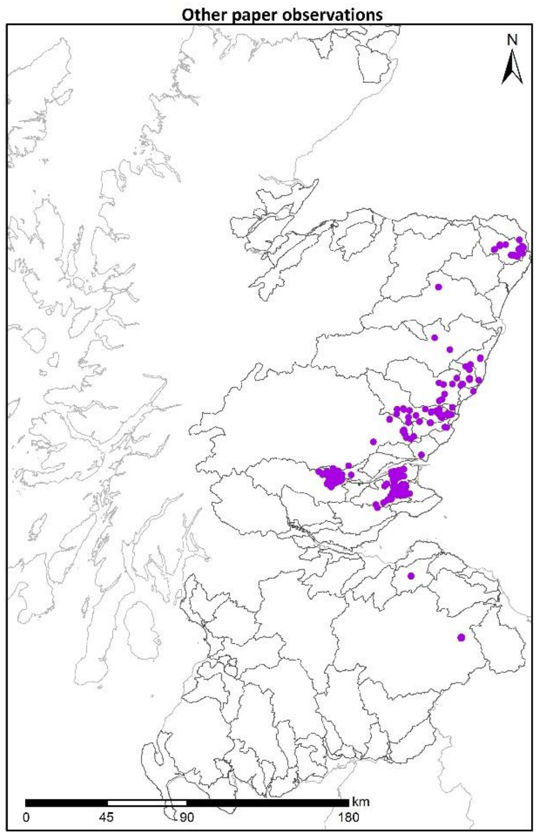


Figure 3. Locations of selected observations of soil erosion in Scotland (black dots = all SEPA observations; red dots = SEPA observations of field runoff; Purple dots = other observations from papers reviewed for the current project).

Table 2. Long list of potential catchments (short list in leftmost column)

Catchment (short listed)	Catchment	Catchment
Coyle	Moray Coastal	Buchan Coastal
Pow	River Nairn	Whiteadder Water
Lunan Water	River Ythan	River Esk (Solway)
River Ugie	Wick River	Inverness Coastal
River Earn	River Esk (Lothian)	South Fife Coastal
River Forth	Cromarty Coastal	River Clyde
Water of Girvan	River Doon	River Almond
River Tweed	Dumfries Coastal	Earn Coastal
River Irvine	Galloway Coastal	Banff Coastal
River South Esk (Tayside)	River Lossie	River Nith
	River Leven (Fife)	Eye Water
	Dundee Coastal	River Garnock
	Forth Estuary (South) Coastal	Urr Water
	Thurso Coastal	River Eden
	Stewartry Coastal	Lochar Water
	River North Esk (Tayside)	River Dee (Solway)
	North Ayrshire Coastal	River Tyne
	East Lothian Coastal	River Ayr
	River Dee (Grampian)	Dighty Water
	Stirling Coastal	River Deveron
	River Don	River Tay
	Bervie Water	North Fife Coastal
	Kincardine and Angus Coastal	River Annan

The consensus from the 1st Steering Group meeting was that around 4 - 5 catchments would be selected for the economic analysis of soil erosion rates and associated impacts. The following criteria were considered in selecting the final 5 case study catchments for the project:

- geographical spread (to reflect climate variability);
- representative land uses;
- availability of soil erosion observations;
- range of ecosystems goods and services affected by erosion (e.g. cultural impact, archaeology, historical sites, etc.)
- designated areas of special interest.

Some coastal catchments were not selected because of the small size of catchments included. In consultation with the Steering Group, 5 catchments were selected (Table 3). Maps of land use, Erosion Risk Classes and IACS data for each of the case study catchments are given in Figure 4, Figure 5 and Figure 6 below.

Table 3. Selected catchments

Locality	Selected catchment(s)
North / North East	Ugie (agricultural runoff, peatland areas)
Central	South Esk (selected for impact on cultural services e.g. bathing water, tourism, fishing, shellfish) Pow
South East	Lower Tweed (large upland areas; few observations available, although some SEPA data and from Spiers and Frost). Selected for the impact on cultural services.
South West	Girvan (20% forested). There was some debate as to whether soil erosion was an issue in forested areas. The National Forest Inventory (NFI) can identify areas recently felled and newly planted, which are likely to generate erosion. Of these areas, it is assumed that only a small % erode in any one year. However, the NFI does not identify other 'erosion generating activities' i.e. haul roads, drainage ditches etc.

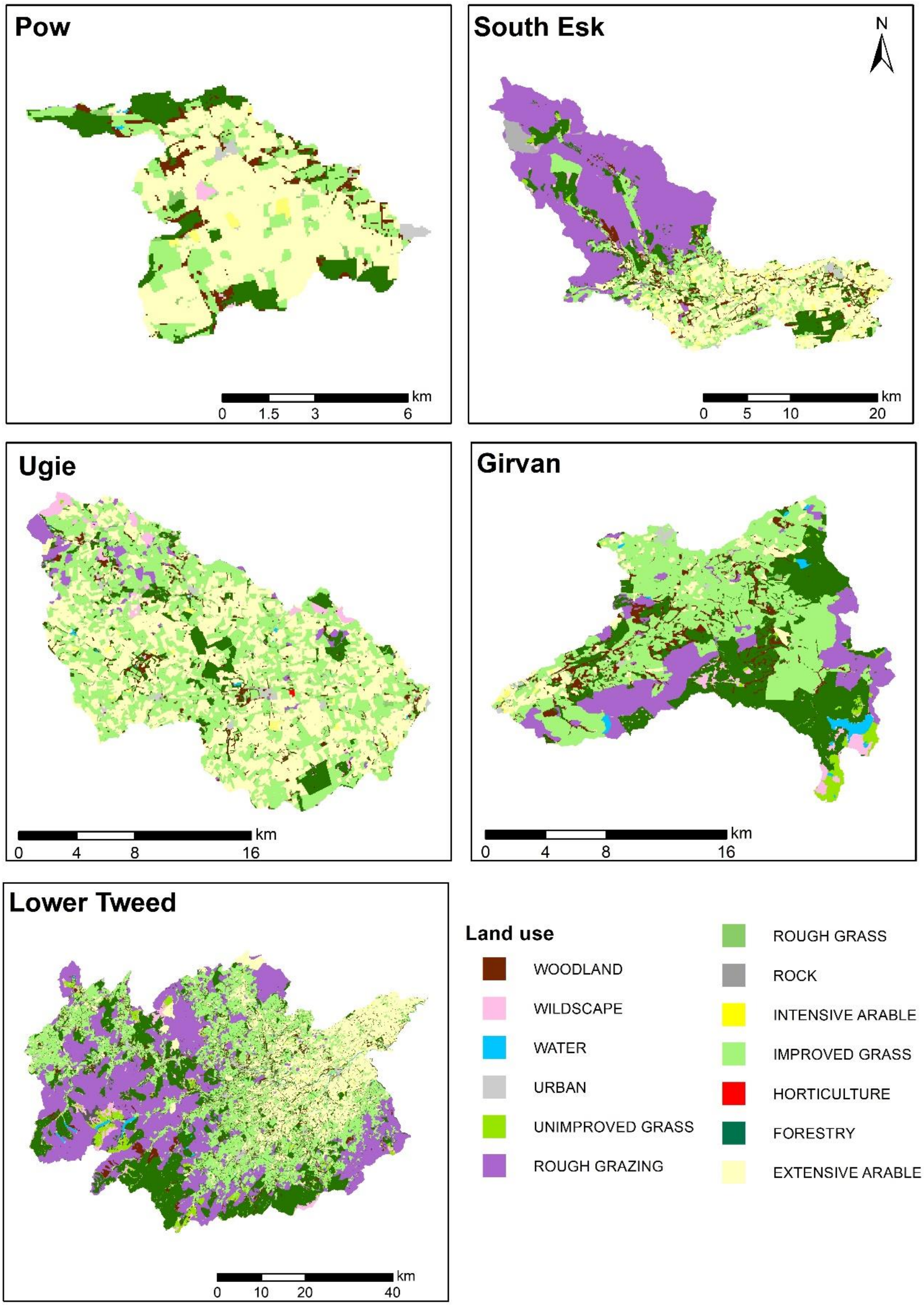


Figure 4. Land use for the five case study catchments, based on the National Forest Inventory, IACS and LCM2007

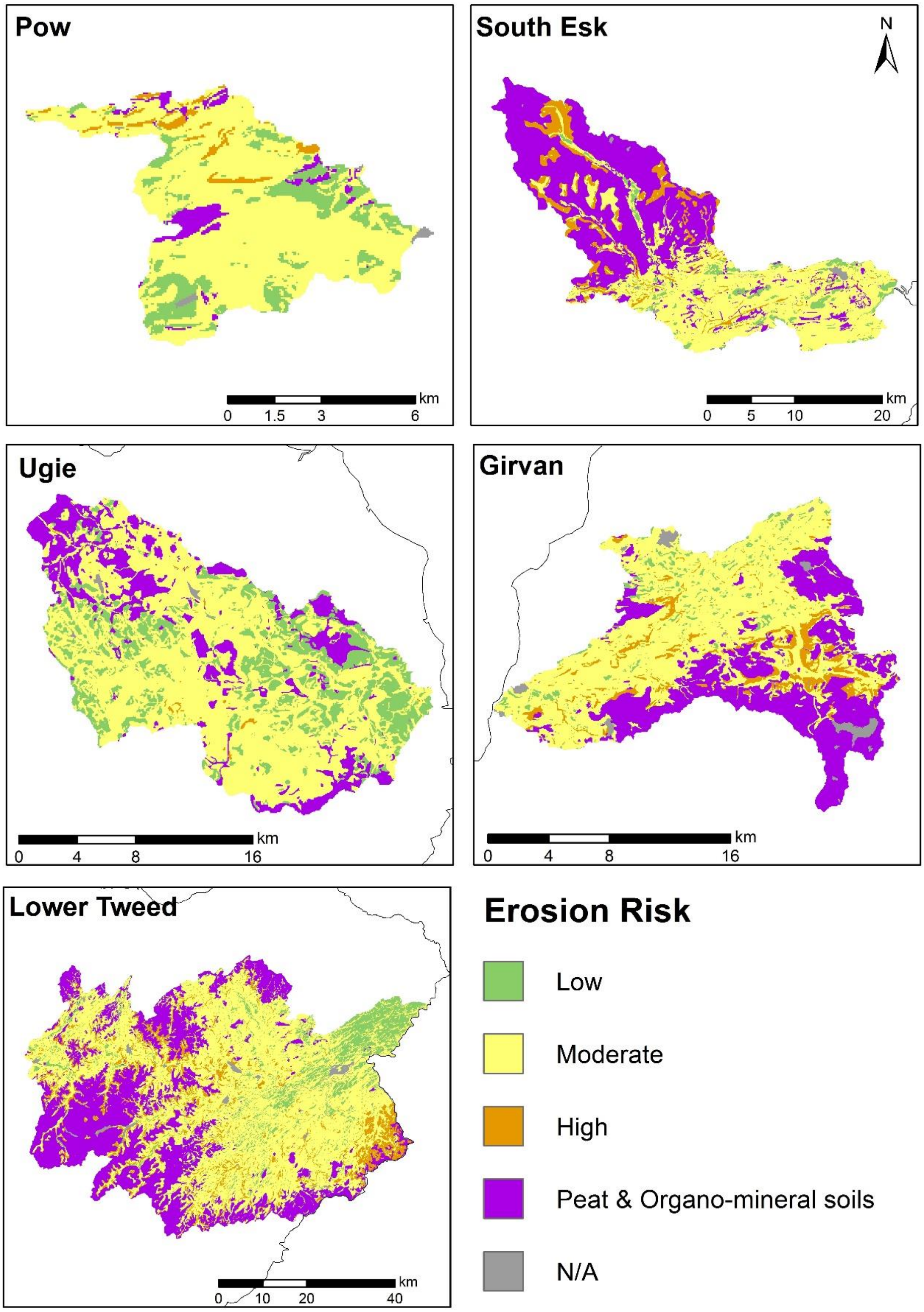


Figure 5. Simplified soil erosion risk classes for the five case study catchments

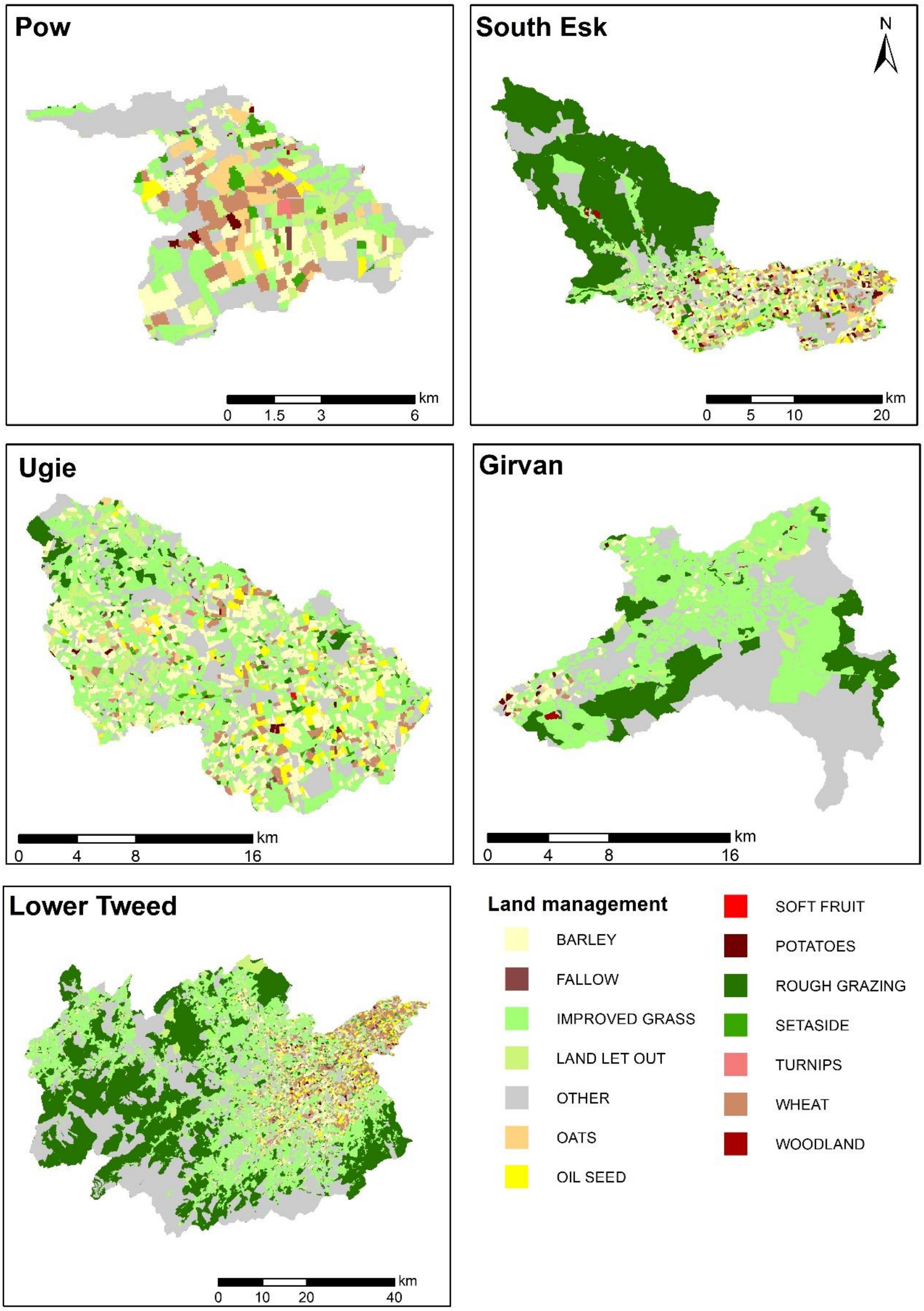


Figure 6. Aggregated IACS classes for each of the 5 case study catchments

4. Soil erosion rates and probabilities

In order to evaluate the economic consequences (impacts and costs) of soil erosion in the selected catchments (followed by national scale analysis), it is first necessary to identify the rates at which soil erosion is likely to occur and then the probability of such an event occurring.

However, despite the comprehensive search of the literature, data on soil erosion rates and the probability of erosion in any one year specifically in Scotland is limited. However, mapping of Erosion Risk Classes has covered an extensive area of Scotland.

4.1. Soil erosion rates

It was decided to create a 'look up' table that assigned a representative soil erosion rate (t ha^{-1} yr^{-1}) to the Erosion Risk Classes identified by Lilly et al. (2002) and Lilly and Baggaley (2014). Due to the large number of possible land use / Erosion Risk Class combinations, it was necessary to simplify the 9 classes for mineral soils and 8 classes for organo-mineral and peat soils. It was decided to have 3 classes (High, Moderate and Low) for the mineral soils and one class for the organo-mineral and peat soils. The Risk Classes had originally been based on soil texture, slope and hydrology class, but did not include land use. Although there are many different land uses in the catchments (and nationally), given the time available to run the analysis, it was necessary to simplify land use into 9 categories (Horticulture; Arable intensive; Arable extensive; Grassland improved; Grassland unimproved; Rough grassland; Forestry; Woodland; and Wildscape). The 'look up table' would include all of these factors affecting erosion, providing a more detailed estimate of soil erosion rates within the catchments than available before. Each cell would have have a representative soil erosion rate (t ha^{-1} yr^{-1}), although some cells may be redundant or unlikely to occur.

Although it was possible to map soil erosion observations to Erosion Risk Classes, many of these are qualitative and very few have quantified rates of soil erosion. Where data on rates did exist, these locations were georeferenced to assign an Erosion Risk Class to that location (with its associated soil erosion rate). We approached Dr Bob Evans for original data from his field surveys of soil erosion rates in Scotland in the 1980s (Watson and Evans, 2007), that could also be georeferenced and assigned an Erosion Risk Class. However, unfortunately, this data was no longer accessible.

4.1.1. Exploring the relationship between Erosion Risk Class and observed soil erosion rates (mineral soils)

Given the lack of a comprehensive dataset of quantified erosion rates in Scotland (see Literature Review), it was agreed that the most extensive field observation dataset in the UK would be used to assign erosion rates to each of the Erosion Risk Classes for any given land use (Evans, pers.comm., 31/07/19). The "National Erosion Survey" of the mid 1980s is still the best empirical data source for erosion for reasons outlined in Evans (2005). The survey was concerned with monitoring rill erosion occurrence and magnitude, based on field assessment provided by Dr. Evans. The original fieldwork made over 1,680 field observations of erosion and deposition in England and Wales between 1982-86. This dataset recorded the site location, year, erosion volume (m^3), field area (ha), slope gradient (including maximum slope gradient), volume of deposition (m^3), location of erosion / deposition, land use and soil type (Figure 7). Notes about the sites were also recorded. The method for converting the volumetric measurements into annual erosion rates ($t\ ha^{-1}\ yr^{-1}$) is described in Defra SP1318 (Rickson et al., 2016). The method for classifying the land uses into those used in the 'look up' table is given in Appendix 2. As it is not possible to analyse every crop individually in the economic model, this is basically a simplification of the land into different categories depending on the way the soil is managed and disturbed.

Each site was georeferenced to obtain slope, topsoil texture and HOST class. This allowed each site and its observed erosion rate to be assigned an Erosion Risk Class. The risk class can then be derived on a field by field basis by applying the rule base shown in Table 4.

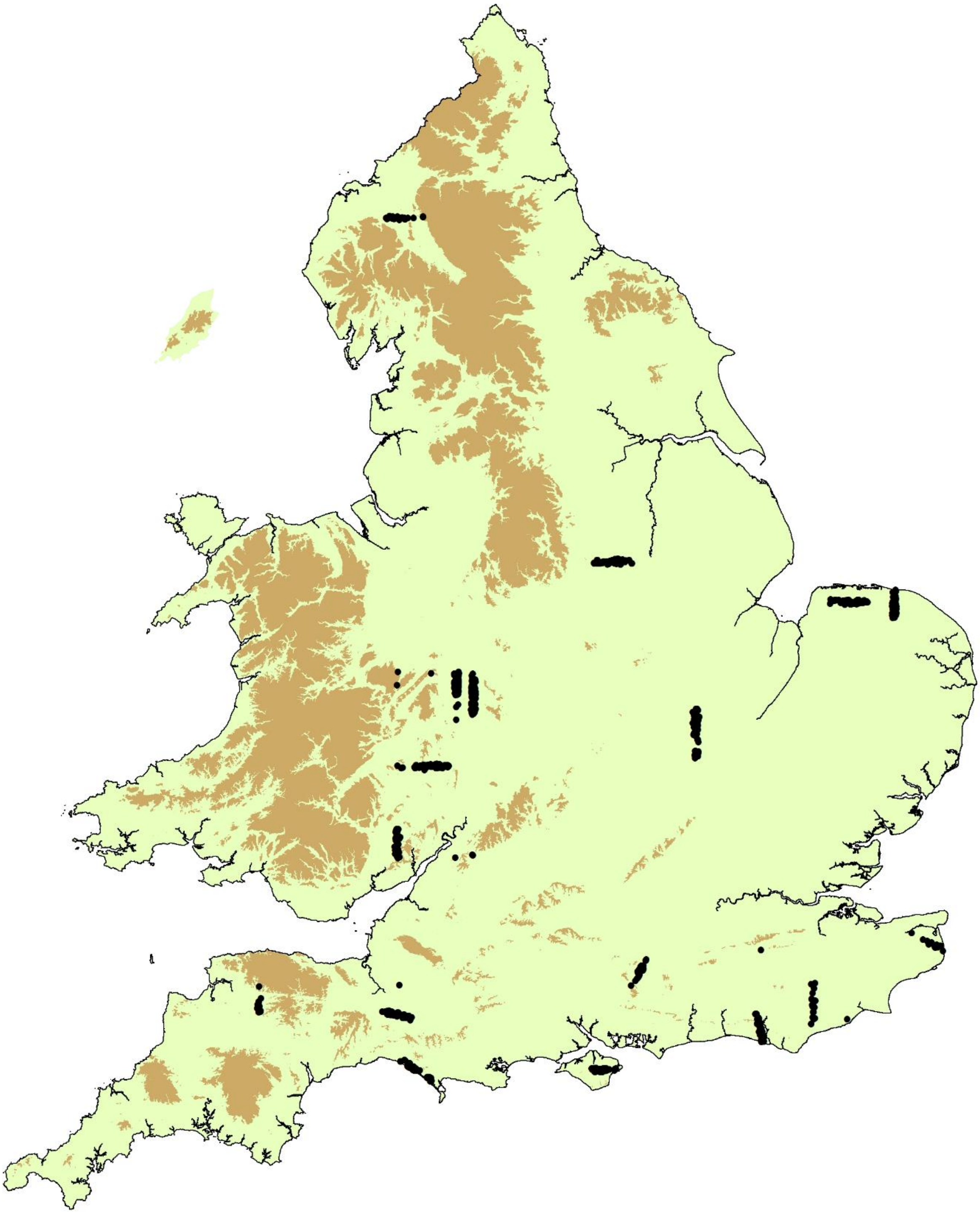


Figure 7. Locations of Evans' field soil erosion surveys

Table 4. Deriving the Erosion Risk Class for sites with measured soil erosion rates (L = low, M = moderate, H = high)

Standard percentage runoff (%)	Texture	Slope 0 - 2°	2 - 5°	5 - 10°	10 - 18°	18 - 30°
0 - 20	Fine	L	L	L	M	M
	Medium	L	L	M	M	M
	Coarse	L	M	M	M	H
	Organic	L	L	L	M	M
20 - 40	Fine	L	L	M	M	M
	Medium	L	M	M	M	H
	Coarse	M	M	M	H	H
	Organic	L	L	M	M	M
40 - 100	Fine	L	M	M	M	H
	Medium	M	M	M	H	H
	Coarse	M	M	H	H	H
	Organic	L	M	M	M	M
Peat		H	H	H	H	H

All the observed soil erosion data was classified into Erosion Risk Classes, using the Lilly and Baggaley (2014) model. As quite a few of the sites had no direct erosion data, the measured volume of deposition was taken instead. This gave around 1,700 data points. The calculated soil erosion rate results are shown in Table 5. It is noticeable that these observed soil erosion rates are lower than those observed in Scotland (see Literature Review), but this is probably because most of the Scottish data were collected in response to dramatic erosion events.

Initial evaluation of the data focussed on whether observed soil erosion rates reflected the corresponding Soil Erosion Risk Classes of Low, Moderate and High for that location. This was expected as the Risk Classes reflect the soil susceptibility to particle detachment (soil texture), the amount of overland flow likely to be generated (from HOST-SPR) and the velocity of that flow (based on slope gradient). However, this progression was only seen in the Extensive Arable class (Table 5).

Within the land use classes, Improved Grassland gave higher soil erosion rates for the Moderate Erosion Risk Class (6.2 t ha^{-1} yr^{-1}) compared to the High Risk Class (4.672 t ha^{-1} yr^{-1}). Only Intensive Arable in the High Erosion Risk class had a higher erosion rate (i.e. 8.44 t ha^{-1} yr^{-1}). The relatively very high rates of erosion in the Improved Grassland could be explained by the fact that many of Evans' Improved Grassland sites were on reseeded grass leys, where a fine seedbed and the lack of a protective cover of surface vegetation and dense root network are likely to have generated high rates of erosion.

Equally, calculating average erosion rates from the Evans' data solely by Risk Class also failed to provide a progression of increasing rates, as Risk Class increased from Low to Moderate to High, with land at Low risk having an annual average soil loss of 3.442 t ha^{-1}, land at Moderate risk having an annual average soil loss of 3.074 t ha^{-1} and land in the High risk class having an annual average soil loss of 4.317 t ha^{-1}.

These results were not unexpected as the Erosion Risk classes developed for Scotland are based on the inherent risk without consideration of land use (Lilly et al., 2002 & Lilly and Baggaley, 2014). However, recent work on soil erosion in Scotland showed the role that land use plays in both mitigating and exacerbating soil erosion (Baggaley, Lilly and Riach, 2017; Lilly et al., 2018 and Baggaley et al., 2017). Thus, it was decided to accept that soil erosion rates should be largely driven by land use, but the probability of erosion happening should be largely driven by Erosion Risk class. The adoption of this approach underpins the assessment of the annual cost of erosion in Scotland.

Table 5. Progression of observed erosion rates (t ha^{-1} yr^{-1}) from Low – Moderate - High Risk Classes by land use (based on observations by Evans for England and Wales)

Land use	Mineral soils		
	Low	Moderate	High
Horticulture	3.131	4.248	2.625
Intensive arable	4.131	3.511	8.44
Extensive arable	2.101	2.304	2.385
Improved grassland	2.826	6.204	4.672
Unimproved grassland	No data	No data	No data
Rough grassland	No data	No data	No data
Forestry	No data	No data	No data

Thus a mean rate of erosion (t ha^{-1} yr^{-1}) associated with the broad land use classes was calculated, based on the Evans data, where available (Table 6).

Table 6. Overall soil erosion rates on mineral soils (t ha^{-1} yr^{-1}) assigned to each land use, based on empirical observations and the literature review

Land use	Mean soil erosion rate (t ha^{-1} yr^{-1})
Horticulture	3.835
Intensive arable	4.314
Extensive arable	2.389
Improved grassland	5.228 (3**)
Unimproved grassland	No data available
Rough grassland	No data available
Forestry	0.593*
Woodland	0.593*
Wildscape	0.593*

*Based on rates cited in the Literature Review. ** See text for explanation

It was agreed that the rate of erosion for Improved Grassland (5.228 t ha^{-1} yr^{-1}) is likely to be an overestimate, due to the inclusion of erosion events on highly erodible reseeded grass leys. The value was later revised to 3 t ha^{-1} yr^{-1}, based on: Scottish data in the Literature Review (although there were few data points: the values ranged from 0.86 to 5 t ha^{-1} yr^{-1} with a mean of 3 t ha^{-1} yr^{-1}) and using other empirical observations which had a range of 0.36 to 4.49 t ha^{-1} yr^{-1} (Graves et al., 2011). Using the limited data from Scotland for 'sense checking', the erosion rate for Extensive Arable was 9.55 t ha^{-1} yr^{-1} (n=37) and 7.47 t ha^{-1} yr^{-1} for Intensive Arable (n=5) after the removal from the data of an exceptionally high rate of erosion of 345 t ha^{-1} from a potato field.

4.1.2. Exploring the relationship between Erosion Risk Class and observed soil erosion rates (organo-mineral and peat soils)

Soil erosion rates for organo-mineral (soils with a peaty surface layer) and peat soils under Forestry and Moorland were found in the Literature Review (0.13 – 0.25 and 0.3 – 0.39 t ha^{1} yr^{-1} respectively). However, few studies exist of equivalent erosion rates for horticulture; intensive arable; extensive arable; or improved grassland on these soil types (assuming this soil type / land use combination exists). The rates (15 t ha^{-1} yr^{-1}) used in Graves et al. (2011) for England and Wales were based on expert judgment. The consensus in the current project is that this seems too high, especially given the low bulk densities (typically 0.16 Mg m^{3}) which would produce massive volumes of eroded soil (and incur significant loss of soil depth, which is important for the modelling of yield losses in the economic model to calculate annual costs of erosion – see Section 6 below).

Other datasets were explored. The National Monitoring Scheme (Evans, 2005) only had 1 site on peatland. Other studies on peat erosion rates (e.g. McHugh (2000)) refer only to uncultivated, upland areas. Accurate soil erosion rates on peat are also difficult to separate from soil losses due to oxidation, shrinkage, drainage and erosion by wind. No studies quantify rates of erosion by water alone (the focus of the current project). In any case, most peat soil is under woodland, moorland or rough grazing (or Grouse moor), so it was assumed that the area of peaty soils under arable production will be limited for the case study catchments. The estimated rates of soil erosion for organo-mineral and peat soils are given in Table 7.

Table 7. Estimated rates of soil erosion for organo-mineral and peat soils

Land use	Peat erosion rate (t ha^{-1} yr^{-1}) (from E&W; Graves et al. (2011))	Erosion rate (t ha^{-1} yr^{-1}) for organo-mineral soils and peats (proposed for Scotland)
Horticulture	15	7
Arable intensive	20	10
Arable extensive	10	5
Grassland improved	7	1
Moorland	-	0.39*
Forest	-	0.13*

*From the Literature Review Appendix 1. Literature Review

4.2. Final erosion rates by land use and Erosion Risk Class

The finalised soil erosion rates (t ha^{-1} yr^{-1}) per land use and Soil Erosion Risk Class are shown in Table 8.

Table 8. Finalised soil erosion rates (t ha^{-1} yr^{-1}) by land use.

Land use	**Mineral soils**	**Organo-mineral and peat soils**
Horticulture	3.8	7
Arable intensive	4.3	10
Arable extensive	2.4	5
Grassland improved	3.0	1
Grassland unimproved	2.07	0.39
Rough grassland	0.75	0.39
Forestry	0.6	0.13
Woodland	0.6	0.13
Wildscape	0.6	0.13

4.3. The probability of soil erosion in space and time

Having estimated the likely erosion rate for a given land use, it is recognised that not all fields in a catchment under a certain land use will erode every year. The rates will be modified by the proportion of that land use actually incurring soil erosion in any one year. Some work on this is reported in the Literature Review. For example, based on field observations, the probability of erosion occurring in cropped fields in England and Wales was presented by Evans (2005) (Table 9).

Table 9. Occurrence and risk of occurrence of rill erosion in cropped fields (Evans, 2005)

Occurrence of erosion		Risk of occurrence of erosion	
crop type	%	crop type	Risk
Winter cereal	42.8	Winter cereal	1 in 42
Sugar beet	18.4	Sugar beet	1 in 7
Spring cereal	11.5	Spring cereal	1 in 34
Potatoes	10.6	Potatoes	1 in 10
Field vegetables	6.3	Field vegetables	1 in 14
Other	3.0	Other	1 in 11
Maize	1.6	Maize	1 in 7
Bare soil	1.5	Bare soil	1 in 21
Oilseed rape	1.5	Oilseed rape	1 in 100
Peas	1.0	Peas	1 in 38
Kale	0.7	Kale	1 in 24
Hops	0.5	Hops	1 in 6
Field beans	0.4	Field beans	1 in 71
Ley grasses	0.2	Ley grasses	1 in 32

Based on these observations, Graves et al. (2011) used the following probabilities of soil erosion occurrence for different land uses:

Grassland	5%
Rough grazing	2%
Forestry	1%
Woodland	1%
Intensive arable and horticulture	17%

For the purposes of the present project (and rather than taking probabilities from the Evans' dataset; Table 9), it was assumed that the Erosion Risk Classes (related to soil type, slope and runoff potential) reflect the differences in probability of erosion occurring (i.e. the proportion of fields likely to erode in a year). To validate this approach, two studies were used, which undertook systematic studies of soil erosion, where all fields were surveyed, and the presence or absence of erosion at the time of survey was recorded. In Strath Earn, data presented by Davidson and Harrison (1995) was analysed and showed that as the inherent vulnerability (i.e.

Erosion Risk Class) increases in each of the fields, so the probability of erosion also increases, both when analysed for all 9 Erosion Risk Classes and for the aggregated risk classes (Table 10).

Table 10. Relationship between Erosion Risk Class (H = High, M = Moderate, L = Low) and percentage of fields eroding (probability) in Perthshire (after Davidson and Harrison, 1995)

Risk Class	Number of eroded fields	Total number of fields	Percentage eroded
H	30	75	40
M	45	204	22
L	0	3	0

Using transects in the Ugie and South Esk catchments (Baggaley, Lilly and Riach, 2017), analysis again shows evidence that the probability of erosion increases with Soil Erosion Risk Class (Table 11).

Table 11. Relationship between Erosion Risk Class (H = HIgh, M = Moderate, L = Low) and percentage of fields eroding (probability) in the Ugie and South Esk catchments**.**

Risk class	Number of eroded fields	Total number of fields	Percentage eroded
High	2	27	7
Moderate	15	372	4
Low	0	28	0

The difference in the absolute values is probably due to different climatic conditions. However, using the mean of these 2 studies gives the probabilities of erosion as:

- Low Erosion Risk Class: 0% (with a nominal value of 2%, recognising that some erosion may occur very occasionally)
- Moderate Erosion Risk Class: 13%
- High Erosion Risk Class: 24% (Table 12).

These values correspond well with those from other Scottish researchers who have reported the % of arable land affected by soil erosion at any one time (and compared to the 17% reported in Evans' work for England and Wales). Namely:

- Kirbride and Reeve (1993) 27%;
- Wade: 25.5%;
- Davidson and Harrison (1995): 26.76%
- Watson and Evans (2007): 11.6%;
- Baggaley et al. (2017): 0.36 - 10%

Additional supporting evidence that the probability of soil erosion increases with Erosion Risk Class comes from an analysis of all the data on erosion observations in Scotland (Figure 3). The Risk Class was determined for each field where erosion had been recorded, then compared to the proportional area of the Risk classes within the cultivated land covered by the erosion risk map. The results showed that the proportion of eroded fields was approximately equal to the proportion of land at moderate risk and the proportions of eroded fields was greater than the proportion of the land area in the High Risk Class and less than for land in the Low Risk Class.

For organo-mineral (soils with a peaty surface layer), humic and peat soils, the 'average' probability of erosion incidence was calculated from the National Soil Inventory of Scotland (NSIS) 1978-88 dataset (Lilly et al., 2010). This dataset has observation on soil erosion on a 5km grid throughout Scotland. The probability for peat erosion (based on observed erosion on peat soils) was 31% (Towers et al., 2006). The equivalent for the organo-mineral soils was calculated as 12.1%. These figures represent national assessments by soil type and by the proportion of occurrence of these soils in Scotland. As only one combined 'peaty soils' class has been used in the current project, the occurrence of erosion on all peats (n = 695) and peaty and humic soils (n = 854) was calculated from the NSIS data to be 21% (Table 12). This will be applied consistently for each catchment and at the national scale.

Table 12. The % of land area at risk of soil erosion per Erosion Risk Class (at soil erosion rates for each land use given in Table 8).

Area at risk (%)			
Erosion Risk Class			
Low	**Moderate**	**High**	**Organo-mineral soils and peat**
2%	13%	24%	21%

In summary, the rates of erosion were calculated from Evans data from England and Wales for broad land use classes. The probability of soil erosion occurring was calculated from Scottish data for each of the mineral Soil Erosion Risk Classes (Low, Moderate and High) and an overall probability calculated for all organo-mineral and peat soils combined. The combination of soil erosion rate and soil erosion probability will allow the determination of potential annual soil losses and allow the cost of soil erosion in Scotland to be calculated.

5. Framework for the economic costs of soil erosion in scotland

Soils are natural capital assets. Soil stocks, described in terms of their quantities and qualities have potential to provide a range of benefits to people in the form of ecosystem services. Whilst soil quantity and quality determine the ability of soils to provide these benefits, their contextual attributes such as altitude, topography, climate, hydrology and location are also important. The misuse of soil natural capital assets in pursuit of benefit can, however lead to their degradation, resulting in loss of benefit or increased costs.

It is impossible to determine the full value of soil stocks. Soils deliver many monetary (e.g. crop production) and non-monetary benefits (e.g. landscape aesthetics and feelings of wellbeing) to individuals and society as a whole, as shown in Table 1. Some of these benefits are tangible (yet still can be non-monetary), others are intangible. It is possible, however, to determine the variations in the condition of stocks of soils (e.g. the degree of degradation of soils assets due to soil erosion) and the likely implications for flows of services. This is the approach adopted here, using the ecosystem service framework, by estimating the change in the value of annual service flows, that is the annual costs of the degradation of soil stocks due to soil erosion by water.

5.1. Soils stocks and flows of ecosystems goods and services

The loss of soil stock through erosion over time leads to a decline in the value stock of soil assets and a reduction in the value of future services provided by them. In other words, soil erosion leads to the depreciation of a physical asset (soil as a natural capital asset), evident in the reduction of its remaining value over time. Thus in Figure 8, degradation is the reduction in the value of soil (in delivering services) over an accounting period, equivalent to the depreciation of physical assets. Degradation, if continued and unabated, would eventually lead to complete loss of soil assets and the services they deliver.

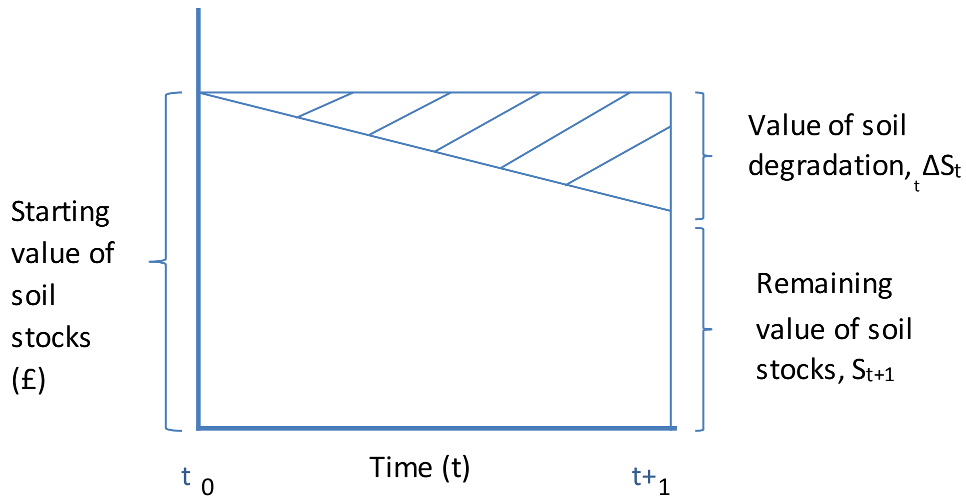


Figure 8. Graphical representation of the degradation of the value of stocks of soil

The stock: flow relationship can be expressed as a difference equation as follows:

$$\boldsymbol{\Delta S_t = f(S_t, X_t, Z)} \qquad \textbf{Equation 1}$$

where:
ΔS_t is the change in S between t and
t+1 S_t is the starting value of the stock
f = soil degradation function
$X_t = (X_1, ..., X_n)$ are external variables that are associated with change in the stock characteristics of soils such as land use and soil structure
$Z = (Z_1, ..., Z_m)$ are the 'state' variables such as type of soil and topographical that do not change.

Usually *f* < 0, indicating that the degradation has a negative effect on the stock value.

Then:

$$\boldsymbol{S_{t+1} = S_t + \Delta S_t} \qquad \textbf{Equation 2}$$

Or

$$\boldsymbol{S_{t+1} - S_t = f(S_t, X_t, Z)} \qquad \textbf{Equation 3}$$

where S_{t+1} is the stock value at a particular point in time

If *f*, the degradation function, is independent of S_t, then the general case applies as follows:

$$= \boldsymbol{S_0} + \sum_{t=0}^{T-1} \boldsymbol{f} \quad \boldsymbol{S_T(X_t, Z)} \qquad \textbf{Equation 4}$$

Where T = time at the end point of running the model (years) (T-1 represents Year 1 – Year n, where Year n is the end point of the model run)

The value of the soil resource at any point in time is a function of its initial value and the cumulative effects of degradation (e.g. soil erosion processes) over time. If, however, as often might be the case, there is an interaction between the stock itself (i.e. soil) and the rate of degradation of that stock (e.g. thin, eroded soils are more susceptible to further erosion due to loss of structure and organic matter) then a more complex relationship applies.

From an economist's perspective, the value of a stock at a point in time is determined by the present value of the future flows of services, discounted at the social discount rate[1]. Thus a change in the stock value is indicated by the change in the present value of flows of services rendered. For example: the reduction in carbon content of soils associated with emissions to atmosphere results in costs borne by society measured at the social cost of carbon. The present value sum of these emissions can indicate a decline in the value of soil carbon stocks between any two points in time. A similar approach can be used in principle for the value of soils as a medium for food production. It is noted however that some degraded services may be substituted by other 'replacement' inputs, such as artificial fertilisers. This does not reduce the loss of stock value. Rather it substitutes the natural functions of soil at an additional cost.

5.2. The counterfactual 'without degradation' situation

It is required to define a baseline 'counterfactual' situation against which the economic costs of soil degradation can be ascertained. The counterfactual is the condition of soils, both in terms of stock and flow values, which would prevail in the absence of degradation, ($S_{t+1} = S_t$; Equation 2)

The degradation that arises from the particular land use is identified together with the costs of degradation associated with that particular land use. As explained below, the analysis focuses on loss of value added and additional costs, whether associated with substitution of soil properties or mitigation to prevent their loss.

5.3. Classifying the costs of soil degradation

An ecosystem services framework is adopted here to assess the economic costs of different processes of soil degradation. Many of the services provided by soils are intermediate supporting services that underpin provisioning, regulating and cultural services. Emphasis is placed on the generation of 'final goods' that are of value to people.

Consistent with other classification approaches, these final goods incorporate on-site and offsite effects, private and public benefits, as well as use and non use benefits (Table 13). Soil degradation results in a reduction in the quantity and quality of soil as natural capital and hence a reduction in the quantity and quality of flows of ecosystem services. These changes in stocks and flows are expressed in economic terms where possible.

[1] See HMT (2003), The Green Book. Her Majesty's Treasury, London for a discussion on the choice of discount rates for public investment appraisal. High discount rates tend to encourage relatively rapid depletion of soils whereas low discount rates tend to encourage soil conservation strategies in order to secure continued future benefits from soils.

Table 13. Generic classification of costs of soil degradation and basis for valuation

Spatial extent	Type of cost	Ecosystems services perspective	Economic perspective	Basis for valuation
On site:	Productivity loss, Damage costs Mitigation costs	Mainly provisioning services e.g. agricultural production Some supporting services e.g. providing habitats and media for flora, nutrient cycling etc. Cultural services to onsite users	Mainly 'private' costs borne by individuals and organisations Some non market costs borne by site users	Mainly market prices Non market prices for uncompensated site users
Offsite:	Damage costs Mitigation costs.	Mainly regulation e.g. flood control, GHG regulation and cultural services e.g. recreational (swimming, fishing, boating), property values	Public costs borne by society at large Some private costs e.g. water treatment	Combination of market and nonmarket prices Non-monetary (intangible) impacts
Total	Combined on- and off site	Combined value of provisioning, regulating and cultural services	Combined value of private and public costs	Mix of market prices (adjusted for taxes and subsidies) and non market prices. Non monetary (intangible) impacts

The identified and quantifiable costs of erosion include:

- the annual onsite costs of the decline in agricultural and forestry yields caused by the reduction in soil depth, and the cost of replacing losses in C, N, P and K. The economic analysis was unable to account for the on-site costs of soil erosion mitigation measures at the catchment and national scale. Although costs of mitigation have been reported in the Literature Review, they cannot be included in the economic analysis at the catchment or national scale, because there is no information on the numbers of measures used or their geographical location. This would require mapping these measures at a much finer resolution than used in the present study (e.g. location of field buffer strips; identification of minimum tillage use; etc.).

- the annual offsite costs associated with impacts on environmental water quality (e.g. 'good ecological status' in the Water Framework Directive), drinking water quality, and greenhouse gas regulation. Onsite costs accrue at the location of the degradation processes. They are mainly (but not exclusively) borne by those causing degradation and as such are mainly 'private' costs to individuals and organisations. Offsite costs accrue elsewhere and are borne by third parties, usually without compensation, and are therefore mainly public/societal costs. Some on-site costs may be public costs that accrue to users, such as walkers in the countryside, whose non market benefits are reduced without compensation (assuming they cannot go elsewhere to derive the same net benefit).

The majority of onsite private costs can be valued using market prices. The valuation of offsite, public costs may involve a mix of market and non-market prices. It is noted, however, that onsite costs may include some non-market costs, such as the stress or loss of amenity or reputation caused by a degradation process, such as a serious soil erosion incident on farm land.

From an economic viewpoint the cost of soil degradation is the sum of onsite and offsite costs (with some adjustments to market prices to remove the effect of taxes and subsidies). Evidence to date suggests that offsite costs exceed onsite costs by a large margin (Graves et al., 2015), and that the onsite benefits of soil erosion control (mitigation) may be less than the costs involved (Posthumus et al., 2013a). This might not, however, be the case from the public perspective, because the benefits of soil conservation are accrued to others besides the land manager / farmer who will implement these measures on their land. It is difficult to predict the ratio of on-site to off-site costs and benefits, as this will vary over both time (e.g. changing prices and costs) and space (soil erosion is very localised in extent) (Posthumus et al., 2013a). Thus, much of soil policy is concerned with identifying total costs of soil degradation, and where appropriate, using cost effective policy measures to reduce degradation in the public interest. This may involve a mixture of regulatory, economic and voluntary instruments.

6. Applying the model to the case study catchments and national scale

We have updated data going into the economic costing model, including typical crop yields for Scotland (for a number of years); prices of crops (and hence impact of yield penalties due to soil erosion); costs of fertilisers; Gross Margins; forestry model (coniferous v. broadleaved); carbon values; soil nutrient values; GDP inflators; non market costs e.g. carbon sequestration etc.

6.1. Loss of crop yields through soil erosion

Typical yields for each crop in Scotland were taken from the Scottish Farm Management Handbook (2018/19) https://www.fas.scot/downloads/farm-management-handbook-2018-19 (SAC Consulting, 2018). For example, winter wheat has an indicative yield in Scotland of between 4.5 – 8.5 t ha yr.

Using Pimentel's equation (Pimentel et al., 1995) to calculate yield penalties due to soil erosion (the rates of erosion should reflect the soil and crop type to some extent), relative to typical yield can be used to calculate costs of yield penalties.

6.2. Losses of nutrients and carbon

Soil properties are needed in the economic model. Bulk density (BD) is used to convert the estimated erosion rates into a loss of soil depth, which is associated with yield losses (Pimentel, 1995). Soil nutrients (nitrogen (N), phosphorus (P), potassium (K) and carbon (C)) are eroded with soil particles, so the costs of replacing them have to be estimated. The values used were spatially weighted averages calculated from the SSKIB dataset for each broad land use that occurred within the four Soil Erosion Risk Classes (L, M, H, and organo-mineral and peat soils) (Appendix 3; Appendix 4; Appendix 5; Appendix 6; Appendix 7).

Strictly speaking, the model should only consider plant available nutrients (e.g. bioavailable N and P), as the loss of these through soil erosion will affect plant growth and crop yields, rather than total nutrient content. The partitioning of bioavailable versus total nutrient content is highly dynamic and values for bioavailable nutrients were not available. We investigated whether we could predict bioavailable nutrients from total contents. Data held within the Scottish Soils Database on both Total P and a more limited dataset of acetic acid extractable P (bioavailable P) shows that one cannot be used to predict the other, as there is a poor correlation between these P values (Figure 9). Figure 10 shows similar results for the correlation between Total P and another measure of bioavailable P, Olsen P, for a range of UK soils. As a result of the challenge of using only bioavailable P in the calculations, the analysis was based on total P content of the (eroding) soil.

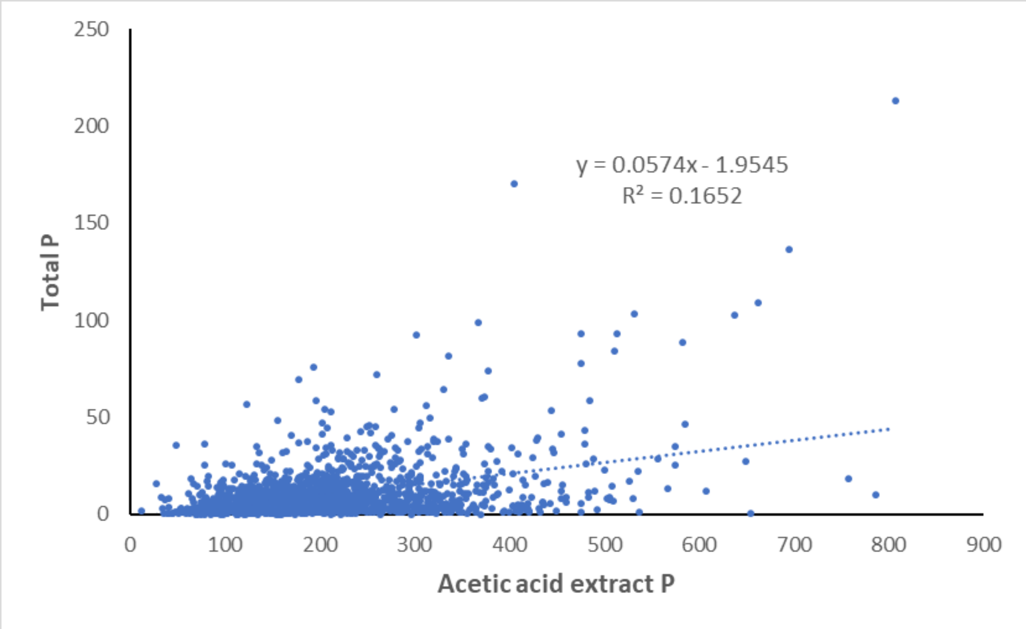


Figure 9. Correlations of Total P v available P from the Scottish Soils Database

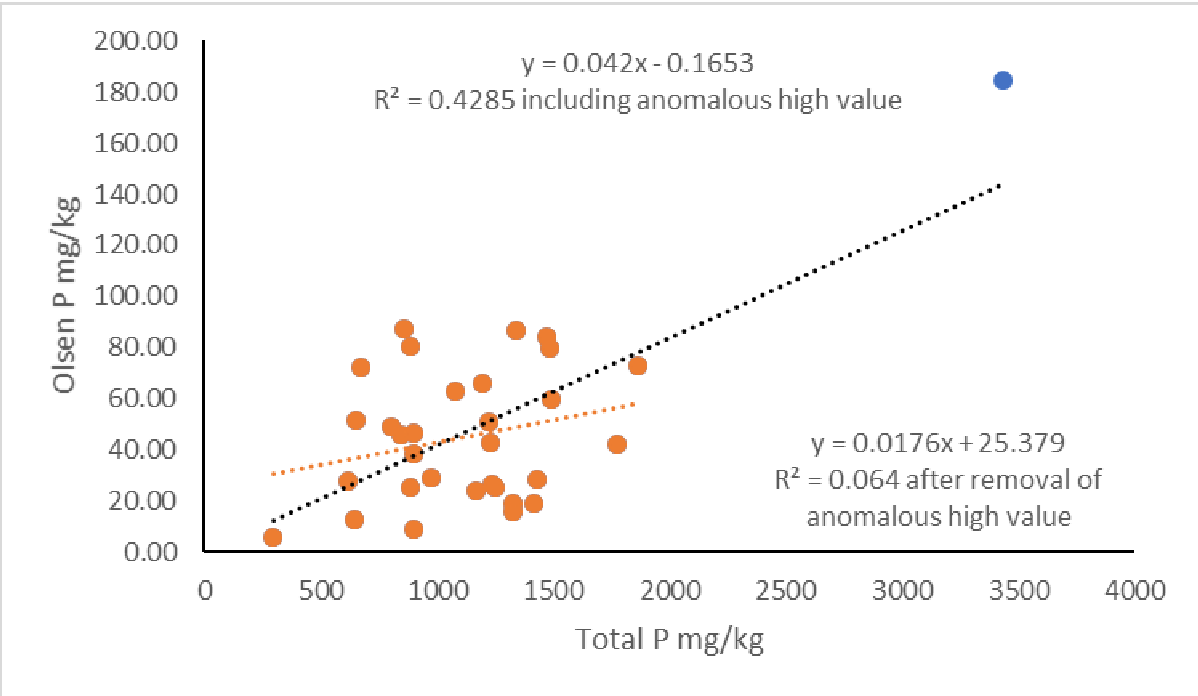


Figure 10. Correlations of Total P v Olsen P (bioavailable) from a range of UK soils

6.3. Land use allocations in the selected case study catchments

The current methodology uses land use to determine the soil erosion rate, modified by Erosion Risk Class to determine the probability of that erosion rate occurring in any given year / on any given field. Soil erosion rates and probabilities for urban

areas were excluded from the analysis, as these are likely to be low, due to the high proportion of sealed surfaces.
Also, data on this for Scotland was unavailable. Land use is also used to indicate current levels of soil nutrients (assuming more intensive land uses have higher levels of soil nutrients than the extensive land uses e.g. horticulture versus moorland). Production outputs (e.g. crop yields) are also linked to land use. For example, in grassland systems, it is assumed that 'Improved Grassland' is the most productive and intensively managed (e.g. around 8-10 t ha^{1} yr^{-1}), 'Unimproved Grassland' is less productive and intensively managed (e.g. around 5-7 t ha^{-1} yr^{-1}), and 'Rough Grazing' is low yielding with very low inputs (e.g. around 2-4 t ha^{-1} yr^{1}). This land use category includes natural or semi-natural vegetation so it could include heather moorland, for example, whereas rough grass is just semi natural (unimproved) grass such as *Molinia* or *Nardus* or bent species. Thus accurate information on the spatial distribution of land use (and how it coincides with Erosion Risk Class) in the 5 case study catchments and for the whole of Scotland is needed as input to the economic model.

Integrated Administration and Control System (IACS) data is accurate and of high resolution (i.e. field by field). It was used to give annual snapshots of agricultural land use at the field level, allowing for high resolution spatio-temporal land use change studies at the national scale. It identifies arable, grassland and horticulture, but not forestry, woodland, wildscape or moorland. The detailed IACS land use classes then had to be linked to the crops already embedded in the economic model (and to the erosion rates assigned to each of these land uses).

Appendix 8 shows how the IACS crops found in Scotland were assigned a category relating to a) soil erosion rate (i.e. what broad land use category did the crops belong to) and b) the economic model's range of crop types.

The National Forest Inventory (NFI) of Scotland was used to identify woodlands and forests. Where IACS or NFI data was not available, LCM 2007 was used to assign land use to the remaining areas. It is recognised that LCM 2015 would have given more up to date data but was not available to the project team within the timescales of the project.

These datasets (IACS, LCM 2007 and NFI) were combined to estimate the % of each land use in each of the five catchments. Maps of land use and Erosion Risk Class for each case study catchment were produced (Figure 4, Figure 5 and Figure 6) and the proportion of the catchment in each combination was calculated.

6.3.1. Crop rotations within arable land

Within the arable areas, the cropping patterns are needed to assign the area under each crop in any particular year. The economic model will predict yields for each of these crops. The classification of IACS classes observed into the crop types incorporated into the economic model is shown in Appendix 8. Given the broad range of crops grown under arable, some assumptions and simplifications had to be made. Set aside and fallow were assumed to be part of an ‘Extensive Arable’ rotation.

Distribution of crops over space in any one year is used as an analogy for time (i.e. ‘pseudorotation’). It was assumed that the spatial / temporal distribution of crops within arable areas would be similar in all catchments (and for the national scale). Field margins were not identified as a separate land use within arable areas.

6.3.2. Farm infrastructure

It was decided to exclude areas of farm infrastructure, such as farm buildings, yards, tracks and roads from the subsequent analyses. These can take up a proportion of the land and will have much lower soil erosion rates than the surrounding farmland, as they are often sealed by concrete, tarmac and hard standings etc.. The area involved was assumed to vary with land use, but not Erosion Risk Class (Table 14). The Countryside Information System (CIS) data was used to estimate these areas. It was assumed that these proportions would be the same for all agricultural land at the catchment and national scale.

Table 14. Proportion of land under infrastructure (and excluded from the analysis)

	Proportion of land as infrastructure (%)			
	Erosion Risk Class			
Land use	Low	Moderate	High	Organo-mineral soils and peats
Horticulture	15%	15%	15%	15%
Arable intensive	15%	15%	15%	15%
Arable extensive	15%	15%	15%	15%
Grassland improved	10%	10%	10%	10%
Grassland unimproved	10%	10%	10%	10%
Rough grassland	2%	2%	2%	2%
Forestry	2%	2%	2%	2%
Woodland	-	-	-	-
Wildscape	-	-	-	-

6.4. Calculating annual on-site costs

6.4.1. Erosion induced productivity loss

The effect of soil erosion on crop yields is frequently given in relation to a change in soil depth (Lal, 1998; Pimentel et al., 1995). Observed reductions show wide variation, depending on the crop rooting trait (some crops are deeper rooted than others), nutrient storage and availability, water holding capacity, soil profile characteristics, the crop grown, existing soil and crop management, and the microclimate (Lal, 1998; Pimentel et al., 1995). It could be seen that there is also a loss of opportunity in which crops can continue to grow in eroded (i.e. shallower) soils. This may require change in crop type and even land use. Since erosion induced yield declines are of considerable importance, especially in low input agriculture, tools such as EPIC (Williams, Renard and Dyke, 1983) have been developed to examine long-term effects of various components of soil erosion on crop production. Here, a simplified approach was developed, using the relationships developed by Pimentel et al. (1995). Based on a variety of measured data, Pimentel et al. (1995) found that crop yields declined by 20% over a period of 20 years (Table 15).

Table 15. Erosion induced yield penalty, based on Pimentel et al. (1995)

	Yield penalty (%)		
Parameter associated with soil erosion	**20 year total**	**Average annual**	**per mm soil loss**
Water runoff	7	0.35	0.3
Nitrogen loss Phosphorus loss Potassium loss	8	0.4	0.3
Soil depth loss	7	0.35	0.3
Organic matter loss	4	0.2	0.1
Water holding capacity loss	2	0.1	0.1
Soil biota loss	1	0.05	0.0
Total on-site losses	20	1	0.74

The following example can illustrate the approach. Assuming soil was eroded at a mean rate of 17 t ha^{-1} yr^{-1} and the bulk density was 1.25 Mg/m^3, the annual loss of soil depth would be estimated to be 1.36 mm yr^{-1} using Equation 5. This therefore equated to a yield loss of 0.74% per mm of soil loss = 1% yield loss per annum for a soil depth loss of 1.36 mm due to erosion.

Depth of soil loss per annum (mm yr $^{-1}$)

$$= \frac{\textbf{Mass of soil loss per unit area per year (tonnes/ha/yr)}}{\textbf{Bulk density of soil (Mg/m}^3\textbf{)}} \div \mathbf{10}$$

Equation 5

The bulk density (Mg/m^3) of soils in each of the 5 case study catchments and for the national scale was determined using a set of (as yet unpublished) regression equations; one to predict the bulk density of mineral topsoils and a separate one to predict the bulk density of organic top soils, based on the proportion of carbon and clay (mineral soils) and carbon concentration (peaty soils) derived from the SSKIB dataset. As an illustration, the bulk density values for each land use and Erosion Risk Class for Scotland as a whole (national scale) are given in Table 16. The values for each of the case study catchments are given in Appendix 3. The data for each of the catchments and for the country as a whole were then used in Equation 5 to derive the depth of soil loss per annum from the rate of soil loss given for each land use in Table 8. The results for soil depth loss for Scotland as a whole are shown in Table 17.

Table 16. Soil bulk density values obtained for Scotland

	Bulk density (Mg/m^3)			
	Erosion Risk Class			
Land use	**Low**	**Moderate**	**High**	**Organo-mineral soils and peats**
Horticulture	1.30	1.09	1.13	0.18
Arable intensive	1.44	1.29	1.13	0.18
Arable extensive	1.53	1.40	1.41	0.22
Grassland improved	1.41	1.45	1.11	0.15
Grassland unimproved	1.57	1.14	0.41	0.10
Rough grazing	1.07	1.06	0.62	0.12
Rough grass	1.10	0.98	0.62	0.05
Forestry	1.53	1.40	1.41	0.22
Woodland	1.63	1.31	0.83	0.12
Wildscape	0.70	0.49	0.33	0.05

Table 17. Soil depth loss (mm yr^{-1}) for land use categories and Erosion Risk Classes for Scotland.

	Soil depth loss (mm yr^{-1})			
	Erosion Risk Class			
Land use	**Low**	**Moderate**	**High**	**Organo-Mineral soils and peats**
Horticulture	0.26	0.30	0.27	4.11
Arable intensive	0.30	0.33	0.31	5.87
Arable extensive	0.16	0.17	0.17	2.31
Grassland improved	0.21	0.21	0.27	0.68
Grassland unimproved	0.13	0.18	0.50	0.38
Rough grassland	0.07	0.07	0.12	0.35
Forestry	0.04	0.05	0.07	0.08
Woodland	0.04	0.05	0.07	0.11
Wildscape	0.09	0.12	0.18	0.26

In order to calculate the impact of erosion on the loss of yield using the calculated soil depth losses, a production model was developed based on the proportion of crops in each land use / erosion risk class category. The area of those categories that were “unknown” in the spatial data were distributed to the known categories in proportion to their occurrence. The distribution was then simplified, as appropriate, to the key crops that were used in the modelling.

Crop yield data and crop sale values for these land use/ erosion risk class categories were developed from The Farm Management Handbook 2018/19 (SAC Consulting, 2018), cofunded by the Scottish Government and EU as part of the SRDP Farm Advisory Service. Grass yields for peat were taken from Morris et al. (2010) and the annual per hectare yield of timber was developed from Forestry Commission data for timber production and values (Haw, 2017).

6.4.2. Erosion induced nutrient loss

The mean organic carbon (C; % by weight of air-dried soil), nitrogen (N), phosphorus (P) and potassium (K) concentrations (mg kg^{-1} of air-dried soil) of each of the Soil Erosion Risk Classes were calculated for each catchment and at the national scale from the data held within the Scottish Soils Knowledge and Information Base (SSKIB). This dataset comprises summary data derived from the soil profile data held within the Scottish Soils Database for the main Scottish Soil Series. Organic C content (% by weight of air-dried soil) for top soils was derived primarily by CN analyser or by dichromate digestion. Total P concentration was determined by colorimetric methods following sodium hydroxide fusion and using a Discrete Analyser. K concentrations (mg kg^{-1}) were determined by inductively coupled plasma emission spectrometry in a ammonium acetate solution. N concentrations (mg kg^{-1}) were mainly determined by CN analyser. The data to calculate nutrient loss was derived for each of the 5 individual catchments and for Scotland as a whole for the national scale erosion costings (Appendix 4 - 7). Results for C and nutrient contents at the national scale are shown in Table 18; Table 19; Table 20; and Table 21.

Table 18. The mean carbon content values (kg t^{-1}) for Scotland

	Soil erosion risk class			
Land Use	Low	Moderate	High	Organo-mineral soils and peats
Horticulture	43.33	35.82	30.19	283.19
Arable intensive	48.54	39.12	30.19	283.19
Arable extensive	50.71	48.23	41.64	352.05
Grassland improved	58.77	70.67	86.23	334.56
Grassland unimproved	87.46	137.31	91.91	299.90
Rough grassland	76.73	127.55	102.73	361.97
Forestry	56.74	124.53	155.77	467.11
Woodland	72.87	107.35	135.37	301.59
Wildscape	71.47	86.71	59.61	166.73

Table 19. The mean N content (kg t^{-1}) for Scotland

	Soil erosion risk class			
Land Use	Low	Moderate	High	Organo-mineral soils and peats
Horticulture	3.44	2.60	1.83	11.06
Arable intensive	3.87	2.94	1.83	11.06
Arable extensive	4.04	3.70	2.97	14.14
Grassland improved	4.65	5.44	5.96	14.01
Grassland unimproved	6.09	8.11	4.63	12.41
Rough grassland	5.09	7.95	5.76	14.66
Forestry	4.05	8.05	9.55	18.66
Woodland	5.34	7.05	8.41	12.34
Wildscape	4.16	4.65	3.12	6.73

Table 20. The mean P content (kg t^{-1}) for Scotland

	Soil erosion risk class			
Land Use	Low	Moderate	High	Organo-mineral soils and peats
Horticulture	1.19	0.85	0.76	0.58
Arable intensive	1.31	1.01	0.76	0.58
Arable extensive	1.36	1.25	1.05	0.82
Grassland improved	1.19	0.85	0.76	0.58
Grassland unimproved	1.41	1.63	1.30	0.73
Rough grassland	1.01	1.22	0.71	0.64
Forestry	1.03	1.31	1.15	0.85
Woodland	1.63	1.31	0.83	0.12
Wildscape	0.70	0.49	0.33	0.05

Table 21. The mean K content (kg t^{-1}) for Scotland

	Soil erosion risk class			
Land Use	Low	Moderate	High	Organomineral soils and peats
Horticulture	0.04	0.08	0.07	0.35
Arable intensive	0.13	0.10	0.07	0.35
Arable extensive	0.14	0.13	0.10	0.36
Grassland improved	0.15	0.16	0.17	0.30
Grassland unimproved	0.19	0.21	0.12	0.26
Rough grassland	0.14	0.20	0.15	0.31
Forestry	0.14	0.21	0.25	0.43
Woodland	0.17	0.20	0.22	0.28
Wildscape	0.11	0.11	0.08	0.13

Whilst Table 18 to Table 21 provide data on the quantity of C, N, P and K in the soil, it is worth noting that erosion selectively takes the most important components of the soil first and eroded soils can typically contain three times more nutrients than the soil left behind (Ali, Khan and Bhatti, 2006; Lal, 1998; Sharpley, 1980). Enrichment ratios measure the relative concentrations of nutrients in deposited material and in the soil from which that eroded material came. A range of enrichment ratios and the enrichment ratios used in this study are shown in Table 22. These were used to calculate the eventual quantity of C, N, P and K lost in the eroded material per annum for each of the land use / erosion risk class combinations. It should be noted that it was not possible to differentiate between the bioavailable and total fraction of P and K. The total soil nutrient content was used in the calculations.

Table 22. A range of enrichment ratios uses to show the proportion of nutrients in eroded soils relative to the parent soils and the enrichment ratios used in this study

Nutrient	Range of enrichment ratios	Mean ER
P	1.32 – 3.04 (Zheng et al., 2005) 1.47 (Sharpley, 1985) 2.79 (Ali et al., 2006)	2.15
OC / OMC	1.08 – 1.4 (Zheng et al., 2005) 0.9 – 2.6 (Schiettecatte et al., 2008) 2.00 (Sharpley, 1985) 1.23 (Ali et al., 2006)	1.56
N	0.89 – 1.26 (Zheng et al., 2005) 1.61(Sharpley, 1985) 1.43 (Ali et al., 2006)	1.37
K	2.90 (Ali et al., 2006)	2.90

The value of the soil nutrients was given by the SAC Farm Management Handbook (SAC Consulting, 2018; Table 23) and used to calculate the value of the N, P, K and C lost in the eroded material.

Table 23. The value of soil nutrients (from SAC Farm Management Handbook (2018/19))

Fertiliser cost of N	0.67	£ / kg
Fertiliser cost of P	0.68	£ / kg
Fertiliser cost of K	0.45	£ / kg
Fertiliser cost of C	0.67	£ / kg

6.5. Calculating annual off-site costs

As well as the on-site impacts of erosion, there are a variety of off-site costs incurred each year, associated with the cost of Greenhouse Gas Emissions, and costs associated with reduced environmental and drinking water quality associated with the eroded sediment and nutrients.

6.5.1. Greenhouse gas impact of soil erosion

Greenhouse gases such as methane (CH_4) nitrous oxide (N_2O) and carbon dioxide (CO_2) contribute to climate change. Several studies have estimated the per unit cost of this. For example, Eyre et al. (1997) proposed costs of £63 t^{-1} for CO_2, £263 t^{-1} for CH_4 and £7,530 t^{1} for N_2O. Jacobs and SAC (2008) uses a value of £25 t^{-1} CO_2 based on the shadow price of carbon proposed by Defra. More recently, the EU Emissions Trading System (ETS) has created a market in GHG emissions, which provides a traded carbon price based on abatement costs. Agricultural emissions currently exist outside the ETS, but the UK Government's Department for

Business, Energy and Industrial Strategy (BEIS) (BEIS, 2019) has advised that non-traded carbon prices (£68 t^{-1} CO_2e for 2019) should be used in such cases. It should be noted that these value will increase in future years as carbon trading process increase (Tom McKenna, personal communication). Jacobs and SAC (2008) has provided ratios (21:1 for CH_4 and 310:1 for N_2O) to calculate global warming potential (GWP) for other GHG gases giving a per unit cost of £1,428 t^{-1} CH_4 and £20,080 t^{-1} N_2O.

However, in the present study, no data on methane or nitrous oxide emissions specifically linked to soil erosion were found. Some studies refer to management practices that will reduce GHG emissions whilst also controlling soil erosion (Jarecki and Lal, 2006; Johnson et al., 2007; Smith and Olesen, 2010). However, they do not quantify the amount of these GHGs that are associated with soil erosion. Ball (2013) draws on research from Scotland, Japan and New Zealand to examine how soil structures affected by wheel compaction, animal trampling, tillage and land-use change influence GHG emissions in order to help identify key controlling properties, but soil erosion is not mentioned explicitly.

Whilst many papers (e.g. Powlson et al. (2011) outline the importance of the stock of soil C in climate regulation, data on the proportion of C in eroded material that is released to the atmosphere to form CO_2 is also lacking. Lal (2003) provides an estimate at a global scale in which he proposes that approximately 20% of the soil C that is eroded each year is emitted to the atmosphere as CO_2. The ratio of organic C in the soil to CO_2 in the atmosphere is given as 3.67 (Williams, Audsley and Sandars, 2006), and the assumed quantity of eroded C emitted to the atmosphere was multiplied by this ratio to obtain its Global Warming Potential (t CO_2e). Using these assumptions, the annual cost of GHG emissions from eroded soils in Scotland was estimated to be £10.881 million (Table 24).

Table 24. The annual cost of GHG emissions from CO_2 emitted from eroded soils in Scotland (national scale)

Land use	GHG cost of soil C loss (£ per annum)				
	Soil Erosion Risk Class				
	Low	**Moderate**	**High**	**Organo mineral soils and peats***	**Total**
Horticulture	55	528	40	62	685
Arable intensive	1,391	25,110	934	11,262	38,698
Arable extensive	26,312	425,092	16,046	302,657	770,107
Grassland improved	57,709	1,700,707	247,893	959,597	2,965,907

Grassland unimproved	677	55,880	122,885	435,721	615,163
Rough grassland	2,155	230,979	342,575	4,084,078	4,659,787
Forestry	1,236	147,471	131,185	817,902	1,097,794
Woodland	1,298	87,036	79,003	118,426	285,763
Wildscape	254	23,568	73,039	350,040	446,901
Total	91,088	2,696,371	1,013,601	7,079,747	10,880,806

* The calculations of all costs for arable and improved grassland on organo-mineral soils and peats may be an overestimate as there is a mismatch in scale between the soil spatial data set and the land use (see Section 8.6 for full explanation).

6.5.2. Impact on watercourses of nutrients lost in eroded material

Whilst the loss of nutrients in eroded material represents the loss of a productive asset, the removal of the N and P into water represent a risk to the quality of the water environment, the costs of which are born by third parties. A summary of those costs associated with eroded soils are shown in Table 25. Figures specific to Scotland were not available, so Table 25 uses data derived previously for England and Wales.

Table 25. Summary of economic data used to estimate off-site cost of soil erosion in the water environment (see sections below for further explanations)

			Value	**Unit**
Environmental water quality	Rivers, canals	NO_3-N	190	£ t^{-1}
	Freshwater lakes	P	1,407	£ t^{-1}
	Transitional water	NO_3-N	10	£ t^{-1}
Drinking water quality	Nitrate	NO_3-N	203	£ t^{-1}
	Sediment	Soil	18	£ t $soil^{-1}$

It is noticeable that data are only available for P in freshwater lakes and NO_3-N only in rivers, canals and transitional waters. This is discussed in Section 10.4.4 below.

6.5.3. Costs of N in rivers and canals

Damage costs to rivers and canals are linked to levels of NO_3-N and the apportionment to agriculture was estimated as £47.4 million (adjusted to 2009 values) in Jacobs and SAC (2008). Since NO_3-N data are not given in Jacobs and SAC (2008), the total of 295,409 t NO_3-N for agriculture in the UK was taken from Defra project WQ0106 (Anthony et al., 2009) giving a 'per unit' damage cost of £161 t^{-1} NO_3-N. This value was inflated to 2019 values using GDP inflators from BEIS (2019) to obtain a cost of £190 t^{-1} NO_3-N.

The off-site damage cost associated with N in the eroded soil in rivers and canals at the national scale was estimated to be £1.858 million per annum (Table 26).

Table 26. The annual costs of N in rivers and canals (£) in Scotland

	Cost of N in rivers and canals (£ per annum)				
	Erosion Risk Classes				
Land use	**Low**	**Moderate**	**High**	**Organomineral soils and peats**	**Total**
Horticulture	14.79	132.10	9.60	8.01	164
Arable intensive	371.48	6,283.13	223.06	1,462.97	8,341
Arable extensive	7,055.54	109,118.05	3,830.23	40,651.08	160,655
Grassland improved	15,362.91	437,726.36	57,343.83	134,270.66	644,704
Grassland unimproved	158.41	11,034.69	20,687.11	60,255.20	92,135
Rough grassland	501.78	48,752.73	64,396.64	553,452.02	667,103
Forestry	294.55	31,887.70	26,885.45	109,197.57	168,265
Woodland	318.07	19,150.08	16,417.44	16,196.62	52,082
Wildscape	49.53	4,219.93	12,763.58	47,242.96	64,276
Total	24,127	668,305	202,557	962,737	1,857,726

6.5.4. Sediment removal by dredging rivers and canals

No figures are available specifically for Scotland. In England and Wales, Anthony et al. (2009) divided the annual costs of dredging sediment out of water courses (£9.8 million in 2009) by the total sediment load (1,906,260 t yr^{-1}) to give a unit cost of £5.2 t^{-1} sediment. This value was inflated in the present project to 2019 values using GDP inflators from BEIS 2019 to obtain a cost of £6.1 t^{-1} eroded material.

From this, the off-site damage cost associated with sediment removal from water courses in Scotland was estimated to be £4.733 million per annum (Table 27).

Table 27. The annual costs of sediment removal in Scottish rivers and canals (£)

	Cost of sediment removal in rivers & canals (£ per annum)				
	Erosion Risk Classes				
Land use	**Low**	**Moderate**	**High**	**Organo-Mineral soils and peats**	**Total**
Horticulture	75	882	64	14	1,036
Arable intensive	1,891	41,966	1,484	2,64	47,986
Arable extensive	34,468	582,662	25,483	56,73	699,350
Grassland improved	65,303	1,593,534	191,011	189,430	2,039,278
Grassland unimproved	515	26,923	88,380	96,06	211,885
Rough grassland	2,286	132,466	221,584	768,540	1,124,876
Forestry	1,454	78,197	55,601	115,826	251,079
Woodland	1,178	53,682	38,620	25,98	119,464
Wildscape	238	17,702	80,917	138,889	237,745
Totals	107,408	2,528,013	703,145	1,394,13	4,732,699

6.5.5. Costs of P loads in lakes / lochs

Graves et al. (2011) estimate the cost of eutrophication in lakes in the UK as £62.6 million
(adjusted to 2009 values) and linked this to an estimated P load of 45% from agriculture (Jacobs and SAC, 2008), giving an apportionment of £28.2 million to agriculture. It should be noted that the apportionment to agriculture varies significantly amongst different sources and has been reported as 29.2% in Defra Project WT0701CSF (White and Hammond, 2006) (Table 28). Since physical units for P are not given in Jacobs and SAC (2008), the total load given for the UK in Defra Project WT0701CSF (43,796 t yr^{-1}) is used as a proxy to develop a 'per unit cost' for phosphorus (£ t^{-1} P) from the total cost in Jacobs and SAC (2008), giving a 'per unit cost' of £1,407 t^{-1} P (Table 25) that can be attributed to the risk of P in lakes / lochs, lost from soils via erosion.

The off-site damage cost associated with the P in eroded soil (sediment) in lakes was estimated to be £3.708 million per annum (Table 29).

Table 28. Total phosphorus input from agricultural, household, industrial and background sources to the waters of England, Scotland, Wales and N. Ireland (source: White and Hammond, Defra project WT0701CSF)

	England	Wales	Scotland	N Ireland	UK
	t yr^{-1}	t yr^{-1}	t yr^{-1}	t yr^{-1}	t yr^{-1}
Agriculture	8,391	2,151	1,223	1,023[a]	12,788
Household	21,677	1,333	2,246	988[b]	26,245
Industrial	645	70	1,179	40	1,934
Background	1,561	243	902	123	2,829
Total	32,274	3,797	5,551	2,174	43,796
Percentage contributions (%)					
Agriculture	26	56.6	22	47.1	29.2
Household	67.2	35.1	40.5	45.4	59.9
Industrial	2	1.8	21.2	1.8	4.4
Background	4.8	6.4	16.2	5.7	6.5
[a] Adjusted for rural population (-107 t TP yr^{-1}) as described by Smith et al. (2005)					
[b] Adjusted for P removal programme (-145 t TP yr^{-1}) as described by Smith et al. (2005)					

Table 29. The annual costs of P in freshwater lakes (£) (Scotland)

Land use	Cost of P in fresh water lakes (£ per annum) Erosion Risk Class: Low	Moderate	High	Organomineral soils and peats	Total
Horticulture	69	622	46	6	743
Arable intensive	1,731	29,572	1,075	1,059	33,437
Arable extensive	32,698	506,520	18,458	32,394	590,070
Grassland improved	64,147	1,792,235	171,749	95,635	2,123,765
Grassland unimproved	527	24,770	27,989	35,602	88,888
Rough grassland	1,619	108,677	108,871	330,570	549,738
Forestry	1,035	71,127	44,388	67,937	184,487
Woodland	1,176	49,740	26,324	9,715	86,954
Wildscape	110	6,683	18,047	25,094	49,934
Total	103,112	2,589,944	416,947	598,012	3,708,016

6.5.6. Costs of N loads in transitional waters

The costs of damage by soil erosion to transitional waters are also linked to nitrate and are estimated from Jacobs and SAC (2008) to be to be £79,147 yr^{-1} (adjusted to 2019 values) for Scotland. The physical data developed by Defra project WQ0106 (Anthony et al., 2009) for nitrate losses by agriculture in England and Wales was used to obtain the 'per unit' value of £8.9 t^{-1} NO_3-N. This value was inflated to 2019 values using GDP inflators from BEIS 2019 to obtain a cost of £10 t^{-1} NO_3-N (Table 25).

The off-site damage cost associated with N in the eroded soil (sediment) in transitional waters was estimated to be £97,775 per annum (Table 30).

Table 30 The annual costs of N in transitional waters (£) (Scotland)

	Cost of N in transitional waters (£ per annum)				
	Erosion Risk Classes				
Land use	**Low**	**Moderate**	**High**	**Organomineral soils and peats**	**Total**
Horticulture	1	7	1	0	9
Arable intensive	20	331	12	77	439
Arable extensive	371	5,743	202	2,140	8,456
Grassland improved	809	23,038	3,018	7,067	33,932
Grassland unimproved	8	581	1,089	3,171	4,849
Rough grassland	26	2,566	3,389	29,129	35,111
Forestry	16	1,678	1,415	5,747	8,856
Woodland	17	1,008	864	852	2,741
Wildscape	3	222	672	2,486	3,383
Total	1,270	35,174	10,661	50,670	97,775

6.5.7. Nitrate removal in drinking water

Removal of nitrate in freshwater imposes costs on water companies. The agricultural apportionment of this is assumed to be 61% giving a total cost (adjusted to 2009 values) of £51 million (Jacobs and SAC, 2008). The agricultural load of NO_3-N (295,409 t yr^{-1}) estimated for England and Wales by Anthony et al. (2009) is used to derive the per unit cost (£ 172 t^{-1} NO_3-N) for removal of nitrate from drinking water (in that case associated with livestock applications on grassland, but the removal costs will be the same, whatever the mechanism of getting the nitrate into the sources of drinking water). This value was inflated to 2019 values using GDP inflators from BEIS 2019 to obtain a cost of £203 t^{-1} NO_3-N (Table 25).

The off-site damage cost associated with the N in eroded soil in drinking water was estimated to be £1.985 million per annum (Table 31).

Table 31. The annual costs of N removal in drinking water (£) (Scotland)

	Cost of N in drinking water (£ per annum)				
	Erosion Risk Class				
Land use	**Low**	**Moderate**	**High**	**Organo mineral soils and peats**	**Total**
Horticulture	16	141	10	9	176
Arable intensive	397	6,713	238	1,563	8,911
Arable extensive	7,538	116,584	4,092	43,432	171,647
Grassland improved	16,414	467,676	61,267	143,458	688,815
Grassland unimproved	169	11,790	22,103	64,378	98,439
Rough grassland	536	52,088	68,803	591,320	712,747
Forestry	315	34,069	28,725	116,669	179,778
Woodland	340	20,460	17,541	17,305	55,646
Wildscape	53	4,509	13,637	50,475	68,674
Total	25,778	714,031	216,416	1,028,609	1,984,833

6.5.8. Sediment removal in drinking water

The total cost of sediment removal is assumed to be 50% of OFWAT's 'other' expenditure (Jacobs and SAC, 2008). This gives a total cost of sediment removal of £38.6 million. Agriculture is assumed to contribute about 75% of the total sediment load in watercourses (Collins et al., 2012), suggesting a cost of £29 million to remove this sediment. If this number is divided by the total load of sediment from agriculture (given as 1,906 kt yr^{-1} by Anthony et al. (2009) for England and Wales (in the absence of equivalent figures specifically for Scotland)), this gives a per unit cost of £15.4 t^{-1} sediment. This value was inflated to 2019 values using GDP inflators from BEIS 2019 to obtain a cost of £18 t^{-1} erosion.

The off-site damage cost associated with sediment removal in drinking water was estimated to be £16.542 million per annum (Table 32).

Table 32. The annual costs of sediment removal in drinking water (£) (Scotland)

	Cost of sediment removal in drinking water (£ per annum)				
	Erosion Risk Classes				
Land use	**Low**	**Moderate**	**High**	**Organomineral soils and peats**	**Total**
Horticulture	263	3,084	223	51	3,621
Arable intensive	6,610	146,677	5,187	9,245	167,719
Arable extensive	120,470	2,036,487	89,067	198,306	2,444,330
Grassland improved	228,243	5,569,634	667,612	662,085	7,127,575
Grassland unimproved	1,800	94,098	308,902	335,767	740,568
Rough grassland	7,989	462,989	774,468	2,686,159	3,931,605
Forestry	5,083	273,309	194,335	404,830	877,557
Woodland	4,118	187,626	134,984	90,816	417,543
Wildscape	831	61,872	282,815	485,436	830,955
Totals	375,407	8,835,775	2,457,594	4,872,696	16,541,473

7. Modelling results

The results for each case study catchment and the national picture are given below. All figures are on a 'per annum' basis. Costs are itemised to show detail, then summed to give:

- Total on-site costs;
- Total off site costs (with drinking water costs);
- Total off-site costs (without drinking water costs);
- Total costs (with drinking water costs);
- Total costs (without drinking water costs).

At present, the Ugie is the only catchment where drinking water is abstracted (so incurring greater costs associated with water treatment). However, these costs have also been presented for the other 4 catchments, to reflect any future plans to abstract drinking water from these catchments

The annual costs of soil erosion in each catchment are given in Tables 33, 34, 35, 36 and 37 for the Ugie, Pow, Girvan, Esk and Tweed catchments respectively. Summary tables for all catchments are given in Table 38

Detailed tables of annual costs for the Ugie catchment (as an illustration) are shown in Appendix 9.

7.1. Catchment 1: Ugie

Table 33. Annual costs of soil erosion in the Ugie catchment

Physical data	Total Catchment area (ha)	29,878
	Total areas at risk within catchment (ha)	3,632
	Proportion at risk (%)	12%
	Soil depth loss (mm yr^{-1})	0.29
	Catchment soil erosion (t yr^{-1})	7,392
	Average catchment soil erosion (t ha^{-1} yr^{-1})	0.25
	Soil N loss (t yr^{-1})	54
	Soil P loss (t yr^{-1})	19
	Soil K loss (t yr^{-1})	3
	Soil C loss (t yr^{-1})	1077
On-site costs	Total catchment productivity loss due to erosion (£)	8,829
	Catchment productivity loss due to erosion in risk area (£ ha^{-1})	2.4
	Total catchment productivity loss due to erosion in total area (£ ha^{-1})	0.3
	Total catchment N loss cost due to erosion (£)	36,328
	Average catchment N loss cost due to erosion (£ ha^{-1} risk area)	10
	Average catchment N loss cost due to erosion (£ ha^{-1} category area)	1.2
	Total catchment P loss cost due to erosion (£)	13,076
	Average catchment P loss cost due to erosion (£ ha^{-1} risk area)	3.60
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.44
	Total catchment K loss cost due to erosion (£)	1,329
	Average catchment K loss cost due to erosion (£ ha^{-1} risk area)	0.37
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.04
	Total catchment C loss cost due to erosion (£)	718
	Average catchment C loss cost due to erosion (£ ha^{-1} risk area)	0.20
	Average catchment C loss cost due to erosion (£ ha^{-1} category area)	0.02
Off-site costs	Cost of sediment removal in rivers & canals (£)	38,066
	Cost of sediment removal in drinking water (£)	133,048
	Cost of N in rivers and lakes (£)	10,302
	Cost of N in transitional waters (£)	542
	Cost of N in drinking water (£)	11,007
	Cost of P in freshwater lakes (£)	31,902
	GHG cost of soil C loss (£)	53,767
Total costs	**Total onsite cost**	60,281

	Total offsite cost (with drinking water costs)	278,634
	Total offsite cost (without drinking water cost)	134,580
	Total costs with drinking water costs	338,915
	Total costs without drinking water	194,861
	Total cost / ha (without drinking water) (£ ha^{-1})	6.52
	Total cost / ha (with drinking water) (£ ha^{-1})	11.34

7.2. Catchment 2: The Pow

Table 34. Annual costs of soil erosion in the Pow catchment

Physical data	Total Catchment area (ha)	4,332
	Total areas at risk within catchment (ha)	511
	Proportion at risk (%)	12%
	Soil depth loss (mm yr^{-1})	0.21
	Catchment soil erosion (t yr^{-1})	1,016
	Average catchment soil erosion (t ha^{-1} yr^{-1})	0.25
	Soil N loss (t yr^{-1})	4
	Soil P loss (t yr^{-1})	2
	Soil K loss (t yr^{-1})	0
	Soil C loss (t yr^{-1})	81
On-site costs	Total catchment productivity loss due to erosion (£)	1,042
	Catchment productivity loss due to erosion in risk area (£ ha^{-1})	2
	Total catchment productivity loss due to erosion in total area (£ ha^{-1})	0.2
	Total catchment N loss cost due to erosion (£)	3,010
	Average catchment N loss cost due to erosion (£ ha^{-1} risk area)	6
	Average catchment N loss cost due to erosion (£ ha^{-1} category area)	0.7
	Total catchment P loss cost due to erosion (£)	1,465
	Average catchment P loss cost due to erosion (£ ha^{-1} risk area)	2.86
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.34
	Total catchment K loss cost due to erosion (£)	154
	Average catchment K loss cost due to erosion (£ ha^{-1} risk area)	0.30
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.04
	Total catchment C loss cost due to erosion (£)	54
	Average catchment C loss cost due to erosion (£ ha^{-1} risk area)	0.11

	Average catchment C loss cost due to erosion (£ ha^{-1} category area)	0.01
Off-site costs	Cost of sediment removal in rivers & canals (£)	5,230
	Cost of sediment removal in drinking water (£)	18,280
	Cost of N in rivers and lakes (£)	854
	Cost of N in transitional waters (£)	45
	Cost of N in drinking water (£)	912
	Cost of P in freshwater lakes (£)	3,573
	GHG cost of soil C loss (£)	4,059
Total costs	**Total onsite cost**	5,724
	Total offsite cost (with drinking water costs)	32,953
	Total offsite cost (without drinking water cost)	13,761
	Total costs with drinking water costs	38,677
	Total costs without drinking water	19,485
	Total cost / ha (without drinking water) (£ ha^{-1})	4.50
	Total cost / ha (with drinking water) (£ ha^{-1})	8.93

7.3. Catchment 3: Girvan

Table 35. Annual costs of soil erosion in the Girvan catchment

Physical data	Total Catchment area (ha)	23,393
	Total areas at risk within catchment (ha)	3,533
	Proportion at risk (%)	15%
	Soil depth loss (mm yr^{-1})	0.20
	Catchment soil erosion (t yr^{-1})	4,652
	Average catchment soil erosion (t ha^{-1} yr^{-1})	0.20
	Soil N loss (t yr^{-1})	33
	Soil P loss (t yr^{-1})	11
	Soil K loss (t yr^{-1})	2
	Soil C loss (t yr^{-1})	605
On-site costs	Total catchment productivity loss due to erosion (£)	4,236
	Catchment productivity loss due to erosion in risk area (£ ha^{-1})	1.20
	Total catchment productivity loss due to erosion in total area (£ ha^{-1})	0.18
	Total catchment N loss cost due to erosion (£)	22,182
	Average catchment N loss cost due to erosion (£ ha^{-1} risk area)	6.28
	Average catchment N loss cost due to erosion (£ ha^{-1} category area)	0.95
	Total catchment P loss cost due to erosion (£)	7,236
	Average catchment P loss cost due to erosion (£ ha^{-1} risk area)	2.05

	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.31
	Total catchment K loss cost due to erosion (£)	881
	Average catchment K loss cost due to erosion (£ ha^{-1} risk area)	0.25
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.04
	Total catchment C loss cost due to erosion (£)	403
	Average catchment C loss cost due to erosion (£ ha^{-1} risk area)	0.11
	Average catchment C loss cost due to erosion (£ ha^{-1} category area)	0.02
Off-site costs	Cost of sediment removal in rivers & canals (£)	23,959
	Cost of sediment removal in drinking water (£)	83,740
	Cost of N in rivers and lakes (£)	6,291
	Cost of N in transitional waters (£)	331
	Cost of N in drinking water (£)	6,721
	Cost of P in freshwater lakes (£)	17,654
	GHG cost of soil C loss (£)	30,187
Total costs	**Total onsite cost**	34,939
	Total offsite cost (with drinking water costs)	168,882
	Total offsite cost (without drinking water cost)	78,421
	Total costs with drinking water costs	203,821
	Total costs without drinking water	113,360
	Total cost / ha (without drinking water) (£ ha^{-1})	4.85
	Total cost / ha (with drinking water) (£ ha^{-1})	8.71

7.4. Catchment 4: The Esk

Table 36. Annual costs of soil erosion in the Esk catchment

Physical data	Total Catchment area (ha)	51,763
	Total areas at risk within catchment (ha)	8,834
	Proportion at risk (%)	0.17
	Soil depth loss (mm yr^{-1})	0.20
	Catchment soil erosion (t yr^{-1})	9,140
	Average catchment soil erosion (t ha^{-1} yr^{-1})	0.18
	Soil N loss (t yr^{-1})	71
	Soil P loss (t yr^{-1})	19
	Soil K loss (t yr^{-1})	5
	Soil C loss (t yr^{-1})	1,680
On-site costs	Total catchment productivity loss due to erosion (£)	11,196
	Catchment productivity loss due to erosion in risk area (£ ha^{-1})	1.27

	Total catchment productivity loss due to erosion in total area (£ ha^{-1})	0.22
	Total catchment N loss cost due to erosion (£)	47,302
	Average catchment N loss cost due to erosion (£ ha^{-1} risk area)	5.35
	Average catchment N loss cost due to erosion (£ ha^{-1} category area)	0.91
	Total catchment P loss cost due to erosion (£)	12,600
	Average catchment P loss cost due to erosion (£ ha^{-1} risk area)	1.43
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.24
	Total catchment K loss cost due to erosion (£)	2,125
	Average catchment K loss cost due to erosion (£ ha^{-1} risk area)	0.24
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.04
	Total catchment C loss cost due to erosion (£)	1,120
	Average catchment C loss cost due to erosion (£ ha^{-1} risk area)	0.13
	Average catchment C loss cost due to erosion (£ ha^{-1} category area)	0.02
Off-site costs	Cost of sediment removal in rivers & canals (£)	47,069
	Cost of sediment removal in drinking water (£)	164,511
	Cost of N in rivers and lakes (£)	13,414
	Cost of N in transitional waters (£)	706
	Cost of N in drinking water (£)	14,332
	Cost of P in freshwater lakes (£)	30,740
	GHG cost of soil C loss (£)	83,831
Total costs	**Total onsite cost**	74,343
	Total offsite cost (with drinking water costs)	354,603
	Total offsite cost (without drinking water cost)	175,760
	Total costs with drinking water costs	428,946
	Total costs without drinking water	250,103
	Total cost / ha (without drinking water) (£ ha^{-1})	4.83
	Total cost / ha (with drinking water) (£ ha^{-1})	8.29

7.5. Catchment 5: The Tweed

Table 37. Annual costs of soil erosion in the Tweed catchment

Physical data	Total Catchment area (ha)	351,190
	Total areas at risk within catchment (ha)	53,901
	Proportion at risk (%)	15%
	Soil depth loss (mm yr^{-1})	0.20
	Catchment soil erosion (t yr^{-1})	66,220
	Average catchment soil erosion (t ha^{-1} yr^{-1})	0.19
	Soil N loss (t yr^{-1})	525
	Soil P loss (t yr^{-1})	160
	Soil K loss (t yr^{-1})	35
	Soil C loss (t yr^{-1})	10,258
On-site costs	Total catchment productivity loss due to erosion (£)	66,941
	Catchment productivity loss due to erosion in risk area (£ ha^{-1})	1.24
	Total catchment productivity loss due to erosion in total area (£ ha^{-1})	0.19
	Total catchment N loss cost due to erosion (£)	351,722
	Average catchment N loss cost due to erosion (£ ha^{-1} risk area)	6.53
	Average catchment N loss cost due to erosion (£ ha^{-1} category area)	1.00
	Total catchment P loss cost due to erosion (£)	108,668
	Average catchment P loss cost due to erosion (£ ha^{-1} risk area)	2.02
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.31
	Total catchment K loss cost due to erosion (£)	15,684
	Average catchment K loss cost due to erosion (£ ha^{-1} risk area)	0.29
	Average catchment P loss cost due to erosion (£ ha^{-1} category area)	0.04
	Total catchment C loss cost due to erosion (£)	6,839
	Average catchment C loss cost due to erosion (£ ha^{-1} risk area)	0.13
	Average catchment C loss cost due to erosion (£ ha^{-1} category area)	0.02
Off-site costs	Cost of sediment removal in rivers & canals (£)	341,032
	Cost of sediment removal in drinking water (£)	1,191,956
	Cost of N in rivers and lakes (£)	99,742
	Cost of N in transitional waters (£)	5,250

	Cost of N in drinking water (£)	106,566
	Cost of P in freshwater lakes (£)	265,117
	GHG cost of soil C loss (£)	512,012
Total costs	**Total onsite cost**	549,854
	Total offsite cost (with drinking water costs)	2,521,675
	Total offsite cost (without drinking water cost)	1,223,153
	Total costs with drinking water costs	3,071,529
	Total costs without drinking water	1,773,007
	Total cost / ha (without drinking water) (£ ha^{-1})	5.05
	Total cost / ha (with drinking water) (£ ha^{-1})	8.75

7.6. Summary of catchment scale costs of soil erosion per annum

Tables 38 - 42 summarise the annual costs of soil erosion for each of the 5 case study catchments, by land use type, land use area and Erosion Risk Class. Areas occupied by each land use are given in Appendix 9.1 and in Tables 38 - 42. Table 43 gives an overview of all on-site and off-site costs (£) for all catchments. Table 44 gives the costs per hectare for each of the case study catchments. Finally, Table 45 gives the ranges of output values for all catchments.

Table 38. Summary of annual costs of soil erosion for the Ugie catchment (including drinking water treatment costs) L = Low, M = Moderate, H = High erosion risk class

Ugie		**Onsite and offsite costs (£ per annum)**				**Total (£)**	**% of total**
Land use	**Area (ha)**	**Erosion Risk Class**					
		L	**M**	**H**	**Organomineral soils and peats**		
Urban	320	-	-	-	-	-	-
Horticulture	13	27	425	-	77	529	0%
Arable intensive	177	129	3,285	19	579	4,013	1%
Arable extensive	12,122	5,712	101,754	546	56,952	164,964	49%
Grassland improved	11,583	5,428	115,582	1,563	27,337	149,910	44%
Grassland unimproved	5	-	2	5	39	46	0%
Rough grassland	1,642	82	2,116	36	7,150	9,384	3%

Forestry	2,297	62	3,070	61	2,558	5,752	2%
Woodland	1,015	54	1,993	39	468	2,554	1%
Wildscape	705	8	153	-	1,603	1,764	1%
Total	**29,878**	**11,501**	**228,380**	**2,270**	**96,764**	**338,915**	**100%**
% of total	100%	3%	67%	1%	29%	100%	

Table 39. Summary of annual costs of soil erosion for the Pow catchment (including drinking water treatment costs) L = Low, M = Moderate, H= High erosion risk class

Pow		**Onsite and offsite costs (£ per annum)**				**Total (£)**	**% of total**
Land use	**Area (ha)**	**Erosion Risk Class**					
		L	**M**	**H**	**Organominerals soils and peats**		
Urban	80	-	-	-	-	-	-
Horticulture	-	-	-	-	-	-	0%
Arable intensive	48	1	953	8	499	1,462	4%
Arable extensive	2,268	700	18,909	1,172	3,878	24,660	64%
Grassland improved	811	437	7,672	777	290	9,175	24%
Grassland unimproved	-	-	-	-	-	-	0%
Rough grassland	82	5	229	12	23	269	1%
Forestry	715	23	1,678	269	253	2,223	6%
Woodland	293	15	528	110	142	795	2%
Wildscape	35	0	89	-	3	93	0%
Total	**4,332**	**1,181**	**30,059**	**2,349**	**5,088**	**38,677**	**100%**
% of total	100%	3%	78%	6%	13%	100%	

Table 40. Summary of annual costs of soil erosion for the Girvan catchment (including drinking water treatment costs) L = Low, M = Moderate, H = High erosion risk class

Girvan		**Onsite and offsite costs (£ per annum)**				**Total (£)**	**% of total**
Land use	**Area (ha)**	**Erosion Risk Class**					
		L	**M**	**H**	**Organomineral soils and peats**		
Urban	169	-	-	-	-	-	-
Horticulture	-	-	-	-	-	-	0%
Arable intensive	62	92	814	-	-	907	0%
Arable extensive	1,053	384	8,397	805	5,290	14,876	7%
Grassland improved	9,177	2,240	107,825	19,148	6,322	135,536	66%
Grassland unimproved	471	-	517	228	3,463	4,207	2%
Rough grassland	3,964	39	8,033	3,416	11,116	22,604	11%
Forestry	6,438	27	7,483	2,645	9,332	19,486	10%
Woodland	1,537	23	3,315	1,011	401	4,750	2%
Wildscape	521	2	409	48	995	1,454	1%
Total	**23,393**	**2,808**	**136,794**	**27,300**	**36,919**	**203,821**	**100%**
% of total	100%	1%	67%	13%	18%	100%	

Table 41 Summary of annual costs of soil erosion for the Esk catchment (including drinking water treatment costs) L = Low, M = Moderate, H = High erosion risk class

Esk		**Onsite and offsite costs (£ per annum)**				**Total (£)**	**% of total**
Land use	**Area (ha)**	**Erosion Risk Class**					
		L	**M**	**H**	**Organo-mineral soils and peats**		
Urban	358	-	-	-	-	-	-
Horticulture	16	28	397	-	-	425	0%
Arable intensive	923	423	16,669	486	609	18,187	4%

Arable extensive	11,635	2,282	106,438	7,237	17,835	133,792	31%
Grassland improved	6,485	1,348	64,198	13,277	15,415	94,237	22%
Grassland unimproved	302	7	495	498	1,451	2,452	1%
Rough grassland	23,191	85	12,388	28,885	113,130	154,487	36%
Forestry	5,920	31	7,312	3,487	6,807	17,637	4%
Woodland	2,559	24	3,543	631	2,531	6,728	2%
Wildscape	374	2	59	285	657	1,002	0%
Total	**51,763**	**4,229**	**211,498**	**54,785**	**158,435**	**428,946**	**100%**
% of total	100%	1%	49%	13%	37%	100%	

Table 42 Summary of annual costs of soil erosion for the Tweed catchment (including drinking water treatment costs) L = Low, M = Moderate, H = High erosion risk class

Tweed		**Onsite and offsite costs (£ per annum)**					
Land use	**Area (ha)**	**Erosion Risk Class**				**Total (£)**	**% of total**
		L	**M**	**H**	**Organo-mineral soils and peats**		
Urban	2,376	-	-	-	-	-	-
Horticulture	1	-	24	-	-	24	0%
Arable intensive	1,222	852	20,031	451	811	22,146	1%
Arable extensive	53,535	24,455	395,297	19,526	215,433	654,710	21%
Grassland improved	90,152	18,896	1,134,338	141,200	62,463	1,356,897	44%
Grassland unimproved	7,607	254	27,587	20,567	30,704	79,112	3%
Rough grassland	108,624	858	148,702	134,886	402,561	687,008	22%
Forestry	66,807	1,053	87,061	43,008	77,470	208,592	7%
Woodland	15,219	509	30,710	10,296	6,013	47,528	2%
Wildscape	5,648	34	2,473	1,597	11,410	15,513	1%
Total	**351,190**	**46,911**	**1,846,223**	**371,531**	**806,865**	**3,071,529**	**100%**
% of total	100%	2%	60%	12%	26%	100%	

Table 43. Summary of on-site and off-site annual costs (£) for all catchments. L = Low, M = Moderate, H = High erosion risk class

Catchment	Area of catchment (ha)	On-site (£)	Off-site (without drinking water) (£)	Off-site (with drinking water) (£)	Total (without drinking water) (£)	Total (with drinking water) (£)
1. Ugie	29,878	60,281	134,580	278,634	194,861	338,915
2. Pow	4,332	5,724	13,761	32,953	19,485	38,677
3. Girvan	23,393	34,939	78,421	168,882	113,360	203,821
4. Esk	51,763	74,343	175,760	354,603	250,103	428,946
5. Tweed	351,190	549,854	1,223,153	2,521,675	1,773,007	3,071,529

Table 44. Summary of annual costs / ha (£ ha^{-1})

Catchment	**Cost / ha (without drinking water) (£ ha^{-1})**	**Cost / ha (with drinking water) (£ ha^{-1})**
1. Ugie	6.52	11.34
2. Pow	4.50	8.93
3. Girvan	4.85	8.71
4. Esk	4.83	8.29
5. Tweed	5.05	8.75

Table 45. Ranges of annual values for the 5 study area catchments

Total catchment areas (ha)	4,332 – 351,190
Total areas at risk within catchments (ha)	511 – 53,901
Proportion at risk (%)	12% - 17%
Soil depth loss (mm yr^{-1})	0.20 – 0.29
Catchment soil erosion (t yr^{-1})	1,016 – 66,220
Average catchment soil erosion (t ha^{-1} yr^{-1})	0.18 – 0.25
Soil N loss (t yr^{-1})	5 – 525
Soil P loss (t yr^{-1})	2 – 160
Soil K loss (t yr^{-1})	0.34 – 35
Soil C loss (t yr^{-1})	81 – 10,258
On site costs £	5,724 – 549,854
Off site costs (without drinking water) £	13,761 - 1,223,153
Off site costs (with drinking water) £	32,953 – 2,521,675
TOTAL COSTS (without drinking water) £	**19,485 – 1,773,007**
TOTAL COSTS (with drinking water) £	**38,677 – 3,071,529**
Cost / ha £ ha^{-1} (without drinking water)	4.50 – 6.52
Cost / ha £ ha^{-1} (with drinking water)	8.29 – 11.34

7.7. The national scale

Glenk et al. (2010) tried to estimate the total costs of soil erosion at the national scale, but concluded that a more case study specific approach was needed first (hence this project). The methodology has been applied successfully to the 5 case study catchments. The same approach was then applied at the national scale, running the economic model with national estimates of land use (to determine soil erosion rate) and Soil Erosion Risk Classes (to determine erosion probability).

A summary of the physical results, and the on-site and off-site costs per annum are shown in Table 46.

Table 46. Total annual costs of soil erosion in Scotland

Physical data	Total area (ha)	7,108,057
	Total areas at risk within catchment (ha)	1,271,735
	Proportion at risk (%)	18%
	Soil depth loss (mm yr^{-1})	0.23
	Catchment soil erosion (t yr^{-1})	918,971
	Average catchment soil erosion (t ha^{-1} yr^{-1})	0.13
	Soil N loss (t yr^{-1})	9,778
	Soil P loss (t yr^{-1})	2,235

	Soil K loss (t yr^{-1})	520
	Soil C loss (t yr^{-1})	218,000
On-site costs	Total Scotland productivity loss due to erosion (£)	1,244,832
	Scotland productivity loss due to erosion in risk area (£ ha^{-1})	1.0
	Total Scotland productivity loss due to erosion in total area (£ ha^{-1})	0.2
	Total Scotland N loss cost due to erosion (£)	6,550,928.0
	Average Scotland N loss cost due to erosion (£ ha^{-1} risk area)	5.2
	Average Scotland N loss cost due to erosion (£ ha^{-1} category area)	0.9
	Total Scotland P loss cost due to erosion (£)	1,519,862
	Average Scotland P loss cost due to erosion (£ ha^{-1} risk area)	1.20
	Average Scotland P loss cost due to erosion (£ ha^{-1} category area)	0.21
	Total Scotland K loss cost due to erosion (£)	234,178
	Average Scotland K loss cost due to erosion (£ ha^{-1} risk area)	0.18
	Average Scotland P loss cost due to erosion (£ ha^{-1} category area)	0.03
	Total Scotland C loss cost due to erosion (£)	145,333
	Average Scotland C loss cost due to erosion (£ ha^{-1} risk area)	0.11
	Average Scotland C loss cost due to erosion (£ ha^{-1} category area)	0.02
Off-site costs	Cost of sediment removal in rivers & canals (£)	4,732,699
	Cost of sediment removal in drinking water (£)	16,541,473
	Cost of N in rivers and lakes (£)	1,857,726
	Cost of N in transitional waters (£)	97,775
	Cost of N in drinking water (£)	1,984,833
	Cost of P in freshwater lakes (£)	3,708,016
	GHG cost of soil C loss (£)	10,880,806
Total costs	**Total onsite cost**	9,695,133
	Total offsite cost (with drinking water costs)	39,803,328
	Total offsite cost (without drinking water cost)	21,277,022
	Total costs with drinking water costs	**49,498,461**
	Total costs without drinking water	**30,972,155**
	Total cost / ha (without drinking water) (£ ha^{-1})	**4.36**
	Total cost / ha (with drinking water) (£ ha^{-1})	**6.96**

8. Discussion of results

8.1. Catchment 1: The Ugie

	Total costs £ per annum (2019 prices)				
	On-site (£)	Off-site (without drinking water) (£)	Off-site (with drinking water) (£)	Total (without drinking water) (£)	Total (with drinking water)(£)
Ugie	60,281	134,580	278,634	194,861	338,915

For total annual on-site costs of soil erosion in the Ugie, 60% and 22% are associated with losses of soil N and soil P respectively through loss of soil via erosion, with only 15% due to losses of crop productivity brought about by reduced rooting depth (water store of plant available water etc.) due to soil erosion. For total annual off-site costs, the highest costs come from having to remove eroded soil (sediment) from waterbodies used for drinking water supplies (48% of total off-site costs), followed by the costs associated with greenhouse gas emissions arising from carbon stored in the soil being exposed to the atmosphere via soil erosion processes (19%). Off site costs are substantially higher than on-site costs (£278,634 (including drinking water costs) versus £60,281 respectively), demonstrating the importance of preventing erosion at source, rather than treating it after it has occurred. Annual costs of soil erosion per hectare of catchment area (including treatment for drinking water) are the highest (£11.34 ha^{-1}) for the Ugie catchment, compared with the other case study catchments.

8.2. Catchment 2: The Pow

	Total costs £ per annum (2019 prices)				
	On-site (£)	Off-site (without drinking water) (£)	Off-site (with drinking water) (£)	Total (without drinking water) (£)	Total (with drinking water)(£)
Pow	5,724	13,761	32,953	19,485	38,677

Of all on-site costs, 53% comes from losses of soil N. Losses of soil P make up 26% of all on-site costs. Crop yield losses due to soil erosion make up 18% of all on-site costs. Most off-site costs (55%) are associated with sediment removal for drinking water (so may be an overestimate as no drinking water abstraction currently takes place). The next largest contribution to off-site costs is removal of sediment from rivers and canals (16% of all off-site costs). The costs of greenhouse gas emissions due to soil erosion contribute 12% of the total off-site costs.

8.3. Catchment 3: The Girvan

	Total costs £ per annum (2019 prices)				
	On-site (£)	Off-site (without drinking water) (£)	Off-site (with drinking water) (£)	Total (without drinking water) (£)	Total (with drinking water)(£)
Girvan	34,939	78,421	168,882	113,360	203,821

15% of the Girvan catchment is considered to be at risk of soil erosion. Most of the annual on-site costs of erosion are related to losses of soil N (£22,182 = 63% of all on-site costs). Annual losses of soil P due to erosion are also important (21% of all on-site costs). Crop yield losses due to erosion cost £4,236 per annum (= 12% of total on-site costs). Half of the total annual off-site costs are associated with removal of sediment from watercourses where drinking water may be abstracted. Costs of N and P in watercourses are relatively low. Costs of greenhouse gas emissions make up 18% of the total off-site costs of soil erosion in the catchment.

8.4. Catchment 4: The Esk

	Total costs £ per annum (2019 prices)				
	On-site (£)	Off-site (without drinking water) (£)	Off-site (with drinking water) (£)	Total (without drinking water) (£)	Total (with drinking water)(£)
Esk	74,343	175,760	354,603	250,103	428,946

As with the other catchments, the majority of annual on-site costs are associated with soil N losses (64% = £47,302) and P losses (£12,600 = 17%). This demonstrates the importance of controlling erosion to keep nutrients on the land / in the soil, rather than washing off during erosion events. If catchment waters are needed for drinking water abstraction (although not the case currently), then this will incur costs of £164,511 for removal of sediment and £14,332 for N removal. This represents 46% and 4% of total offsite costs associated with soil erosion respectively. This is in addition to the annual dredging costs of removing sediment from rivers and canals (estimated to costs £47,069 = 13% of total off-site costs). Almost a quarter of off-site costs are associated with greenhouse gas emissions from soil erosion exposing buried soil carbon (£83,831).

8.5. Catchment 5: The Tweed

	Total costs £ per annum (2019 prices)				
	On-site (£)	Off-site (without drinking water) (£)	Off-site (with drinking water) (£)	Total (without drinking water) (£)	Total (with drinking water)(£)
Tweed	549,854	1,223,153	2,521,675	1,773,007	3,071,529

As the largest of the case study catchments (351,190 ha), total annual soil erosion costs are highest for the Tweed (£1.773 million (without drinking water treatment costs); £3.071 million with drinking water treatment costs). Most on-site costs came from losses in soil nutrients, N (£351,722 = 64% of total on-site costs) and P (£108,668 = 20% of total onsite costs). Reduced yields contributed 12% of the total on-site costs. Off-site costs were incurred when drinking water was treated to remove sediment (47% of total off-site costs). Greenhouse gas emissions were also important costs associated with soil erosion (20% of total off-site costs).

8.6. The national scale

	Total costs £ per annum (2019 prices)				
	On-site (£)	Off-site (without drinking water) (£)	Off-site (with drinking water) (£)	Total (without drinking water) (£)	Total (with drinking water)(£)
Scotland	9,695,133	21,277,022	39,803,328	30,972,155	49,498,461

The total area of the unsealed land use/soil type categories was 7.108 million ha, of which approximately 18% or 1.271 ha was estimated to erode each year at the rates defined for the different land use categories identified for Scotland. This resulted in estimated erosion of 0.9 Mt yr^{-1}, at a mean erosion rate of 0.13 t ha^{-1} yr^{-1}, and implied a mean soil depth loss of 0.23 mm yr^{-1}. Overall, the estimated annual on-site costs of £9.695 million were substantially less than the estimated annual off-site costs of £39.803 million (with drinking water treatment costs) or £21.277 million (without drinking water treatment costs). The annual costs associated with lost productivity were relatively minor (£1.244 million = 13% of all on-site costs) and it is primarily the replacement value of the stock of nutrients (especially N) that are removed in the eroded material that comprise the majority of the on-site costs. The annual off-site costs are primarily associated with a) the cost of removing sediment from drinking water (£16.541 = 42% of all off-site costs million), b) carbon losses through greenhouse gas emissions (£10.880 million = 27% of all off-site costs) and c) sediment removal from water courses (£4.732 million = 12% of all off-site costs).

The calculations of annual costs for arable and improved grassland on organo-mineral soils and peats may be overestimated due to mismatches in scale between the soil spatial data and the land use data and as soil attributes and probabilities of erosion were averaged for both organo-mineral and peat soils. This means that small areas of arable and improved grasslands are predicted to occur on organo-mineral soils and peats which are then estimated to have high erosion rates, higher probability of erosion and greater concentrations of carbon and nitrogen compared to the mineral soils. In reality, these areas are likely to have carbon concentrations close to the threshold between mineral and organo-mineral soils (i.e. around 12% carbon). However, the assigned weighted averages of carbon and nitrogen concentrations are around an order of magnitude greater than mineral soils. This is further compounded by assigning a single probability of erosion risk of 21% to both organo-mineral and peat soils whereas, the organo-mineral soils had a calculated probability of only 12.1% compared with 30% for peats.

For example, while these mismatches may be small in extent (<3% of the land area of Scotland), they are responsible for 12% of the costs of GHG emissions from eroded soils (Table 24) and 9% of the annual cost of removing N from rivers and canals (Table 26).

8.7. National estimates: comparison with England and Wales (Graves et al., 2011)

The current estimates of annual soil erosion costs in Scotland were based on a methodology similar to that used by Graves et al. (2011; 2015) for England and Wales. Meaningful comparison of results is not possible because of the revisions made to the approach used in the present project. Also, market prices used to value soil services and costs of production will have changed since 2011, making the values for England and Wales out of date.

For reference, the on-sites of soil erosion in England and Wales were estimated at £39.874 million (on-site) and £108.153 million (off-site) per annum (Graves et al., 2015), making total annual costs being £148.027 million for England and Wales (2011 prices are used in Graves et al. (2015)).

9. Implications for policy and practice

Policy interventions are needed if soil resources (and the services they provide) are being degraded, compromising progress towards sustainability goals. Policy intervention may also be considered where soil resources are at risk of being degraded. Quantifying the degree and extent of soil erosion can be used to identify priority areas in need of soil protection. Quantifying the costs of soil degradation (here specifically, soil erosion) can be used to justify the need for and expenditure on soil protection interventions that control or even reverse the damage being done to soils. This logic can be applied at the local, regional and national scale.

Table 76 in Appendix 10 provides details of the key policy instruments in Scotland and their applicability to soil erosion. Key highlights from the analysis of current policy / legislation dealing with specifically soil erosion in Scotland are summarised below.

- There is no policy related specifically to soil protection in Scotland (McKee, 2018). Most policy instruments are not explicitly designed to target soil, rather they view soil as an asset that underpins agricultural production, water quality or climate change mitigation (Prager et al., in press).
- It is difficult to define and bound Scottish environmental policies (Prager et al., in press), specifically those that relate to soil. It is not always clear how to map the parent policy to an Act and a delivery mechanism. This has implications for the uptake of mitigation measures for soil erosion.
- In many cases the policy instruments related to soil erosion are framing principles and standards, rather than policies addressing environmental protection and regulation.
- Key regulatory policies relate to only very specific situations, with small areas or areas under low risk scenarios or those that have not been modelled in this

study. For example there are requirements to minimise soil erosion during land development (Environmental Assessment (Scotland) Act) or to minimise disturbance in protected areas (The Conservation of Habitats and Species Regulations).

- Areas that are likely to have high soil erosion risk (due to vulnerable soil type and land use combinations – e.g. intensive arable) have some protection by policy, but this is often limited to specific situations (e.g. implementation of GAEC linked to single farm payments under CAP) or the policy instrument is only a guideline or resource rather than a regulation (e.g. Farming for Climate guidance under the Land Use Strategy in the Climate Change Act). There are therefore are no direct regulatory requirements to minimise soil erosion on agricultural land. Post-CAP, these guidelines should be incorporated into national policies, although their efficacy to prevent soil erosion should be reviewed.
- The offsite impacts on drinking water, which have the greatest offsite costs, are protected by various water environment policies (e.g. Water Environment Regulations). However, these focus on preventing eroded soil reaching water courses (e.g. by putting in barriers or buffer strips) and do not offer guidance or requirements to reduce soil erosion at source. Whilst many surface water catchments in Scotland are not abstracted for drinking water, the Water Environment Regulations should be followed to ensure that waters comply with 'good ecological status' (reflecting the EU Water Framework Directive) to avoid any adverse impact on the aquatic environment.
- Other large offsite costs are the GHG costs of soil carbon lost from eroded soil (as CO_2) and these are primarily associated with peaty soils (organo-mineral and peat soils) under rough grassland. However, the mis-match in scales between national scale soils data and field-scale IACS data means that there is a chance that unlikely land use/soil combinations such as arable production systems with relatively high erosion rates on peat soils with high probability of erosion will occur in the GIS analysis leading to an overestimate of the soil C losses at a national scale. There are many guidance and advice documents advocating minimising soil carbon loss (e.g. Forestry Standard), however there are no specific regulatory frameworks or polices that directly address carbon loss by erosion, especially in these peaty soil types.
- Under forestry land use, the Forestry Standard offers guidance on soil erosion. This sets out guidance for suitable forest management for minimising soil erosion during forestry operations, but these are not statutory requirements.

Mitigation measures for soil erosion have been reviewed in the Literature Review (Appendix 1) and then characterised in terms of their applicability to Scotland, based on discussions with James Hutton Institute staff (Appendix 11). The current analysis identifies the major contributors to the total costs of soil erosion. Having identified these, mitigation measures can be targeted to combat these losses. For example, if significant costs are incurred from the losses of greenhouse gases associated with erosion processes, measures can be targeted to control these losses. Practices could include: avoiding inversion ploughing; adoption of reduced tillage; covering bare soil at all times e.g. cover cropping, companion cropping, stubbles, precious seasons crop residues; sequestering carbon from the atmosphere through high density, quick growing crops; avoiding drainage of peats and organic soils; etc.

The question arises as to who should pay for implementation of mitigation measures, if deemed necessary (i.e. to reduce the costs of soil erosion), which has policy implications. For example, it could be argued that some on-site benefits of soil protection (control of erosion) are accrued directly by individuals (e.g. farmers or growers through sustained production and market forces), so they should be responsible for the costs of soil protection measures. However, other on-site benefits accrue to society as a whole (such as reduction in CO_2 emissions from eroded soil and the impact on climate change), suggesting government subsidies may be appropriate. Off-site costs of erosion and benefits of soil protection tend to accrue to society as a whole too, again suggesting that governmental support could be appropriate and justified.

10. Assumptions, limitations and gaps

10.1. Soil erosion rates

There are few examples of quantified soil erosion rates in Scotland. Often these are related to specific soils, land uses and slopes, so identifying representative rates for a given combination of these variables is challenging. For the purposes of this project, a comprehensive database of erosion observations (>1,680) under a range of field conditions was used to estimate representative erosion rates for a range of land uses (Evans, pers.comm., 31/07/19). However this data was sourced from England and Wales and analysis showed that only some of the data agreed with the progression from Low to High Risk Soil Erosion Risk Classes as developed by Lilly et al. (2002) and Lilly and Baggaley (2014).

The outcome of the project was to estimate a total annual cost of soil erosion, so the erosion rates used should be on an annual basis. However, it is not known if the Evans' data referred to one event or several events, or the duration over which the erosion (and depositional) features had developed. For the purposes of the analysis, it was assumed that the rates of erosion observed by Evans were the equivalent of a representative annual rate. This is likely to be an underestimate of actual erosion that occurs in any one year, but may be an overestimate if the feature has existed for a long time. The latter case is unlikely on arable land due to cultivations and other field operations. The Evans' data was recorded during the 1980s and may not be representative of current (or future) erosion rates. Some researchers argue that soil erosion is being aggravated by climate change and associated extreme weather events, resulting in higher rates (and probabilities) of erosion ((Boardman et al., 1990; Boardman and Favis-Mortlock, 2001; Hough et al, 2010; IPCC, 2019; Mullan, 2013a, 2013b). Finally, it is recognised that most erosion surveys are by their nature biased, as only eroding fields are recorded. However, this limitation was not the case for the observations used in estimating the probability of Scottish soils eroding in any one year.

10.2. Probabilities of soil erosion occurring in any one year / field

Scottish observations were used to estimate the probability of soil erosion occurring in any one field in any one year. NSIS (1978-88) data was used to analyse the probability of erosion for the organo-mineral and peat soils (that are grouped under the "Organo-mineral and peat soils" in the present project). When combined, the probability of erosion was estimated to be 21% (Section 4.3). It is possible to separate these different soil types and estimate the probabilities of erosion in these classes: Peat = 31%; organo-mineral = 12%. However, should the analysis be extended, a L, M and H erosion risk for organo-mineral and peat soils could be undertaken. This would require considerable more time to run the economic model for what would become 6 Erosion Risk Classes (rather than the 4 currently modelled). Also, the evidence base of differentiating associated costs for all 6 Classes is very limited.

Given that Soil Erosion Risk Class was used to determine probability, it should be noted that this classification based on soil texture, slope and HOST class is likely to remain unchanged, even under future climate change scenarios

10.3. Land use

Land use will be a 'snap shot' in time and there will have been changes in land use since the data (LCM2007, IACS and NFI) were collected. However, we have assumed that any changes in land use will cancel out in space and time (i.e. areas going into arable = areas going out of arable etc.). It was also assumed that the spatial / temporal distribution of crops within the arable areas (as part of the arable rotation) would be similar for all catchments (and at the national scale). For arable crops, typical rotations (different crops) may be available from the Scottish Farm Management Handbook (2018/19) (https://www.fas.scot/downloads/farm-management-handbook-2018-19/). IACS returns over several years could identify actual rotational patterns in each catchment. This is particularly important for reseeding of ley grasses within an arable rotation, as this represents a significant increase in erosion rates for that year of reseeding.

The Countryside Information System (CIS) data, aggregated at national level was used to estimate areas of farm infrastructure (that would not be included in the analysis). It was assumed that these proportions would be applicable to all agricultural land at the catchment and national scale.

Soil erosion rates and probabilities for urban areas were excluded from the analysis, due to the paucity of data in the case study catchments and for Scotland as a whole. Soil erosion rates in urban areas are likely to be low due to the high proportion of sealed surfaces. During construction phases, exposure of bare soil and soil disturbance by heavy plant and machinery may cause erosion rates to be much higher (Blum, 1998), but data on this for Scotland was unavailable.

10.4. Assumptions and limitations of the economic model

This assessment of the annual costs of soil degradation largely confirms the difficulties, evident in previous reviews, of deriving complete and reliable estimates of the benefits provided by soils and how these change according to soil condition. There are three aspects to this challenge (i) 'identifying' biophysical relationships between soil properties, soil functions and 'performance' of soils in particular applications (ii) 'valuing' the diverse range of market and non-market benefits and costs attributable to soils in different applications and (iii) assessing the 'dynamics' of soil properties, especially under conditions of climate change, as these affect changes in the supply and value of services.

The ecosystems approach adopted provides a systematic framework for the identification and valuation of soil services, although in many respects it confirms that knowledge is insufficiently complete to allow a full assessment. Furthermore, although some information is available for soil erosion rates and probabilities on specific sites, it is difficult to aggregate this at the regional and national scale to support policy. A number of key gaps and uncertainties can be identified.

There is considerable information and knowledge pertaining to soils that has been developed over time, much of it to support provisioning services (i.e. agricultural production). While this remains a key aspect of soil management, the ecosystems service perspective requires that soil science and management adopt a broader remit to include the wide range of soils functions as they support regulating and cultural services as well as provisioning services.

An attempt was made here to link soil erosion processes to indicators of soil quality (e.g. soil depth and nutrient content) and ecosystem services. Examples include soil erosion rates, loss of soil depth and crop yield. It proved difficult to confidently predict these process/indicator/service relationships, yet this is clearly the way forward if the ecosystems approach is to be comprehensively applied.

A better understanding of the relation between soil erosion and service provision is also needed to inform 'safe' or 'target' indicator levels beyond which ecosystems services might be undesirably or irreversibly compromised. Linked to this, there is clearly a need to better understand how the use of soils drives the relationship between the stock of soil resources, defined in terms of soil quantities and qualities, and the flow of soil-based services. Pressures of more intensive land use and climate change make this a priority.

The ecosystems approach emphasises how soil erosion can reduce the capacity of the stock of soil 'capital' to provide soil services now and into the future. Over utilisation of soils beyond their natural ability to maintain or reinstate their inherent properties leads to degradation of stocks and service flows. In some cases this can be corrected by measures to prevent or minimise degradation, in others by substituting lost soil properties with man-made inputs such as artificial fertiliser. These interventions can be costly.

Further data and knowledge are required to adequately understand the complex relationships between soil stocks and service flows, especially under alternative management scenarios. Associated with this, as referred to earlier, is the issue of critical stocks of soil capital, of thresholds and of non linear effects, whereby soil erosion leads to non marginal, step changes in both stocks and flows. Here, uncertainty-based safe minimum standards, set within a strong regulatory regimes, are appropriate. It is recommended that critical threshold / tolerable values are explored for soil erosion rates and probabilities.

The analysis here clearly shows that there is considerable spatial variability not only in the processes of soil erosion but also in its consequences. The approach of using Soil Erosion Risk Classes and land use in determining soil erosion rates explicitly considers spatial distribution of causes and effects. An appreciation of spatial variation and scale are critical to the assessment of the consequences of soil erosion, especially in the context of diverse ecosystems services.

Variation in time is also important, especially as soil erosion processes and effects can be cumulative over time. There is incomplete understanding of cumulative rates of soil erosion associated with for example soil organic matter loss. This aspect, to develop a better understanding of the relationship between changing soil stocks and diverse service flows over time, is essential for a strategic approach to the management of soil resources. It is recommended that this is a priority for future research.

The analysis has identified a number of gaps and uncertainties in the valuation of service flows that are both specific to soils and generic to the valuation of non market ecosystem services as a whole. The main non market impacts of soil erosion appear to relate to water quality impacts and GHG emissions, all of which are subject to uncertainties in valuation. Water quality impacts will vary considerably according to the sensitivity of local 'receptors', while GHG valuation rests on the social price of carbon (based here on the cost of CO_2 abatement). It is noted that market prices used to value soil service are also uncertain, for example for agricultural inputs and products. For this reason it is important to separate as far as possible biophysical and pricing assumptions, and to generate a range of values to reflect uncertainty.

The calculations of costs for arable and improved grassland on organo-mineral soils and peats may be an overestimate for several reasons. Firstly there is a mismatch in scale between the soil spatial data set and the land use and land management data meaning that some small areas which are unlikely to be cultivated appear on organic soils. Secondly there is an overestimation of the probability of erosion in this soil, land use combination because peat and organo-mineral soils have been grouped into one erosion risk class for the economic analysis. However most of the arable and improved grasslands will be on organo-mineral soils with relatively low soil carbon content and the probability of erosion of these soils from the analysis of the NSIS data, was 12.1% compared with the combined probability of 21% used in the economic model.

It should be noted that the erosion losses/rates do not necessarily mean that all sediment (and associated nutrients) are transported to surface water bodies and some may be retained in-field.

10.4.1. Crop yields in the economic model

When the economic model was applied in England and Wales, crop yields were assumed to vary with soil type (clay, silt, sand and peat). However, in Scotland, soil texture is less differentiated, so it was assumed that it is unlikely that yield will vary much between soil types. In the present study, soil type is taken into account in the Erosion Risk Classes, along with slope and potential to generate runoff. As such, there was no expected relationship between Risk Class and yield. Therefore, for a given crop / land use, the present study used the same crop yield for each Erosion Risk Class. Further studies could test whether representative yields for different crops are sensitive to Erosion Risk Class.

10.4.2. Drinking water extractions

Of the 5 catchments, water is extracted for drinking purposes only in the Ugie catchment. This is reflected in the greater water treatment costs for this catchment. If the other catchments are used for (drinking) water abstractions, then the costs of treating water containing eroded sediment will increase. The results are presented both with and without drinking water treatment costs.

10.4.3. Costs of carbon in water

The project team were unable to find quantified evidence of the amounts, impacts and associated costs of carbon in waterbodies (rivers, canals, lakes, lochs etc.) that is directly associated with soil erosion (and would therefore be an input to the economic model). Whilst there is generic information about DOC (Dissolved

Organic Carbon), particularly in Scottish catchments with peatlands, we cannot say for sure if this DOC has been the direct result of soil erosion processes. For example, it could be the result of non-erosive runoff carrying the DOC. On the other hand, it could be the result of water running over the land which will dislodge particles, causing the organic material to dissolve and be transported (as DOC), along with particulate material.

It could also be argued that POC (Particulate Organic Carbon) is more likely to be associated with soil erosion, but we couldn't find any data that partitioned waterborne C into the DOC v. POC fractions. In any case, according to Duan et al. (2014) "….POC is a small fraction of TOC present in most lakes (with respect to dissolved organic carbon, DOC), ….. (Dhillon and Inamdar, 2013, Son et al., 2009)"…so it is likely that POC is not as big an issue as DOC. Fraser Leith (Scottish Water) confirmed that POC may be as little as 10% of all C in watercourses.

10.4.4. Costs of N in water

The current model includes costs associated with nitrate in water as a result of erosion. This follows the methodology used in Graves et al. (2015). However, it is appreciated that N is usually carried in the water phase rather than associated with particulate material. As with carbon in watercourses, it is very difficult to disentangle N carried in the water flow and that carried by particulate matter that has been eroded. Better understanding of the partitioning of dissolved and particulate N (and C) is therefore needed.

10.4.5. P associated with soil erosion

It is accepted that the economic analysis takes no account of P in rivers / canals, only in lakes / lochs. This is because it is uncertain how much P in rivers and canals is directly attributable to soil erosion. P can result from point or diffuse sources, which may or may not relate to soil erosion processes in the catchment. The project team could not find evidence that linked levels of P in rivers directly to soil erosion events. Most P associated with soil erosion is sorbed onto eroded particles, that are likely to be deposited somewhere in the catchment – possibly in lakes / lochs. Also, the Jacobs and SAC Report (2008), used to estimate the costs of nutrients in watercourses does not give values for P in rivers and canals (although N levels are given and have been taken into account in the economic analysis).

10.4.6. GHG costs

The economic model has not accounted for methane or nitrous oxide emissions due to soil erosion (only carbon). As such, the costs given in this category will be an underestimate. Very little literature was found on the relationship between soil erosion processes and the production of methane and/or nitrous oxide.

10.4.7. Other costs

Costs of roads and properties damages are not included, due to lack of data for Scotland.

10.4.8. Mitigation measures

The economic analysis was also unable to account for the costs of soil erosion mitigation measures at the catchment and national scale. Although costs of mitigation have been reported in the Literature Review, they cannot be included in the economic analysis at the catchment or national scale, because there is no information on the numbers of measures used or their geographical location. This would require mapping these measures at a much finer resolution than used in the present study (e.g. location of field buffer strips; identification of minimum tillage use; etc.).

11. Recommendations for future research

The estimates of the total annual costs of soil erosion in Scotland have been calculated from land uses based on LCM 2007. Land use would be more accurate if based on LCM2015, but this dataset was not available to the team.

No information on current use of soil erosion mitigation measures in the case study catchments (or in Scotland as a whole) was available at the time of the project. If the type (Appendix 11) and location of soil erosion mitigation measures were known, this would improve the accuracy of the estimate of total costs of soil erosion in Scotland. Installation and maintenance of these measures would add to the costs of soil erosion (i.e. costs of controlling soil erosion). However, by controlling soil erosion rates and probabilities (and on-site and off-site impacts), these measures would also reduce the associated costs of these impacts. This identifies another gap in knowledge: how effective those mitigation works would be in controlling soil erosion. It is likely their effectiveness would vary over space and time (Maetens, Poesen and Vanmaercke, 2012; Rickson, 2014). This needs to be better understood if this additional information is to be incorporated into models estimating the total costs of soil erosion. Given the predicted increase in soil erosion rates due to climate change (Boardman et al., 1990; Boardman and Favis-Mortlock, 2001; Hough, Towers and Aalders, 2010; IPCC, 2019; Mullan, 2013a, 2013b; Favis-Mortlock and Mullan, 2011; Nearing, Jetten and Stone, 2005; Nearing, Pruski and O'Neal, 2004), the environmental and economic need for soil erosion mitigation measures is likely to increase.

The current analysis has included organo-mineral soils and peats into one 'soil erosion risk class'. It is recognised that most soils in this category are organo mineral soils, but have been given the same erosion risk class as peats. The results may be different if these 2 soil types were separated (see Section 10.4).

The present study is likely to have underestimated some off-site costs. The figures do not include the costs of P in watercourses (only in freshwater lakes / lochs). This is on the assumption that most P is moved with the sediment and becomes a cost when deposited in still waters (i.e. lakes). The load and concentration of P in rivers and canals is not accounted for (although N is included). Further investigation of the loads, concentrations and impacts of P in watercourses would improve the costs estimates associated with soil erosion.

Better understanding of the partitioning, loads, concentration and impacts of soil carbon losses (including DOC and POC), that are specifically associated with soil erosion would improve the accuracy and reliability of the estimates. Similarly, the present study found no data on methane or nitrous oxide emissions specifically linked to soil erosion, yet these will have environmental and economic impacts, and associated costs.

Future soil research should explore the annual costs of other soil degradation processes (e.g. soil compaction, loss of soil organic matter, loss of soil biodiversity), as was attempted by Graves et al. (2011) for England and Wales. The correlations, trade-offs and synergies amongst different soil degradation processes (e.g. soil erosion and loss of organic matter, compaction and loss of biodiversity) and their economic and other effects should be recognised, particularly where these are cumulative and integrated. Similarly, the multiple beneficial effects of mitigation measures should also be recognised (e.g. measures that control soil compaction will also reduce erosion risk).

The links between soil quality and ecosystem services are best developed for provisioning (mainly agricultural production) and regulating services (water quality, GHG emissions and flooding). Information to reflect the contribution of soils to supporting cultural services, such as landscape, biodiversity, recreation and heritage is less developed. The condition of soils can make a difference to the quality of important and highly valued habitats. They are important in the preservation of archaeological artefacts. They affect the condition of footpaths that provide access to the countryside, and the visual appearance of landscapes. The extent to which this affects the value of services has not been explored to any great extent to date, and has not been developed here. It is recommended that the cultural dimension of soils are assessed to provide a more complete assessment of soil value.

12. Conclusions

Soil erosion was identified as one of the main threats to Scotland's soils in the comprehensive 'State of Scotland's Soil Report' (2011). The Scottish Soils Framework sets out a vision for soils to be "safeguarded for existing and future generations". Soil erosion can result in significant costs, not only to immediate users of soils but also to society as a whole. Climate change projections for Scotland indicate more heavy rainfall days and an increase in winter rainfall, leading to greater risks of soil erosion in the future, making the status of 'Soils and agriculture' in Scotland of 'high concern' (Committee on Climate Change, 2019).

The literature review demonstrates that evidence on soil erosion rates, impacts, mitigation and costs in Scotland tends to be sparse, and anecdotal rather than quantitative. These estimates may have some uncertainty, given the paucity of data.

For the economic analysis, rates of soil erosion had to be estimated from empirical data primarily derived for England and Wales. However, the probability of erosion taking place in any one year / field was based on Scottish field observations and analysis of the Soil Erosion Risk Classes, derived for Scottish conditions.

The ecosystem services framework adopted here assesses the economic costs of soil erosion in terms of its effects on the services provided by soils: provisioning, regulating, supporting and cultural. Inevitably, gaps in the evidence remain, whether it is capturing all the ways in which soil erosion impedes the delivery of ecosystem goods and services; how to put a cost to that effect; and understanding any feedback mechanisms between the erosion process, soil properties and soil functions. Even so, the framework is robust and flexible enough to incorporate more evidence as and when it becomes available. For example, although costs of mitigation have been reported in the Literature Review, they were not included in the economic analysis at the catchment or national scale, because there was no information on the numbers of measures used or their geographical location. This would require mapping these measures at a much finer resolution than used in the present study (e.g. location of field buffer strips; identification of minimum tillage use; etc.).

The present study estimated that the total costs of soil erosion in Scotland per annum are £49,498,461 (including drinking water treatment costs) or £30,972,155 (not including water treatment costs). Annual off-site costs of soil erosion always exceeded those associated with on-site costs for all the 5 study catchments. The same was true at the national scale.

Understanding the impacts and costs of soil erosion will inform national policies and local practices designed to value the soil resource in delivering a range of ecosystem goods and services that support a broad spectrum of human activities and associated benefits.

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14. Appendices

Appendix 1. Literature Review

Developing a method to estimate the costs of soil erosion in high-risk Scottish catchments:

Literature review

PROJECT NO: UCR/004/18 CRF CR/2015/15

Literature Review Executive Summary

Scotland's soils provide economic, social and environmental support to the country, but inappropriate soil management threatens this finite natural resource. Soil erosion was identified as one of the main soil threats in the 'State of Scotland's Soil Report' (2011). Soil loss can result in significant costs, not only to immediate users of soils, but to society as a whole.

This review has collated the evidence on current soil erosion rates; how these are modified by mitigation measures; the associated 'on-site' and 'off-site' impacts of soil erosion; and any costs associated with those impacts. The aim is to estimate the total costs of soil erosion in Scotland. Understanding the costs of soil erosion will inform policies designed to value the soil resource.

The literature review suggests that soil erosion by water is the dominant erosion process in Scotland. Notable soil erosion events are triggered by either high intensity rainfall; prolonged, low intensity rainfall; or rapid snowmelt. Land uses affected include forests and agriculture (especially bare, recently ploughed / seeded arable fields in winter cereals). Observed erosion rates in arable areas of Scotland range from 0.01 t ha^{-1} yr^{-1} to 23.0 t ha^{-1} yr^{-1}, which can exceed an identified tolerable limit of 1 t ha^{-1} yr^{-1}. Limitations of the current evidence base include a tendency to focus on small areas of severe soil erosion, rather than a systematic approach to monitor and assess more insidious erosion. In general, quantified rates for all forms of soil erosion in Scotland remain sparse.

Regarding the on-site impacts of soil erosion, there is very little quantification of the reductions in crop yields due to soil erosion in Scotland. Single soil erosion events rarely cause significant problems for farmers, but over time may impact on the long-term sustainability of the land and can still result in loss of ecosystem goods and services such as crop production, but also carbon sequestration and water storage. These on-site impacts of soil erosion may take a long time to take effect, especially on deeper soils or where inputs of fertilisers can mask yield declines due to soil loss.

Off-site, soil erosion contributes to increased suspended sediments and turbidity in Scottish watercourses, which can diminish water quality and damage aquatic life, including salmon spawning ground and freshwater pearl mussel beds. In general, the greater the proportion of arable cropping in a catchment (and thus soil erosion risk), the greater the increase in suspended sediment load in waterways. However, the present review has found few quantified studies of the off-site impacts of soil erosion in Scotland.

There is some evidence on the use of erosion mitigation measures in Scotland: most was related to practices on forested land. However, monetary costs (and benefits) associated with measures to combat soil erosion and sediment transport are lacking for Scotland.

The ‘on-site’ and ‘off-site’ costs of soil erosion are incurred in many different ways, affecting a diverse range of ecosystems services and benefits to people, over a range of spatial and temporal scales. This makes estimating the costs of soil erosion particularly challenging and may explain the limited quantified evidence on the costs associated with soil erosion in Scotland.

Whilst the literature review demonstrates that evidence on soil erosion rates, impacts, mitigation and costs in Scotland tends to be anecdotal rather than quantitative, there are proven approaches that can estimate these parameters in a logical and justified manner. These estimates may have some uncertainty, given the paucity of data. Even so, this information can then be used to calculate an estimated mean soil erosion rate for different combinations of land use/ soil type/ slope at the local, regional and national scale (along with likely impacts and associated costs).

1. Introduction

Soil erosion is a natural process that is dependent on climate, topography, soil type, vegetation cover, land use and land management. Inappropriate land use and land management can trigger accelerated rates of soil erosion that have both on-site (where the erosion takes place e.g. the field) and off-site (away from the erosion site e.g. road or river) impacts.

Soil erosion was identified as one of the main threats to Scotland's soils in the comprehensive 'State of Scotland's Soil Report' (2011). Within the current Scottish biodiversity strategy, the Scottish Government 'aims to promote the sustainable management and protection of soils, consistent with the economic, social and environmental needs of Scotland' (https://www.gov.scot/policies/biodiversity/soils/). The Scottish Soils Framework sets out a vision for soils to be "safeguarded for existing and future generations". It is recognised that soils provide a range of ecosystem goods and services that support a broad spectrum of human activities and associated benefits (**Table 47**). The continued provision of benefits from soil depends on successfully maintaining its physical, chemical and biological properties. However, evidence suggests that the way soils are currently used degrades the resource (e.g. by soil erosion) resulting in loss of soil quantity and quality, along with the functions that soils support and the ecosystem goods and services delivered by these functions. This can result in significant costs, not only to immediate users of soils but also to society as a whole. Climate change projections for Scotland indicate more heavy rainfall days and an increase in winter rainfall, leading to greater risks of soil erosion in the future, making the status of 'Soils and agriculture' in Scotland of 'high concern' (Committee on Climate Change, 2019).

The aim of this review is to determine the total costs of soil erosion in Scotland. This will be based on the evidence of:

- The current soil erosion rates in Scotland;
- The on-site and off-site impacts of soil erosion in Scotland;
- The use of mitigation measures that are used to control soil erosion in Scotland.

The review will be used to identify gaps in current knowledge and to propose ways to fill these gaps in order to develop a practical method to estimate on-site and off-site costs of soil erosion in Scotland. While four forms of soil erosion are recognised (erosion by water, wind and tillage, and by co-extraction on harvested crops and/or vehicles), soil erosion by water is considered to contribute the most to the national levels of soil erosion (Owens et al., 2006). This review will consider all forms of soil erosion to assess the evidence base for Scotland, but the wider project will focus on erosion by water.

Table 47. Millennium Ecosystem Assessment categories of ecosystem services and examples relating to soil (adapted from a table in Defra, 2007)

Category	Examples of ecosystem services provided by soil
Provisioning services i.e. products obtained from ecosystems	• Food • Fibre and fuel • Genetic resources
Regulating services i.e. benefits obtained from the regulation of ecosystem processes	• Climate regulation • Water regulation • Water purification/detoxification • Bioremediation of waste
Cultural services i.e. non-material benefits that people obtain through spiritual enrichment, cognitive development, recreation etc.	• Spiritual and religious value • Inspiration for art, folklore, architecture etc • Social relations • Aesthetic values • Cultural heritage • Recreation and ecotourism
Supporting services, necessary for the production of all other ecosystem services	• Soil formation and retention • Nutrient cycling • Primary production • Water cycling • Provision of habitat

2. Methodology

Using the approach of Denyer and Tranfield (2009), a semi-structured systematic review of the literature (journal articles, reports and grey literature) and other data sources was undertaken. The structure of the review consisted of an initial search based on key words and phrases anywhere in an article (listed in Table 48). This list was then sifted, based on key words in title and abstract, and a quick search of the document looking for key word relevance. Documents that made it through the sift were then reviewed using a structured matrix template to extract information consistently and systematically from all documents. The structured matrix, with an example, is presented in Appendix A.

Table 48. Search terms used in literature review

Search term	Google Scholar / Scopus (value outside bracket is limited to 2010-2019 publications; inside bracket is not time limited.)
"Review" AND "soil erosion rates" AND "Scotland"	280 (440)
"soil erosion rates" AND "Scotland"	310 (519)
"soil erosion rate*" AND "Scotland"	68 (122)
"soil erosion rate*" +Scotland	68 (122)
"soil erosion rate*" +Scotland +field	62 (114)
"muddy flood" AND "Scotland"	0 (0)
"sediment" “ditches” “Scotland”	1 (1)
"sediment" “dredging” “Scotland”	13 (21)
“soil erosion” “impact” “Scotland”	7 (22)
“soil erosion” “costs” “Scotland”	4 (5)
“soil erosion” “impact” “costs” “Scotland”	4 (6)
“soil erosion” “mitigation” “Scotland”	24 (29)
“soil erosion control” “Scotland”	10 (17)
“soil conservation” “Scotland”	59 (117)

A comprehensive review of soil erosion was undertaken in the ‘State of Scotland’s Soil Report’ published in 2011 (Dobbie et al., 2011). Since 2011, there have been a number of studies (Lilly and Baggaley, 2014a; Hallett et al. 2016; Baggaley et al., 2017, Silgram et al., 2015, Lilly et al., 2011, Griffiths et al., 2015; SEPA Catchment walks and associated dataset) that have attempted to quantify or characterise the current state of erosion in Scottish soils and to identify some of the key drivers of soil erosion in relation to land management. Therefore, in the current review, greater emphasis was placed on finding new information published after 2011 and combining this with the information from pre-existing reviews.

The purpose of the review was to investigate current observed (quantified) rates of soil erosion in Scotland (t ha^{-1} yr^{-1}), associated on-site and off-site impacts (e.g. reduced crop yields; reduced water quality), associated costs and details of any erosion mitigation measures used (use of buffer strips, reduced tillage, cover cropping, land use change etc.). Quantified rates of erosion are needed to estimate the costs of soil erosion in Scotland (including its impacts on natural capital and the delivery of ecosystem goods and services). In order to help assign costs associated with these impacts, we drew on the extensive material already reviewed by Glenk et al., (2010); Dobbie et al., (2011); and Graves et al. (2011). We also consulted with SEPA and Scottish Water (Dr Fraser Leith, Catchment Analyst, Sustainable Land Management) to identify the impacts of soil erosion on water quality and quantity, the mitigation measures that have been installed to control soil erosion and any associated costs (e.g. water treatment and dredging).

Ultimately, the acquired information is needed to estimate quantified (as opposed to anecdotal or qualitative) soil erosion rates (and associated impacts and costs) for any given combination of soil type (texture) / land use / slope / erosion risk category (Lilly and Baggaley, 2018). This approach will be applied in the selected case study catchment areas (identified in the project's Work Package 3 and at the 2nd Project Steering Group meeting held on 01/05/19).

3. Results

3.1. Rates of soil erosion in Scotland

The review of the literature identified 26 references where quantified information on soil erosion in Scotland was reported. The evidence relating to soil erosion by water (23 of the 26 references) far outweighed the evidence of other forms of erosion (i.e. by tillage, wind and coextraction on harvested crops; see Table 49 and Table 51). This justifies the project's focus on soil erosion caused by water (i.e. rainfall and runoff), given the lack of evidence available for other forms of erosion in Scotland. The information extracted from the 26 sources is summarised in Appendix B, Table A1. References relating to soil erosion by water included erosion by snowmelt and rainfall (25 references in total).

Table 49. Number of references that mention soil, slope, soil erosion rates and land use

Erosion by:	Total (of 26)*	Soil	Slope	Soil erosion rates^	Land use
Water	23	14	13	22	19
Snowmelt & rainfall	2	2	1	1	1
Tillage	2	1	1	2	1
Wind	1	1	0	1	1
Co-extracted	0	0	0	0	0

*A reference may include more than one form of erosion; ^Erosion rates explained in **Table 50**

The units of measurement used are not consistent in the references. The magnitude and extent of soil erosion is expressed either as a measured value (e.g. tonnes per hectare), a percentage of land area, a relative scale (low, medium or high risk of erosion) or a simple observation of presence or absence of erosion (see Table 50). Some references consist of a mixture of depth of soil loss / volume of eroded soil and rates of erosion. Some references relate to single or multiple erosive events in a year: others refer to annualised figures (see Appendix B, Table A1). It was decided to standardise the reported units of soil erosion wherever possible. This would a) allow comparisons of erosion rates over space and time; and b) follow the methodology of Graves et al. (2011) that used rates of soil erosion to estimate the costs of soil lost via erosion.

Table 50. Ways in which soil erosion was expressed (as a percentage of references related to soil erosion by water and snowmelt). Values in brackets equal number of references.

	Value[1]	% area	L,M,H[2]	Y/N3
Water	76 (19)	20 (5)	19 (1)	
Snowmelt & rainfall	4 (1)			19 (1)

[1]Value expressed in units (e.g. mm, m^2, t ha^{-1} yr^{-1}); [2]L,M,H = low, medium, high; [3]Y/N = presence or absence of erosion, Y=yes & N=no

It is possible to convert soil depth loss (mm) to the mass of soil lost (t ha^{-1}) by assuming a bulk density (Mg m^3) for the soil and using Equation 1.

$$Mass\ of\ soil\ loss\ (t\ ha^{-1}) = Depth\ of\ soil\ loss\ (mm) \times Bulk\ density\ of\ soil\ (Mg\ m^{-3})$$

[Equation 6]

If annual soil depth loss is known, then t ha^{-1} yr^{-1} can be calculated (and vice versa). It is also possible to estimate an annualised figure of soil erosion from single and multiple events by taking into consideration how likely these events are to be repeated in a year, within a rotation (e.g. how frequently do crops prone to soil erosion occur in the rotation) and/or across a catchment area (e.g. how many fields in the catchment are under crops prone to soil erosion).

The literature suggests that the majority of soil erosion in Scotland is triggered by either high intensity rainfall or prolonged, low intensity rainfall (Lilly et al., 2002). Speirs and Frost (1985) found empirical evidence that 15-20 mm of rainfall over 24h was required to initiate soil erosion. Other evidence suggests that rainfall in excess of this does not initiate erosion or that sometimes erosion is initiated at rainfall amounts <15mm (Kirkbride and Reeves, 1993). Kirkbride and Reeves (1993) observed erosion to occur at rainfall intensities of <6mm hr^{-1}, concluding that low intensity rainfall over long duration and wide extent is capable of severe damage. Erosion was initiated when rainfall intensity exceeds the infiltration capacity of the soil, or more commonly in Scotland, when heavy or prolonged rainfall led to the soil becoming saturated (Lilly and Baggaley, 2014b). However, unlike other areas in Britain, Scotland also experiences soil erosion caused by runoff generated by rapid snowmelt. Snowmelt has led to large-scale soil erosion in areas that are not predicted to be at high erosion risk based on their inherent landscape characteristics (Wade & Kirkbride, 1998).

According to Davidson and Harrison (1995), the dominant cause of water erosion in Scotland is concentration of runoff within a topographic feature. Next important was runoff generated in fields upslope of the affected field. Less common was erosion caused by runoff from drains, ditches, road or in end furrows. While soil characteristics play a part in determining the underlying risk of erosion, the likelihood of erosion occurring cannot wholly be determined from soil characteristics alone. Other factors such as slope, runoff and land use need to be included when considering soil erosion (Lilly and Baggaley, 2014a).

Frost and Speirs (1996) observed that 74% of fields over an area of 24 km^2 in East Lothian showed no signs of soil erosion, with no significant erosion on 89% of the area. Baggaley et al. (2017) observed that soil erosion had occurred in only 17 out of 439 fields. Even within a field, soil erosion by water is usually localised.

Table 51. References to soil erosion by water and snowmelt in Scotland

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Wormit Farm (NO367247); North Callange Farm (NO4208112232); North Fife in general	Obs and data	Field	Arable, cereal and grassland	Brown earths (Sourhope series; Sandy silt loam) Noncalcareous gleys (Mountboy Series; Sandy silt loam) Brown earths (Macmerry series; Sandy loam) Noncalcareous gleys (Winton Series; Sandy clay loam)	3^{o}-13^{o}	Field 1: Wormit: 7.7 t km^{-2} yr^{-1} (0.077 t ha^{-1} yr^{-1}) Field 2: Wormit: 32.2 t km^{-2} yr^{-1} (0.322 t ha^{-1} yr^{-1}) Field 3: North Callange: 531.4 t km^{-2} yr^{-1} (5.314 t ha-1 yr-1) Field 4: North Callange: 548.1 t km^{-2} yr^{-1} (5.481 t ha-1 yr-1) Field 5: Wormit: 283.1 t km^{-2} yr^{-1} (2.831 t ha^{-1} yr^{-1}) Field 6: North Callange: 101.2 t km^{-2} yr^{-1} (1.012 t ha-1 yr-1)	Wade (1998)

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Mearns near Stonehaven	Obs	Field	winter cereal, reseeded pasture, pasture and stubble	Sandy loams or loams, freely or imperfectly drained	1.9-2.7% (rills <1 cm) 7.7% (rills 10-25 cm)	H Winter cereal, ploughed M reseeded pasture L Pasture and stubble	Watson and Evans (2007)
Kincardine and Angus	Obs	Field	Cereal, ploughed, oilseed rape, reseeded grass, potatoes			6.7 m^3 ha^{-1} (Assume 1.5 t m^{-3} 10.1 t ha^{-1})	Watson and Evans (1991)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Rumgally Mains (RM; NO 4014), Easter Pitscottie (EP; NO 4113) and Wester Kilmany (WK; NO 3821)	Obs	Field	Winter cereals	Light textured and stony	RM = 8.3º EP = 10.0º WK = 9.5º	RM 12.7 t ha^{-1} EP 10.1 t ha^{-1} WK 0.8 t ha^{-1}	Wade and Kirkbride (1998)
Baldardo Farm, Angus eastern Scotland	Exp	Field	Potatoes	Aldbar series; Clay loam	0 to 18%, concave slope	345 t ha^{-1}	Vinten et al. (2014)
Lunan Water	Obs	Catchment				Suspended sediment range between 1-167 mg l^{-1}	Vinten et al. (2009)
Greens Burn (GB), near Kinross, to the north of Loch Leven	Obs	Field	Arable			48.1 tonnes in four months (14.4 km^2 catchment area = 0.03 t ha^{-1})	Vinten et al. (2004)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Lambieletham Reservoir(LR) Dunoon No. 3 Reservoir, Argull (D3R) Glen Ogle, deposited in L. Earn (GO)	Obs	Reservoir catchment areas (x3)				LR = 1.3-4 mm yr^{-1} D3R = 607 m^3 yr^{-1} GO = 9 mm ha^{-1}	McManus and Duck (1988)
Ugie and South Esk	Obs	Field	Arable (including root crops in S. Esk) and grassland (mainly in Ugie)	Wide range of soils and textures. Eroded fields had slopes derived from DEM of 0-18° with 83% between 2° and 10°. Textures mainly coarse (Sandy loams with some loamy sands)		4% of fields (17 of 439 fields had erosion); 16 of 163 fields in S Esk had erosion	Baggaley et al. (2017)
Balruddery Farm, Perthshire (NO305329)	Obs and data	Field	Arable	Sandy loam	6° to 9°	117 to 417 kg ha^{-1} (over 2 yrs) (0.117 to 0.417 t ha^{-1} 0.06 t ha^{-1} yr^{-1} to 0.21 t ha-1 yr-1)	Lilly et al. (2018)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement^x	Reference
Douglastown (D; NO 418474), Hatton (H; NO 463430) and Kincaldrum (K; NO 430457) around the villages of Douglastown and Inverarity in Angus	Obs	Field	Arable	Sandy loams and sandy clay loams of the closely related Forfar and Balrownie associations D, S=33 Z=43 C=24 (%) H, S=39 Z=47 C=14 (%) K, S=54 Z=35 C=11 (%)	<10^o, but locally up to 15^o	30% of fields D = 1.73 t ha^{-1} K = 1.17 t ha^{-1} H = 2.22 t ha^{-1}	Kirkbride and Reeves (1993)
Nr Kelso	Obs	Field	Field 1 winter barley, Field 2 Peas	Fields 1&2: USDA Sandy loam, Hobkirk Series (Brown earth). High proportion of fine sand. Field 1: clay = 12; silt =14 fs (up to 200microns) 52; remainder 22% Field 2: clay = 10; silt =14 fine sand (up to 200microns) 55; remainder 21%	Field 1: 1.7% Field 2: 1.5%	Field 1: 800 t so 80 t ha^1 in a single event, 4.7% of the area eroded Field 2: 48 t ha^{-1} in a single event. Estimate of > 6 t ha^{-1} yr$^-$ 1	Frost and Spiers (1984)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Between Haddington and Gifford, East Lothian. Colstoun Water, sub-catchment of the Tyne.	Obs	Field	75% arable,16% grass	Winton,Kilmarnock, Humbie, Yester: fine textured tills with 24% clay, fs/z up to 50% - low to moderate erodibility. Macmerry & Moreham: water modified tills with 20% (or less) clay and s/z of 40% - Erodibility greater than heavy glacial tills. Hobkirk and Presmennan: 15-20% clay, vfs/z 60-65% ('coarse tills') – highly erodible. Darvel: 5-15% clay but high medium –coarse sand (glaciofluvial deposits) – moderately erodible	Flat to <20^{o}, modal slope between 5-10%,	1 to >100 t Soil loss per hectare was not calculated and is not particularly meaningful, as in general soil loss did not occur uniformly over the whole field. (0.02 to >100 t ha^{-1} 1 in 20 year rainstorm event 0.001 to >5 t ha^{-1} yr^{-1})	Frost and Spiers (1996)

Woodhill House Farm, Barry (NO523342)	Obs	Field	Winter barley (newly sown)	Fluvioglacial medium sand and some gravel	3.8°	14.7 t ha^{-1}	Duck and McManus (1987)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Lambieletham reservoir (NO502134)	Data	Catchment	Mixed arable	Caprington Series,Noncalcareous gley/Brown earth with gleying; Sandy clay loam	Low relief	0.021 t ha^{-1} yr^{-1} Single storm event of 0.45 t ha^{-1}	Duck and McManus (1988)
Glenfarg (NO016110) and Glenquey (NN 980027) Reservoirs	Data	Catchment	Glenfareg arable with woodland, Glenquey moorland			31.3 t km^{-2} yr^{-1} for Glenfarg, and 9.0 t km^{-2} yr^{-1} for Glenquey (0.313 t ha^{-1} yr^{-1} for Glenfarg, and and 0.090 t ha^{-1} yr^{-1} for Glenquey)	Duck and McManus (1990)
West of Town Yetholm (NT 813282)	Obs	Field	Arable	Predominantly freely drained brown forest soil of low base status (Sourhope Series; Sandy silt loam)		105 m^3 or 5 mm from the field (Assuming 1.5 t m^3, 157.5 t, area of field is 10.3 ha, 15.3 t ha^{-1} yr^{-1})	Davidson and Harrison (1995)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Strath Earn; Gask Ridge between the Earn and Pow Water	Obs	Field		Balrownie (an imperfectly drained brown earth developed on water-sorted till with loam/sandy loam with sandy clay loam subsoil); Lour (a poorly drained noncalcareous gley with similar textures) Buchanyhill (a freely drained brown earth loam/sandy loam).		Occurrence of erosion noted.	Davidson and Harrison (1995)
River Tweed catchment	Modelled	Catchment		Multiple (European Soil Portal)	DTM LiDAR	0.42 to 1.90 t ha^{-1} yr^{-1}	Grabowski et al. (2014)
	Obs	Forest	Forest		25-35°.	136 kg ha^{-1} yr^{-1} (1.36 t ha^{-1} yr^{-1})	Lewis and Neustein (1971)
Kintyre (NGR 896605)	Data	Forest	Forest	Sandy or loamy soils Stagno-orthic gley soil with up to 30 cm peat, sandy loam texture.	10°-12.5°	40 kg m^{-1} yr^{-1} (0.4 t ha^{-1} yr^{-1})	Carling et al. (1993)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Mid-Kame (HU 409596) Ward of Scousburgh (HU 387190), Shetland Islands	Obs	Hillside	Hillside	Peat		1.6 cm yr^{-1} to 3.3 cm yr^{-1}. Average over 4 yrs was 2.3 cm yr^{-1}. (15.0 t ha^{-1} yr^{-1})	Birnie (1993)
Loanleven, Blairhall and Littlelour	Obs	Field				Loanleven,-1.18 kg m^{-2} yr^{-1}; Blairhall -0.27 kg m^2 yr^{-1}; Leadketty -2.30 kg m^{-2} yr^{-1} ; Littlelour -0.42 kg m-2 yr-1 (Loanleven,-11.8 t ha^{-1} yr^{-1}; Blairhall -2.7 t ha^{-1} yr^{-1}; Leadketty -23.0 t ha^{-1} yr^{-1} ; Littlelour -4.2 t ha-1 yr-1)	Bowes (2002)
Coalburn, Southern Uplands	Data	Catchment (3.1 km^2)	Undisturbed moorland			Suspended sediment yield = 3.0 t km^{-2} yr^{-1} (0.03 t ha^{-1} yr^{-1})	Robinson and Blyth (1982)

Coalburn, Southern Uplands	Data	Catchment (3.1 km^2)	Forest (ploughing and ditching)			Suspended sediment yield = 25.0 t km^{-2} yr^{-1} (0.25 t ha^{-1} yr^{-1})	Robinson and Blyth (1982)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Coalburn, Southern Uplands	Data	Catchment (3.1 km^2)	Forest (first 4 years growth)			Suspended sediment yield = 13.0 t km^{-2} yr^{-1} (0.13 t ha^{-1} yr^{-1})	Robinson and Blyth (1982)
Monachyle, Trossachs	Data	Catchment (7.7 km^2)	Undisturbed moorland			Suspended sediment yield = 39.2 t km^{-2} yr^{-1}; (0.39 t ha^{-1} yr^{-1}) Bed load yield = 0.3 t km-2 yr-1 (0.003 t ha^{-1} yr^{-1})	Stott et al. (1986); Johnson (1988, 1993)
Monachyle, Trossachs	Data	Catchment (7.7 km^2)	Forest (ploughing and ditching)			Suspended sediment yield = 122.3 t km^{-2} yr^{-1} (1.223 t ha^{-1} yr^{-1})	Stott et al. (1986); Johnson (1988, 1993)
Kirkton, Trossachs	Data	Catchment (6.9 km^2)	Mature forest			Suspended sediment yield = 56.6 t km^{-2} yr^{-1} (0.566 t ha^{-1} yr^{-1})	Stott et al. (1986); Johnson (1988, 1993)

Table 51. References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
Kirkton, Trossachs	Data	Catchment (6.9 km^2)	Harvesting forest			Suspended sediment yield = 462.8 t km^{-2} yr^{-1} (4.628 t ha^{-1} yr^{-1}) Bed load yield = 2.5 t km-2 yr-1 (0.025 t ha^{-1} yr^{-1})	Stott et al. (1986); Johnson (1988, 1993)
Kirkton, Trossachs	Data	Catchment (6.9 km^2)	Mature forest			Bed load yield = 2.2 t km-2 yr-1 (0.022 t ha^{-1} yr^{-1})	Stott et al.(1986); Johnson (1988, 1993)
L. Ard, Trossachs	Data	Catchment (0.84 km^2)	Mature forest			Suspended sediment yield = 55.2 t km^{-2} yr^{-1} (0.552 t ha^{-1} yr^{-1})	Ferguson et al (1991)
L. Ard, Trossachs	Data	Catchment (0.84 km^2)	Harvesting forest			Suspended sediment yield = 89.6 t km^{-2} yr^{-1} (0.896 t ha^{-1} yr^{-1})	Ferguson et al (1991)
L. Ard, Trossachs	Data	Catchment (0.84 km^2)	Post harvesting			Suspended sediment yield = 98.4 t km^{-2} yr^{-1} (0.984 t ha^{-1} yr^{-1})	Ferguson et al (1991)

M1, Trossachs	Data	Catchment (0.24 km^2)	Undisturbed moorland			Bed load yield = 1.8 t km-2 yr-1 (0.018 t ha^{-1} yr^{-1})	Stott (1997a)

Table 51 References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement[x]	Reference
M2, Trossachs	Data	Catchment ($0.55\ km^2$)	Undisturbed moorland			Bed load yield = 5.9 t km-2 yr-1 ($0.059\ t\ ha^{-1}\ yr^{-1}$)	Stott (1997a)
M2, Trossachs	Data	Catchment ($0.49\ km^2$)	Undisturbed moorland			Bed load yield = 0.9 t km-2 yr-1 ($0.009\ t\ ha^{-1}\ yr^{-1}$)	Stott (1997a)
North Esk reservoir, Midlothian	Data	Catchment	Undisturbed moorland			Suspended sediment yield = $25.4\ t\ km^{-2}\ yr^{-1}$* ($0.254\ t\ ha^{-1}\ yr^{-1}$)	Lovell et al. (1973)
Hopes Reservoir, East Lothian	Data	Catchment	Undisturbed moorland			Suspended sediment yield = $25.0\ t\ km^{-2}\ yr^{-1}$* ($0.25\ t\ ha^{-1}\ yr^{-1}$)	Ledger et al. (1974)
Kelley Reservoir, Strathclyde	Data	Catchment	Undisturbed moorland			Suspended sediment yield = $41.0\ t\ km^{-2}\ yr^{-1}$* ($0.410\ t\ ha^{-1}\ yr^{-1}$)	Ledger et al. (1974)
Glenquay Reservoir, Ochils	Data	Catchment	Undisturbed moorland			Suspended sediment yield = 9.0*; 31.3*; and 27.8 $t\ km^{-2}\ yr^{-1}$* (0.09; 0.313; and 0.278 $t\ ha^{-1}\ yr^{-1}$)	McManus and Duck (1985

Table 51 References to soil erosion by water and snowmelt in Scotland continued…..

Georeference	Type of data*	Area	Land use	Soil type	Slope	Soil erosion measurement^{x}	Reference
Glenquay Reservoir, Ochils	Data	Catchment (6.2 km^2)	Undisturbed moorland			Bed load yield = 26 t km^- 2 yr-1* (0.26 t ha^{-1} yr^{-1})	Richards and McCaig (1985)

*Obs = Observational, Data = measurements collected, Mod = modelled and Exp = experimental; x values in brackets have been calculated from the data presented in the article. *figure estimated from sediment accumulation in check dam or reservoir N.B. Sediment yields, loads and concentrations cannot be directly linked to the sources / origins of the soil erosion process.

3.1.1. Soil erosion in upland areas in Scotland

There is limited evidence for the quantified rates of soil erosion on upland soils in Scotland. However, the rates of erosion that have been observed on bare peat soils on the Shetland Isles (1.6 cm yr^{-1} to 3.3 cm yr^{-1}) are of the same order of magnitude as those on bare peat at higher altitudes in the Pennines (Birnie, 1993).

Some evidence suggests that erosion of peat by water is minimal (Carling et al., 2001) and that erosion does not occur until flow velocities exceed 5.7- 6.0 m s^{-1}. Peat erosion by water may be initiated by particles being detached from an exposed sediment surface by freezethaw cycles (Burt et al., 1983), desiccation (Francis and Taylor, 1989) or rainsplash, in a process known as spalling (Carling et al., 2001). Peat has also been observed to erode where mineral particles are washed over the surface of the peat, causing abrasion.

3.1.2. Forestry and soil erosion in Scotland

Forested areas are often considered to offer protection from soil erosion, due to the extensive canopy cover intercepting rainfall and well developed root systems that increase infiltration, curbing runoff generation and associated soil erosion. However, there is evidence to show that forests can undergo higher soil erosion rates compared to other land uses. Carling et al. (2001) and Lewis and Neustein (1971) have reported rates of soil erosion from forested areas of between 0.4 to 1.36 t ha-1 yr-1, respectively. In a review by Carling et al. (2001), the risk of soil erosion under forestry is associated with forest roads (primarily from excavated soil during road construction), unmetalled roads and rutting on roads (from vehicles compacting the road surface) leading to concentrated flow and erosion of the road surface. Johnson and Brondson (1995) monitored suspended sediment from road surfaces in Kirkton forest, Balquhidder, Scotland, and found sediment yields on heavily trafficked forest roads to be between 2 and 10 times that of little used roads.

Soil erosion in forests is also caused by the exposure of soil surfaces during (re)planting of trees. These surfaces are vulnerable to erosion until they revegetate (this is especially an issue on silty loam soils; Luce and Black, 1997). Changes in groundwater hydrology leading to hillslope instability and landslides, stream crossing points and culvert design can all contribute to soil erosion risk in forests (Carling et al., 2001). McManus and Duck (1988) also noted higher risk of erosion from pre-planting drainage furrows that are oriented up and down hill (allowing concentration of flow), followed by a period of high-intensity rain.

Another source of erosion in forested areas originates from surface drainage furrows and subsurface mole drainage. Surface furrows can be the cause of soil erosion until they revegetate. Research by Moffat (1988) reported soil losses of 1.3 t ha^{-1} yr^{-1} after furrow generation, which reduced to less than 0.25 t ha^{-1} yr^{-1}, in subsequent years. While mole drains have been promoted as an alternative drainage option to surface furrows, work in Glen Skibble, Kintyre, has shown soil loss to be comparable between areas with furrows and mole drains (Carling et al., 1993). Although in the first year after planting sediment yield from the mole drains was much less than from the furrows, between 0.56 and 0.76 t ha^{-1} yr^{-1}. However, unlike furrows, which can revegetate within a season, mole drains remain susceptible to the erosion of bare soil in the second year after planting (Carling et al., 2001). Carling et al. (2001) estimated sediment loss via mole drains to be 0.036 t ha^{-1} yr^{-1}.

Stott and Mount (2004) provide some data on sediment yields from upland forestry operations in the UK, including Scotland. Data includes different stages: undisturbed, ploughing and ditching, first 4 years, mature forest, harvesting and post-harvesting. Suspended sediment yields up to 122.3 t km^{-2} yr^{-1} are reported on forested land, caused by forest operations such as ploughing, ditching and harvesting (Stott et al., 1986) and as high as 462.8 t km^{-2} yr^{-1} during timber harvest (Stott et al., 1986) (Table 51).

In forested upland areas where the underlying soil may be peat, the peat in the drainage furrows may not be directly eroded by runoff. However, runoff may carry material that has become detached from the furrow walls through the process of spalling. The detached material accumulates in the base of the furrow until discharge in the furrow is erosive enough to transport the sediment downslope. Runoff through a mixed mineral / peat landscape may also cause erosion by carrying mineral material that abrades channels running through peat areas.

3.1.3. Soil erosion on agricultural land in Scotland

Observations of soil erosion by water following severe weather or snowmelt have been made, primarily by rapid response surveys. These surveys have tended to focus on agricultural areas, where erosion risk is greatest. The data shows that land use affects erosion risk (e.g. because of the proportion of soil exposed to erosive forces). The area of that land use will also influence the magnitude of erosion from an area. Table 52 serves to illustrate this point, showing the average area sown to a particular crop type in North Fife and the percentage of the fields with this crop type that were eroded. Davidson and Harrison (1995) reported the findings of a rapid response survey in Strath Earn, south west of Perth, following 18 days of severe weather conditions in January 1993. In their survey, 27% of the fields showed signs of erosion. Of the five reported land covers (pasture, stubble, autumn sown cereal, ploughed land and fodder crops and oilseed rape), fields with the highest likelihood of erosion features were either ploughed (45% of ploughed fields) or in autumn cereals (78% of autumn cereal fields). Frost and Speirs (1996) also observed soil erosion on ploughed land (severe >100 t soil lost and slight between 1-10 t soil lost), seedbeds (moderate erosion between 10 and 100 t soil lost) and stubble (moderate and slight soil loss). McManus and Duck (1988) and Kirkbride and Reeves (1993) observed the highest incidence of soil erosion to occur on bare, recently seeded soil. Severe soil erosion was observed for 18 out of 19 fields around Douglastown and Inverarity in Angus, where there was bare soil (Kirkbride and Reeves, 1993). Wade

(1998) in a survey of 223 fields within 100km^2 in North Fife, observed winter cereal and ploughed fields accounted for 77% and 16% (respectively) of fields observed to have some form of soil erosion. Winter cereal and ploughed land occupied the largest percentage of monitored fields (80% of fields monitored). Watson and Evans (2007) also found winter cereal fields in Mearns near Stonehaven, comprised 70-73% of all eroded fields and had some of the deepest gullies found in the area.

Table 52. Crop type, coverage and soil erosion incidence between winter 1993 through to 1997 (Wade, 1998)

Crop	Average area of study area sown to each crop type (%)	% of fields in each crop type seen to erode
Winter cereal	27	63.5
Ploughed	-	20.8
Spring cereal	17.9	5.6
Grass/new grass	25	4.4
Potatoes	4	1.9
OSR	7	1.9
Newly sown	-	1.3
Vegetables	4	0.63

Information about soil erosion from vegetable fields is lacking, primarily because of its low occurrence across the landscape. In North Fife, Wade (1998) found vegetable fields comprised about 1% of all observed fields, but the same land use accounted for up to 2% of fields that were observed to erode.

Runoff from agricultural areas that are associated with lower soil erosion risk e.g. pasture, can contribute to erosion, as in the Kelso area of the Borders Region, described by Davidson and Harrison (1995). Runoff from two upslope pasture fields was subsequently concentrated along tramlines, which created a gully some 1.4 m deep, depositing 105 m^3 of sediment. Wade (1998) in North Fife recorded no soil erosion on fields with stubble or with livestock. However, they did record soil erosion on grass (13% of monitored fields, with 5% of those fields eroded).

Soil erosion risk in Scotland is increased by management decisions. Kirkbride and Reeves (1993) and Watson and Evans (2007) showed that up and down slope operations increased the risk of soil erosion. Also, fine seed beds, before the crop has time to emerge, are susceptible to wind and water erosion, especially when crop rows run up and down slope (Lilly and Baggaley, 2014a). Kirkbride and Reeves (1993) found 58% of all fields worked up and down slope experienced some soil erosion, and 30% had rill erosion. Kirkbride and Reeves (1993) also noted that up/down slope alignment of wheelings and furrows increased risk of erosion. Wade et al. (1998) observed that rills were predominantly aligned by the direction of cultivation and were more severe in compacted tractor wheelings. On steeper slope segments, the rills followed the fall line (maximum slope gradient). Other management factors that increase erosion risk include prior formation of a soil cap (Kirkbride and Reeves, 1993). In the Kelso area of the Borders Region, Davidson and Harrison (1995) found a statistical relationship between orientation of cereal planting or cultivation along the line of maximum slope. Bare ground and poaching by animals where also reported by Watson and Evans (2007) as increasing risk of erosion.

The type of erosion features observed indicate the severity of soil erosion, with sheet erosion generally having lowest rates, followed by rill and then gully erosion. Davidson and Harrison (1995) noted the different forms (and thus severity) of soil erosion (Table 53). The most common soil erosion feature was ephemeral gullies along topographical hollows on ploughed land. Sheetwash and rill erosion were more predominant on autumn sown land, with sheetwash occurring between cereal rows or plough furrows. The dominant cause of erosion by water was concentration of runoff along a topographic feature. Next important was runoff generated in fields upslope of the affected field. Less common was soil erosion caused by runoff from drain, ditch, road or in end furrows. However, statistically the only relationship between cause of soil erosion and type of land cover/land management was between soil loss and orientation of cereal planting or cultivation down the line of maximum slope.

Table 53. Number of instances of soil erosion type and incidences observed within autumn cereals and ploughed land (adapted from Davidson and Harrison, 1995)

Erosion type	Total Instances	Under autumn cereals	Ploughed
Sheet wash between rows/furrows	17	15	2
Sheet wash along topographic hollows	7	5	1
Rills (<10cm deep): topographically controlled	7	3	2
Between rows (linear)	9	9	0
Rills leading into gullies	3	2	1
Tramline erosion	7	6	0
Tramline erosion leading to rill development	0	0	0
Tramline erosion leading to gully network	7	4	1
Gully controlled by topography	33	16	16
Gully along plough furrow	19	0	9
Gully along end furrow	14	6	8

Evidence from sediment cores collected from the bed of Glenfarg reservoir provide evidence of greater erosion rates when there is a change in land use from grassland to arable (i.e. an increase of 243 ha in arable land in the catchment; Duck and McManus, 1984 & 1990).

3.1.4. Other evidence of soil erosion rates in Scotland

As well as land use and management, there are intrinsic characteristics within the landscape that contribute to soil erosion. The gradient and shape of the slope can also increase the risk of soil erosion. Bowes (2002) used measurements of ^{137}Cs to estimate soil erosion at four sites in Scotland (Loanleven, Blairhall, Leadketty and Littlelour). Their observations revealed that slope gradient showed the best statistical relationship with soil erosion/deposition rates, however, it also showed that slope did not play a dominant role. Bowes (2002) observed that rates of erosion were not related to steepness of the slope, but to zones where the rate in slope change was highest. Frost and Speirs (1996) and Doetter et al. (2012) describe a rolling topography as being most vulnerable to erosion. Watson and Evans (2007) recorded soil erosion even at low gradients (1.9 - 2.7%), but did not find a significant link between slope length and soil erosion. Some of the most severe erosion has been found on steep, convex bulges in the lower part of a field by Watson and Evans (1991). Lilly and Baggaley (2014a) commented that the erosive power of runoff increased at a greater rate at lower angles than at greater angles. However, as slope steepness increases, runoff had greater ability to erode.

Within the SEPA “Catchment Walk” data set, SEPA staff observed 3808 breaches of General Binding Rules (GBRs) along the water courses in 11 catchments across Scotland (Figure 1). The majority (96%) of the breaches identified were of “significant erosion or poaching of land within 5 m of a water course” (GBR19a), including 29 breaches of the GBR that were due to in-field or gully erosion.

Lilly and Baggaley (2014a) applied an existing (but unvalidated) Scotland-wide model (Lilly et al., 2002) to assess the role of soil erosion in a deterioration of water quality occurring within Scottish agricultural catchments from sediment and other pollutants being transported to water bodies by erosion events. They demonstrated their approach within two test catchments, the Coyle and the East Pow (2 of SEPA’s designated priority catchments) for which soil, slope and runoff risk data were available. Their approach offers greater understanding of how the soils affect erosion risk including the importance of soil runoff potential. Their underlying assumptions considered the main driver of erosion risk to be the ability of the soil to absorb rainfall (or snow-melt) and restrict the potential for overland flow, while slope angle increases the power of any overland flow. They also assumed that, of the mineral soils, fine textured topsoils to be the least erodible and coarse textured mineral topsoils to be the most erodible They considered peat soils to be highly erodible.

3.2. Impacts of soil erosion in Scotland

The impacts of soil erosion can be expressed in terms of ecosystem services lost or gained by a management decision or action (de Groot et al., 2010). Evidence for the impact of soil erosion in Scotland is presented below in terms of the provisioning, regulating, cultural and supporting ecosystem goods and services.

3.2.1. Provisioning goods and services impacted by soil erosion in Scotland

Frost and Speirs (1996) argue that soil erosion by water was not a severe threat to arable production in Scotland, even in an area considered to be vulnerable, due to the nature of its soils and the topography of the terrain. Others also share this view in Scotland, for example Glenk et al. (2010) conclude that “Given the relatively low frequency of erosion events and the short transport distances of eroded soils, any threat to the biomass production function by soil erosion in Scotland must be viewed as small.” These views are based on the assumption that because the area that is typically eroded is small, the on-site impact is also small. The subsequent damage / impact to crops is therefore limited. Also, soil erosion has little impact on productivity in arable fields, because the change in soil depth due to soil erosion may not currently limit plant growth, especially if topsoil depth is deep (>0.2 m) and/or subsoil texture is not dissimilar to the topsoil texture.

For example, Frost and Spiers (1984) estimated for a farm near Kelso, the site could tolerate between 120-200 years of soil loss before the land capability for agriculture would be affected by either droughtiness or stone content. On deeper soils, the on-site effects of soil erosion on costs may be very small (i.e. undetectable) (Frost and Spiers, 1984). Erosion by water occurs over concentrated flow paths, minimising the spatial extent of damage caused by seed removal or loss of crop. The impact of the effect of soil erosion on soil properties may also take a long time to reveal itself, especially on deeper soils or where inputs of fertilisers or even irrigation will mask yield declines due to soil loss. Frost and Spiers (1984) reported effects of soil erosion on soil droughtiness. For a farm situated in Kelso in Roxburghshire, those authors reported the depth of loamy soil exceeded 2.0 m, with cereal crops needing a depth of 1.20 m. As a result, even at an average rate of soil loss of 25 t ha^{-2} yr^{-1} (which is very high by UK standards), no effect of soil erosion would be felt for ca. 400 years. In the short term, productivity of the site would only be affected by the quantity of crop removed during the erosion event, which in most arable fields is only a limited amount (Frost and Spiers, 1984). However, Davidson and Harrison (1995) note that a general down-slope movement of soil was changing the distribution of the resource in the Kelso area of the Borders Region.

3.2.2. Regulating goods and services impacted by soil erosion in Scotland

Regarding the regulation of carbon and nitrogen fluxes in the environment, eroding agricultural soils may act as sinks or sources of atmospheric carbon and nitrogen, depending on whether soil organic matter is exposed during soil transport or buried when sediment is deposited (Lilly et al., 2018). Frost and Spiers (1984) modelled the potential loss of organic matter from a farm site near Kelso at 0.016 kg m^{-2} yr^{-1} from field soils with an organic matter content of between 1.5 and 1.7%, and an annual soil loss of 25 t ha^{-1}. Lilly et al. (2018) also consider soil erosion to contribute to a decrease in soil carbon storage. Despite these studies, at present, the rate and spatial pattern of redistribution of carbon due to soil erosion is largely unknown and requires further investigation (Lilly et al., 2018).

The regulation of water quantity is also affected by soil erosion in Scotland. Increased sediment loads in rivers have been linked to reduced water storage capacities in reservoirs in Scotland (McManus and Duck,1988). Duck and McManus (1990) in a study of the Midland Valley of Scotland found a range of 0.2-0.6 t ha^{-1} yr^{-1} deposited in reservoirs for small, wellvegetated upland catchments. In upland peat moorlands of Scotland, sediment yields in excess of 1.0 t ha^{-1} yr^{-1} are common (Duck and McManus, 1990, 1994). As noted in Halcrow Water (2001), rates of peat sediment accumulation are particularly important because the dry bulk density of peat sediment can be very low, giving rise to a rapid loss of volumetric capacity. Natural Scotland recognise that soil erosion from agricultural areas in Scotland can contribute to siltation and subsequent flooding (Dobie et al., 2011). Davidson and Harrison (1995) also note that drains and ditches were blocked by sediment in the Kelso area of the Borders Region.

Regarding the impacts of soil erosion on the regulation of water quality, in general, the greater the proportion of arable cropping in a catchment (and thus soil erosion risk), the greater the increase in suspended sediment load in waterways (Lilly et al., 2009). There is also a strong geographical distribution, with catchments draining into the Moray Firth showing an increase in suspended sediment whilst those catchments in the central belt showed a decrease. Lilly and Baggaley (2014a) modelled the risk (not validated) of diffuse pollution from sediment and other pollutants occurring within Scottish agricultural catchments (the Coyle and the East Pow: SEPA's designated priority catchments). Owens et al. (2000) noted 61% of the sediment load of the River Tweed in Scotland was derived from arable and pasture top soils. The Harmonized Monitoring Scheme (HMS), which provides long-term data on suspended sediments in many Scottish rivers, shows that while some rivers have shown an increase in suspended sediment loads through time, others have shown a decrease (Lilly et al., 2018).

Nisbet (2001) reports a number of studies where forest activities associated with detrimental off-site impacts from soil erosion actually had little effect on water quality.

In an afforestation scheme in Kintyre, west Scotland, stream water turbidity, a key indicator of site disturbance and associated soil erosion, generally remained well within the drinking water standard of 4 Nephelometric Turbidity Units (NTU), as prescribed under the UK Water Supply (Water Quality) Regulations (1989). Only the two peaks of 14 NTU in July 1993 and 9 NTU in September 1993 were of any significance, but neither was associated with ploughing and drainage operations, since revegetation was largely complete by then. This demonstrates the importance of timely operations and the short term window of erosion risk.

In another study in the Upper Halladale catchment of north Scotland (Forestry Commission et al., 1998), ploughing operations had a minimal effect on water quality, as well as no detectable impact on the benthic macroinvertebrate population or on the survival of salmon eggs within the river gravels. In fact, populations of both salmon and trout actually rose in the main river following the extensive afforestation of the catchment, although the changes were within the natural year to year variability in fish densities.

Nisbet (2001) concluded that these studies demonstrate that ploughing and drainage operations in forested catchments can be undertaken without detriment to water quality or the freshwater environment within sensitive catchments under typical weather conditions. However, Nisbet (2001) also recognises that a good standard of forestry practice, including careful planning and using cultivation practices that minimise soil exposure wherever possible is essential to control soil erosion and runoff.

3.2.3. Cultural goods and services impacted by soil erosion in Scotland

Plough induced soil erosion on fields containing archaeological records can over time lower the depth of soil above an archaeological feature, gradually increasing the risk of cultivation implements damaging the underlying feature. The Scottish Soil Framework (2009) suggests that soil erosion can expose artefacts leading to their degradation and loss. The ^{137}Cs surveys undertaken by Davidson et al. (1998) at Littleour provide evidence of the rate of erosion induced by ploughing and the risk to the underlying archaeology, but suggest that these observations are applicable to sites with fluvioglacial sand and gravels under similar management regimes.

Recreational activities such as angling can also be impacted by soil erosion. In the Scottish Soil Framework (2009) it is suggested that soil erosion in Scotland contributes to increased suspended sediments and turbidity in watercourses, which can diminish water quality and damage aquatic life, including salmon spawning grounds. Sediment associated pollutants, such as phosphates, were also considered to be contributing to eutrophication of water bodies. These processes can impact on the fishing industry, recreational fishing and angler groups.

3.2.4. Supporting goods and services impacted by soil erosion in Scotland

A healthy freshwater ecosystem requires sediment inputs to maintain habitat and nutrient fluxes, however excessive sediment loading can negatively affect river ecosystem function, including support for biodiversity. Sediment from soil erosion events can have a negative impact on the natural capital of Scotland's rivers (Gilvear et al., 2002). A decline in the salmonid population in Scotland has also been linked with excess sediment load and deposition in rivers (Gilvear et al., 2002), that would have originated from soil erosion in the catchment. Similarly the status of freshwater pearl mussels in rivers such as the River Spey is considered to be 'unfavourable declining' due to water quality issues, including fine sediment load in the river (Sime, 2014).

Soil formation is regarded as a 'supporting service' to ecosystems. The resampling of the National Soil Inventory of Scotland (2007-9) showed that there had been a statistically significant increase in topsoil thickness of cultivated soils rather than a decrease due to erosion. However, the same resampling also showed a decline in soil organic matter in the topsoils. The conclusion drawn was that deeper ploughing had not only diluted richer organic topsoil with carbon-poor subsoils, but it is possible that this had also offset (i.e. masked) any losses in soil depth due to erosion.

3.3. Mitigation of soil erosion in Scotland

Soil erosion mitigation measures can be classified into 'erosion control' and 'sediment control'. The former is almost always more effective than the latter, as it deals with 'control at source' (i.e. prevention), rather than remediation (i.e. cure) of the problem.

3.3.1. Soil erosion mitigation measures in the Scottish uplands

In Shetland, the sensitivity of blanket peat to livestock stocking levels is of concern. Grant et al. (1985) concluded that grazing on Scottish blanket bog should be restricted to one sheep ha^{-1}. However, Birnie (1993) observed that similar rates of peat erosion were seen between two sites with contrasting stocking rates, concluding that erosion rates on bare peat are more strongly controlled by wind, water and frost heave, than by domesticated stock. Stock may affect erosion rates not through trampling but by preventing the recolonization of vegetative cover. Birnie and Hulme (1990) observed that stocking regimes change, both in terms of animal type and quality, meaning that stocking levels should not be regulated simply on numbers to control peat erosion. Account has to be taken of the biological productivity of the available grazing and the nutritional requirements of the animal in order to avoid over grazing (Birnie and Hulme, 1990) that can lead to soil erosion.

3.3.2. Soil erosion mitigation in Scottish forests

There is considerable evidence in the literature of practical soil erosion control and sediment control measures on forested land in Scotland.

a) Erosion control in forested land in Scotland

In the first half of the 20th century, it was believed that afforestation would reduce soil erosion within a catchment (Cuthbertson, 1948). However, the practice of draining the land prior to planting still caused soil losses. Furrows were cut up/down slope (at <5^o angle) to feed into cross-drains traversing the slope at subcritical slope lengths to prevent soil erosion of the furrow. However, the system did not work and soil erosion still occurred in places. Following the publication of the 'Forest and Water Guidelines (Forestry Commission, 1993), advice on site preparation for forestry changed. These guidelines have been incorporated into the United Kingdom Forestry Standards for sustainable forest management in the UK (Forestry Commission, 2017) and soil erosion rates have been reduced as a result. The Forestry Commission recommended that cross-drains should discharge into vegetated areas before entering a watercourse. Drains should have a gradient of <2^o to prevent bed scour and the spacing of drains should be reduced so that drainage velocities did not exceed 1 m s^{-1}. A range of ground preparations are now used, ranging from furrows which disturb 40-60% of the area; mounding which disturbs 30% of the area; moling which disturbs 25% of the area; and hand turfing or hand screefing which only disturb a few percent of the area (Carling et al., 2001). While less soil disturbance should equate to less soil erosion, there is little supportive quantified evidence to show this.

On short furrows (<50 m long) on slopes of <8^o, spalled sediment tends to accumulate rather than be transported along the furrow (Carling et al., 1993). The Forest and Water Guidelines (Forestry Commission, 1993) recommend limiting furrow length to between 50 and 70 m on sites with erodible soils. Following the afforestation guidelines has resulted in no significant increase in soil erosion or damage to aquatic ecology in the Halladale catchment and Kintyre (Nisbet, 1996; Forest Research, 1997).

To avoid scouring of peat soils under forestry, it is recommended to avoid drainage networks that initiate in areas of mineral soils if they flow into deep peats (Carling et al., 2001). This is because of the abrasive power of the mineral fractions when they flow over areas of peat soil. Furrow depths should not extend into underlying mineral material.

To reduce sediment loads caused by harvest, land clear should be kept to 10-20 ha rather than extensively felling an area. Brash mats or thatching should be used during the harvesting operations to limit compaction on susceptible soils such as surface-water gleys, shallow peats over poorly drained clay soil and deep peats

(Carling et al., 2001). Land damage can be limited to an estimated 20% of land at harvest if well-defined extraction corridors are used.

Well designed drainage networks under forestry can result in suspended load or bed load ranges of between 32 and 1331 kg ha^{-1} yr^{-1} (Soutar, 1989 a,b). These levels can be reduced by using buffer strips.

b) Sediment control in forested land in Scotland

To reduce runoff and associated sediment generated from forest tracks, it is recommended that roadside drains should be equipped with sediment catchpits of sufficient capacity. Road culverts should be large enough to pass water and woody debris during peak runoff. Road drains should not be used to capture excessive amounts of water and should discharge into vegetated buffer strips (ca. 30 m wide) (Clinnick, 1985).

Buffer strips have been recommended in forestry systems to reduce the amount of sediment leaving a site (Forestry Commission, 1988). It is recommended that buffer strips are established alongside streams during initial planting. These buffer strips also protect the watercourse from sediment when trees are harvested up to the edge of the woodland. The width of buffer strips affects their efficiency at preventing sediment-entering a watercourse.
Francis and Taylor (1989) observed that 10 to 13 m wide buffer strips reduced, but did not prevent fine sediment entering streams. Where slopes were >5^{o}, vegetated buffer strips of 520 m width are recommended between furrows and cross drains, and >20 m should be left between drains outlets and main streams. The actual buffer width depends on the catchment area that drains to it.

In central Scotland, Johnson and Brondson (1995) found that a well designed drainage system incorporating a vegetated buffer strip could prevent the bulk of sediment generated from established forest roads from entering local watercourses. Nisbet (2001) cites a study near the village of Tayvallich in Kintyre, west Scotland, where a 2.5 km length of forest road was constructed. Sediment discharges were limited by a range of mitigation practices including phasing operations over 3 years; limiting work to periods of dry weather in late spring and summer; using cultivation practices that minimise soil exposure wherever possible; and separating road drains from natural watercourses by installing frequent culverts (100± 200 m intervals) that individually discharged to a small silt trap and a vegetated (10 m) buffer strip. Nisbet (2001) concludes that if best management practice (i.e. Forest and Water Guidelines (Forestry Commission, 1993)) is put in place then the amount of sediment lost from forest areas is reduced ‘to the point of protecting drinking water’. However, Nisbet (2001) also highlights that ‘Pre-guideline roads, which comprise the bulk of the forest road network in the UK, represent a potentially greater problem.’

3.3.3. Soil erosion mitigation measures on agricultural land in Scotland

a) Soil erosion control on agricultural land in Scotland

Soil erosion can be reduced by increasing soil aggregate stability (Lilly and Baggaley, 2014b), so any measures that achieve this aim will help reduce erosion rates. Many of these measures used in Scotland are listed below.

Land use / land cover appears to be an important factor affecting Scottish soil erosion. Frost and Speirs (1984) observed that soils were most prone to erosion when the soil was bare (free from growing crop or crop residues). It is known that good establishment of the crop before seasons with predicted heavy and therefore erosive rainfall can reduce risk of soil erosion (Frost and Speirs, 1996; Watson and Evans, 2007). Kirkbride and Reeves (1993) also noted that timing of planting was important as more established crops offered better erosion protection. Crop rotations that include spring-sown crops on susceptible soils will reduce average soil losses and reduce, but not prevent, incidence of severe erosion events (Frost and Speirs, 1984). Speirs and Frost (1985) observed 65% of erosion events were associated with winter cereal crops that occupied only 19% of the observed tillage area. On the other hand, 60% of the tillage area, which was under spring cereal crops was associated with only 5% of observed erosion. These observations support the argument for reducing the area of winter cereals to limit soil erosion. Soil erosion modelling, corroborated by observed evidence of erosion events in cultivated fields, suggests that much of eastern central lowlands where the greatest density of the total 30,000 ha of Scottish potato cultivation occurs, has mainly moderate soil erosion risk (although the ‘sediment loss’ is predicted to be high or very high) (Lilly et al., 2002, 2011)

Speirs and Frost (1985) advocated leaving stubble over winter to protect the soil surface from erosive agents. Others have also found leaving stubble over winter can reduce soil erosion (Vinten et al., 2004; Baggaley et al., 2017; Lilly et al., 2018). By growing winter barley and oil seed rape to provide over-winter cover from rainfall, rather than spring sown crops, the probability of the seedbed being subject to a potentially erosive event is more than doubled (Frost and Speirs, 1984).

In a survey of 6,000 Scottish farms in 2010 (response rate 77%) 41% of the land area surveyed had plant residues, stubble or a cover crop over winter of 2009/2010 and many holdings were either establishing or maintaining boundary features (Kerr, 2012).

Crop choices within rotations can also mitigate erosion risk. Baggaley et al. (2017) suggested that having grassland as part of a rotation appeared to decrease the risk of erosion even under extreme rainfall events. Cover crops as part of the rotation, if they can be well established, can potentially reduce soil erosion by protecting the soil surface and increasing infiltration (Vinten et al., 2004).

Other options include cultivation practices and field operations to reduce erosion, including strip cropping. Observations by Frost and Speirs (1996) showed no soil erosion to occur on direct drilled fields. Frost and Speirs (1984) also suggested further controls to include increasing soil infiltration and reducing runoff. Infiltration could be increased by not using a heavy roller after drilling and reducing soil capping, thus maintaining infiltration. Ploughing, harrowing and drilling all in the same direction leaves the soil surface uneven compared to cultivating at right angles to the plough. The increased surface roughness increases storage capacity and reduces runoff.

ClimateXChange (2018) reports on different tillage methods for arable land in Scotland (Figure 11). Reduced and zero tillage was used less in 2016 than in 2013 (down from 19% combined in 2013 to 10% combined in 2016), which may suggest an increased risk of soil erosion. The reason for the reduction in use is not known. The Scottish Government (2016) shows the area of agricultural land left bare decreased from 17% in 2013 to 13% in 2016. Land left bare over winter is often as a result of autumn ploughing, allowing the frost and weather to break down the bare soil, which creates an erosion risk. Plant residues and stubbles also declined in this period, whilst winter cropping (which may also leave soil vulnerable to erosion as it relatively more bare) increased. The report states that long term trends cannot be assessed, but it will be useful for this assessment to continue to monitor these trends in the future.

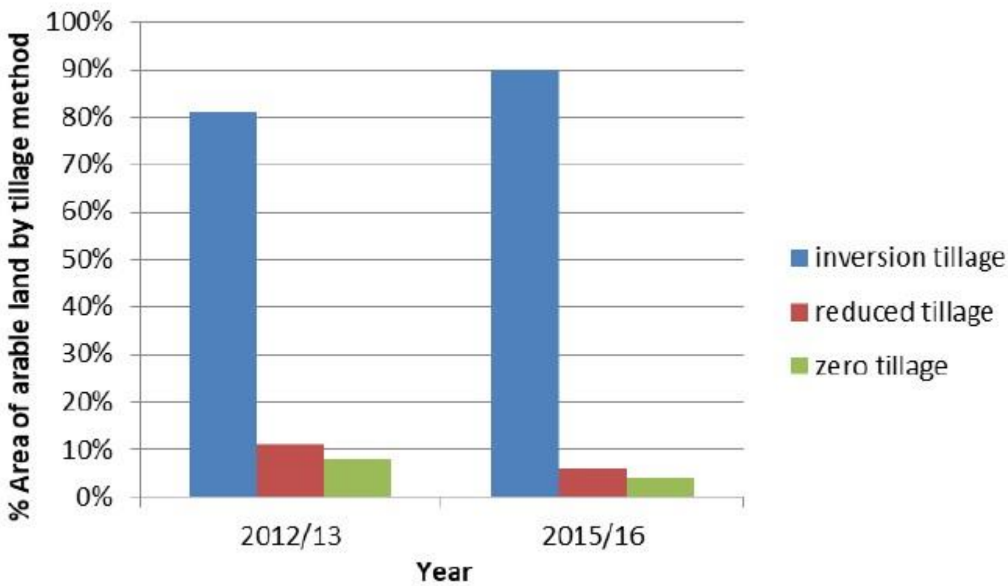

Figure 11. Area of arable land in Scotland by tillage method (2012/13 and 2015/16) (from ClimateXChange (2018))

However, field operations can also enhance soil erosion. Tramlines are prone to surface runoff during periods of excess rainfall. For example, autumn spraying of cereals can cause compaction of soil along tramlines, leading to soil erosion associated with winter rainfall (Silgram et al., 2015; Lilly et al., 2018). Tramlines are particularly problematic if they run up and down slope (Vinten et al., 2004). A case study described in Lilly et al. (2018) showed that by removing compaction from control tyres using a spiked harrow reduced soil loss by between 76% and 98%. Using very flexible tyres reduced soil loss by between 36% and 93%. However, a rotary harrow may be more effective than flexible tyres under certain conditions and circumstances. Also, sowing the tramlines had no consistent effect on soil erosion.

b) Sediment control on agricultural land in Scotland

Where runoff concentrates, such as along the edge of the field, a stable, non-eroding watercourse (e.g. shallow grass lined channel) can be established to safely carry runoff away. Vinten et al. (2004) demonstrated that a 1 m width of grassed strip, in a field with 5^0 slope, produced <10% of the soil loss compared to bare soil (Vinten et al., 2004). Silt fences have been shown by Vinten et al. (2014) to retain sediment upslope (whilst not impacting on erosion processes).

Given future climate change predictions, adhering to policies and associated practices such as Cross Compliance (Good Agricultural and Environmental Condition) and Water Framework Directive will help to reduce future soil erosion (Lilly et al., 2018).

3.4. Costs of soil erosion in Scotland

3.4.1. On-site costs of soil erosion in Scotland

On-site costs are typically incurred by private individuals and include the loss of production of crops, fibre, fuel, fodder, genetic resources, pharmaceuticals, biochemicals and industrial products (Frye et al., 1982).

a) Production costs incurred on-site in Scotland

Davidson and Harrison (1995) note that a general down-slope movement of soil through erosion was changing the distribution of the resource in an erosion survey in the Borders region. Frost and Spiers (1984) reported soil erosion from a single rainfall event caused the loss of 0.15 t ha^{-1} winter barley (at the time worth £18.00) and 3.75 t ha^{-1} peas (at the time worth £20.60). In a season with severe erosion, Frost and Spiers (1984) estimated a cost of £26.80 ha^{-1}, but when averaged over a longer period, they believed the cost would be less because of variable levels of soil erosion.

Frost and Spiers (1984) estimated potential loss of organic matter from a loamy soil at a field sites in Kelso, Roxburghshire. They estimated, via a model, that with an annual rate of soil loss of 25 t ha^{-1}, the organic matter level would change from 2.5 % (for an intensive cereal rotation on this site) to 1.6%. This loss of 0.225 t ha^{-1} of organic matter is the equivalent of 14 bags of compost, which if costed at £5 for 16 kg would represent a replacement cost of c. £70 per ha.

b) Mitigation or remedial costs incurred on-site in Scotland

As well as a cost associated with damage caused by the erosion event per se, there are also costs associated with management solutions to reduce soil erosion. This may include extra labour costs, cost of materials and extra fuel costs. However, the evidence for monetary costs associated with erosion control measures for Scotland is quite sparse. Some exceptions to this are given below.

Frost and Spiers (1984) noted that it also took 2 people 3 days with a tractor and trailer to infill gullies resulting from a single rainfall event, at an estimated cost of £150 for the machinery use alone. The same authors estimated that replacing the 0.225 t ha^{-1} of organic matter lost through soil erosion annually would require the equivalent of 14 bags of compost, which if costed at £5 for 16 kg would represent a replacement cost of c. £70 per ha.

The case study in Lilly et al. (2018) shows how the use of low inflation tyres, a spiked harrow, sowing in tramlines and a rotary harrow to control soil erosion had no effect on fuel use or crop yield. Frost and Ramsay (1996) provided estimates of cost of controlling soil erosion for a range of potential erosion control measures in the Greens Burn Catchment, Perth and Kinross (Table 54). This included the annual net fall in profits (rather than expressed as costs per se) when using a range of erosion control measures, including change in cropping practice, change in rotation and terracing. To prevent eroded soil from leaving the field, a number of silt fences were tested. The cost of this installation in 2012 was £13.55 per m for the product “Terrastop premium”, £13.18 per m for “Square mesh 5 monofilament” and £12.58 per m for “Terrastop Mono 60” (Vinten et al., 2014).

Table 54. Estimated reduction in soil erosion losses in Greens Burn catchment obtained for a range of potential soil erosion control measures (from Vinten et al, 2004)

Option	Erosion Reduction Expected (%)	Annual net fall in profit (%)
Cultivation change + 20% grass	50	11
Cultivation change + 40% grass	75	40
Spring sown cereals & OSR	50	49
Spring sown cereals & OSR + 20% grass	75	55
Increase Grass to 40% of rotation	50	34
Increase Grass to 60% of rotation	75	58
Diversion terracing (wider spacings)	50	23
Diversion terracing (narrower spacings)	75	54

3.4.2. Off-site costs of soil erosion in Scotland

Scottish accounts of the off-site costs of erosion are sparse. Observations of erosion events from 1985 - 2007 by Watson and Evans (2007), recorded the costs of erosion events to include clearing the sediment from blocked culverts under public roads which had to be excavated and re-tarred. Sediment had to be removed from the Aberdeen-Inverness railway near Insch. Deposition of eroded material following an erosion event led to flooding of arable land across Aberdeenshire and Angus (with associated costs of lost production). Wade et al. (1998) reported that an erosion event in 1993 resulted in several hours of work needed to keep the A92 Cupar-St Andrews road clear of sediment. Halcrow Water (2001) reported damage to turbines caused by sediment accumulations near power intakes, leading to increased sediment loads in the water passing through the turbines, which accelerated turbine wear.

3.4.3. The total costs of soil erosion in Scotland

Glenk et al. (2010) propose a useful framework for identifying costs of soil erosion per hectare in Scotland. This covers: on-site costs associated with losses in production (typically incurred by private individuals such as farmers). These were termed ‘private costs’ (PC; e.g. costs for soil nutrient replacement to maintain yields); on-site costs associated with expenditure on mitigation measures (also usually incurred by private individuals, protecting their land against soil erosion). These were termed ‘mitigation costs’ (MC; e.g. expenditure on measures needed to control soil erosion); off-site costs incurred by society as a whole. These were termed ‘social costs’ (SC; (e.g. CO_2 emissions due to soil erosion that ultimately affect global warming, climate change and associated impacts) and; off-site costs of expenditure on infrastructure that will mitigate societal costs (known as ‘defensive expenditure’ (DC), for example, costs of treating drinking water).

These costs may be either incurred by land based industries and businesses at sites where erosion takes place. Once ‘off-field’, the effects of soil erosion are felt at larger spatial and temporal scales, and costs are often borne by society as a whole. A summary of the results is shown below (Table 55). However, the paucity of direct data for Scotland meant that Glenk et al. (2010) had to use figures not specifically derived for Scotland, including from England and Wales.

Table 55. Summary of soil erosion cost estimates across categories (from Glenk et al., 2010)

	Cost category (£2009/ha)[a]				
	Private costs (PC)	Mitigation costs (MC)	Social costs (SC)	Defensive expenditure (DC)	total
Upper bound estimate (unadjusted mean)	6.63	17.52	101.31	15.50	140.96
Intermediate estimate (adjusted mean)[b]	4.53	1.71	51.47	15.50	73.21
Lower bound estimate	0.31	0.00	12.84	0.00	13.15
Source: adapted from Görlach et al (2004). [a] Costs initially quoted in €2003 in Görlach et al., these were converted to £2003 using average 2003 £/€ exchange rate (0.692) and deflated to £2009 values using UK GDP deflator (0.866). [b] Lowest and highest values excluded from calculation of the mean.					

4. Discussion

This section discusses the evidence of soil erosion rates, impacts, mitigation measures and associated costs for Scotland. The information available is then put into a wider context by considering evidence either from generic sources or from other appropriate geographical locations. Finally, where gaps are found in the Scottish data that hinder the estimation of total soil erosion costs, alternative approaches are proposed (Section 4.5).

4.1. Rates of soil erosion

The literature review (and number of items published) suggests that soil erosion by water is the dominant erosion process in Scotland (although other forms of soil erosion may be underreported). Even so, soil erosion by water often only affects a small percentage of the area under investigation at any one time. Limitations of the current evidence base for rates of soil erosion in Scotland include a tendency to focus on small areas of severe or catastrophic soil erosion rather than a systematic approach to monitor and assess the more insidious erosion.

Observed erosion rates in arable areas of Scotland range from 0.01 t ha^{-1} yr^{-1} to 23.0 t ha^{-1} yr^{1} (Table 51), which can be compared with those in England and Wales as collated by Owens et al. (2006; Table 56). It is also possible to compare these rates with a suggested tolerable rate of soil loss of less than 1 t ha^{-1} yr^{-1} (Verheijen et al., 2009).

Table 56. Soil erosion rates in England and Wales (from a review by Owens et al., 2006)

	Wind erosion	Tillage erosion	Co-extraction on roots crops, farm machinery etc.	Water	Scotland water
Typical erosion rate range (t ha^{-1} yr-1	0.1 – 2.0	0.1 - 10	0.1 – 5.0	0.1 – 15.0	0.01 – 23 t ha yr
Land use affected	Arable, upland, some pasture	Arable	Arable	Arable, pasture, upland	
Eroded soil exported off field?	Yes	No	Yes	Yes	

From the literature, there are many factors affecting soil erosion rates in Scotland. Baggaley et al. (2017) demonstrated the importance of land use in determining soil erosion rates, which seemed to be more prevalent in agricultural fields that were more intensively managed e.g. the eroding / eroded field was under potatoes within the preceding 8 years, or had had spring or winter cereal crops for 3 or more years. Studies elsewhere have demonstrated the same strong links between land use and soil erosion rates (Evans, 1990a, 2013; Evans *et al.*, 2016). For example, Leeks and Robers (1987) report that the suspended load in a watercourse in the Coalburn catchment in the Pennines over a 5 year period following cultivation under agroforestry was estimated to be the equivalent of ca. 50 years soil loss from the catchment prior to cultivation (Leeks and Robers, 1987).

Other land uses are also associated with soil erosion, especially newly planted and recently felled forest (Table 51). Much of the erosional processes are centred on haul roads and drainage ditches, as well as the prepared / cleared land that has little cover to protect from rainfall and runoff. Data on the proportion of forested areas affected by soil erosion is sparse. Zimke (2016), working in catchments in West Germany remarks that ‘Often, road network densities greater than 100 m per ha can be observed”. Zimke (2016) also notes that skid trails also have a massive influence on hydrological properties in the forest. Unlike roads, skid trails may be harder to identify and because of this could lead to an underestimated percentage of runoff (and associated erosion) from the area.

As well as land use (both current and historic), soil type and slope are often cited in the literature as factors affecting soil erosion rates in Scotland. Other factors include antecedent moisture content, ground cover and presence of tramlines, making it difficult to be certain when, or if and to what extent soil erosion will occur.

In terms of processes operating, almost uniquely in Britain, Scotland experiences soil erosion in arable areas due to snowmelt. The severity of erosion by snowmelt depends on the depth of snow, the distribution of the snow, rate at which the snow melts and the amount and timing of rainfall during the thaw phase (Wade et al., 1998). Information on depth of snow alone is not sufficient to predict erosional response. Rain falling on snow increases erosional risk as it both generates direct runoff and supplies heat for snowmelt, which adds to runoff. These results demonstrate that erosion rates from snowmelt are dependent on circumstances acting in combination rather than on any one dominant influence. In other areas of the world where snowmelt also contributes to soil erosion, research suggests that snowmelt and heavy rains can work in opposition (Rodzik et al., 2009). Erosive runoff from snowmelt helps to develop gullies, but sediment deposition maintains a shallow profile. However, heavy rainfall then removes the accumulated sediment and deepens the gully profile. The role of snowmelt in aggravating soil erosion rates in Scotland may change under future climate change scenarios. Although the occurrence of frost and snowfall may reduce under climate change predictions, warmer springs may result in more rapid thawing of fallen snow, leading to greater runoff discharge (and erosion risk).

Sediment deposits in reservoirs can be informative with respect to rates of erosion at a catchment level. Suspended sediment loads give indirect indication of trends in soil erosion, but direct estimates are difficult to obtain especially in large catchments where many other factors such as runoff from urban areas may contribute to changes in suspended sediment loads (Lilly and Baggaley, 2014b). Sediment studies are less informative about specific rates of soil erosion from soil types and land uses i.e. the origin of the erosion event and its impacts (Duck and McManus, 1988). However, advances in sediment fingerprinting and tracing technology is enabling better interpretation of sediment sources (Owens et al., 2016).

Due to the paucity of field observations in Scotland, researchers have used soil erosion prediction models to estimate the rates of soil erosion. Based on the application of the Pan European Soil Erosion Risk Assessment model (PESERA; Kirkby, Gobin and Irvine, 2003), many areas of Scotland would experience <1 t ha^{-1} under 1989-1998 rainfall patterns and land uses, although these were primarily upland or grassland areas with expected low erosion risk (Lilly et al., 2009). The arable areas of eastern Scotland on the other hand were predicted to experience >2 t ha^{-1} yr^{-1} based on the dominant crop type in each 1km^2 grid cell (Lilly and Baggaley, 2014b). This compares with a tolerable rate of soil loss of less than 1 t ha^{-1} yr^{-1} (Verheijen et al., 2009). However, as the PESERA model was run on a 1 km grid, small areas of steep slopes and localised high-risk soils are not picked up. Other models such as the Revised Universal Soil Loss Equation (RUSLE) and WaTEM/SEDEM when applied to Scotland using European-scale soil data, tend to predict less soil loss than PESERA (see Appendix 1 of Lilly et al., 2018). However, it is important to note that these models have not been validated for Scotland.

Soil erosion models with sediment yield as an output seem to exaggerate the amount of soil loss and are also difficult to validate (Lilly et al., 2018). Evans et al. (2016) suggest that soil erosion models fail to predict actual erosion rates in Britain because they are often based on severe soil erosion events, which in reality are spatially contained in any individual year. Mean erosion rate across a landscape being a lot lower than individual eroded fields (Evans, 2013). This poses a spatial extrapolation challenge for soil erosion modelling as rates of soil lost cannot be simply extrapolated to all fields in any given year (Evans et al., 2016). Also, as mentioned above, sediment yields, loads and concentrations are not directly linked to the sources / origins of the erosion process. However, soil erosion models do offer a way to examine relative changes in soil erosion rate under different land uses and changing climates (Lilly et al., 2018). Current ruled based models do allow an assessment of soil erosion risk to help minimise impact.

In conclusion, the current review has found few studies that quantify rates of soil erosion observed in Scotland. This evidence gap is acknowledged by Glenk et al. (2010), whose analysis had to be “based on studies from outside Scotland, such as the EU report prepared by Ecologic (Görlach et al., 2004) and the ADAS study commissioned by Defra (ADAS, 2006) and the Soil Strategy for England Supporting Evidence Paper (Defra, 2009)”. The Soil Monitoring Action Plan (SoilMAP) highlighted the need for more systematic data to assess the current state of soil erosion in Scotland (Black et al., 2012). This is supported by a recent report by the Committee on Climate Change (2019), who report that “there are insufficient data and metrics to assess the vulnerability of soils to climate impacts” and “appropriate metrics have not yet been identified or measured for rates of soil erosion, including the uptake of soil conservation measures by farmers”.

4.2. Impacts of soil erosion

There is some evidence of the impacts of soil erosion on different ecosystem goods and services in Scotland. Understanding these impacts and finding evidence of them is the first step in estimating the costs of soil erosion.

4.2.1. On-site impacts of soil erosion

Single soil erosion events rarely cause significant problems for farmers, but over time may impact on the long-term sustainability of the land and can still result in loss of ecosystem goods and services (Davidson and Harrison, 1995; Carling et al., 2001).

A loss of provisioning services due to soil erosion is often the first on-site impact that most people think about. However, there is very little evidence of the quantitative loss of crop yield due to soil erosion in Scotland. The work by Frost and Spiers (1984) near Kelso is one of the most comprehensive works on the impact of soil erosion on land capability in Scotland. Frost and Spiers' work highlights how difficult it can be to attribute losses in production to the rate of soil loss. Lal and Moldenhauer (1987) supported the idea that "although the visual effects of soil erosion can be spectacular, the effects of erosion on crop yields are hard to quantify". This has led to reports of soil erosion enhancing yields; having no effect on yields; slightly reducing yields; to causing complete crop failure. Lal and Moldenhauer (1987) argued that the effects of soil erosion can be cumulative and take a long time to impact yield. The confusion over soil erosion / productivity relationships is due to the complexity of the system and the multiple influences that affect crop performance and yield (Lal and Moldenhauer, 1987). Where the soil is deep, the on-site impact of erosion is not expected to threaten crop production for many years (Bakker et al., 2007; Evans, 2017).

Towers *et al*., (2006) also suggest that soil erosion in Scotland had only minor impacts on soil functions including food and biomass production, carbon storage and gas balance, habitats and biodiversity, heritage and regulating water flow and quality, although regulating water flow (quantity) and quality was locally important.

Frost and Spiers (1984) also considered the potential loss of soil moisture storage due to soil erosion. It is acknowledged that a loss in soil depth (for example by soil erosion) leads to a reduction in available storage space for water within the depleted topsoil and the reduced soil moisture storage capacity of subsoils exposed after erosion of the topsoil (Lal and Moldenhauer, 1987). A reduction in soil moisture storage capacity can, in dry years, cause plant stress, reducing plant quality and quantity (Lal and Moldenhauer, 1987). However, in wetter years, when there is still a sufficient reservoir of water for a plant to access, the impact of soil erosion will be less obvious (Lal and Moldenhauer, 1987). The ability of the soil to store water not only affects plants but also determines soil hydrological functions such as the time between start of rainfall and the generation of overland flow. This function is an important factor affecting soil erosion risk (Lilly and Baggaley, 2014b).

In the Scottish Soil Framework (2009) it is suggested that soil erosion can expose artefacts leading to their degradation and loss. The work by Davidson et al. (1998) gave a good account of how tillage erosion (e.g. soil disturbance using a plough) may impact archaeological sites. Others have attributed ploughing as the greatest agent of attrition to archaeological sites around the world (Wilkinson et al., 2006). However, no other studies were found for Scotland that related other soil erosion processes (e.g. by water) to potential loss or damage of historical artefacts.

Other on-site impacts of soil erosion on ecosystem goods and services have been reported elsewhere (Table 57), but no published data of these impacts (e.g. loss of soil biota, loss of above ground biota and reduced landscape value) was found specifically for Scotland in the literature review. This suggests there is an evidence gap for Scotland.

Table 57. 'On-site' ecosystem services (related to soil functions) and soil erosion impacts

Ecosystem services		Soil erosion impact
Provision	Support of food, fuel, fodder and fibre production	Loss of soil depth leading to stunted root development and limited availability of water and nutrients) Direct crop damage (e.g. displacement of crops; wind abrasion)
	Providing raw materials	Loss of soil depth
Regulation	Regulating the flow of and filtering substances from water	Reduced water holding capacity of exposed subsoils
	Storing carbon	Reduced soil carbon (organic matter content) in subsoil
	Soil fertility / quality	Reduced soil productivity
Supporting	Support of below-ground biodiversity	Loss of soil biota
	Support of above-ground biodiversity	Loss of (above ground) biodiversity
Cultural	Protection of cultural heritage and archaeology	Exposure of archaeological features leading to increased risk of damage
	Cultural landscapes	Reduced landscape value

4.2.2. Off-site impacts of soil erosion

The present review and others (e.g. Frost and Spiers, 1984; Frost and Speirs, 1996) have found little supporting evidence within Scotland for the off-site impacts of soil erosion. Exceptions to this include the sedimentation of reservoirs (Duck and McManus 1988 & 1990). Potential off-site impacts of soil erosion on the wider environment are also discussed by Lilly and Baggaley, 2014a. In the Scottish Soil Framework (2009), it is suggested that soil erosion in Scotland contributes to increased suspended sediments and turbidity in watercourses, which can diminish water quality and damage aquatic life, including salmon spawning grounds. Sediment associated pollutants, such as phosphates, were also thought to contribute to eutrophication of water bodies.

The evidence of off-site soil erosion impacts in Scotland lacks quantification. Part of the problem seems to be that off-site impacts are not always considered when making risk assessments of soil erosion (Boardman et al., 2019). However, recent soil erosion risk mapping has been aimed specifically at reducing the impact of land-based activities on water quality (Lilly et al, 2014a).

In other areas of the UK and Europe, even in areas where soil erosion in not considered to be an on-site problem, off-site damages such as diffuse pollution and muddy floods have still been reported (Boardman et al., 2019). For example, in the Wissey catchment in Norfolk, Eastern England, where soils in the catchment were only considered to be at slight or moderate risk of erosion (Evans, 1990), sediment on the riverbed was still observed to be having an impact on fish stocks (River Wissey Partnership, 2014). In the Rother Valley, West Sussex, and other UK rivers, excessive sediment loads in the river have been reported as causing damage to the local trout fisheries through sedimentation of gravel-beds used by the trout as spawning grounds (Sear, 1996; Kemp et al., 2011). Excessive sediment also affects invertebrates causing an imbalance in the aquatic ecosystem (Bond and Downes, 2003; Yeakley et al., 2016; Conroy et al., 2018). Nationally, Collins et al. (2009) suggest that 76% of suspended sediment in rivers is from agricultural sources.

In a report by Halcrow Water (2001), accumulation of sediments in reservoirs in Britain are reported to cause a range of problems:

- Increased flood risk due to greater likelihood of reservoir / dam overtopping in storm events
- Reduced storage capacity in the reservoir
- Build-up of sediment against the dam causing instability in some structures
- Sediment load in intake water leading to accelerated wear and tear on turbine blades

Despite these studies, Spencer et al. (2008) claim there is insufficient evidence available to quantify off-site damages from soil erosion. Other off-site impacts of soil erosion on ecosystem goods and services have been reported elsewhere (**Table 58**), but little evidence of these impacts was found specifically for Scotland in the literature review. This suggests there is an evidence gap for Scotland. Comparing the current evidence for off-site impacts of soil erosion for Scotland with the wider known impacts, reveals several data gaps for Scotland including rates and impact on siltation / deposition of eroded material in rivers, effects on aquatic habitats, eutrophication of water bodies and recreational water quality.

Table 58. 'Off-site' ecosystem services affected by soil erosion

Ecosystem services		Soil erosion impact
Provisioning	Support of food, fuel, fodder and fibre production	Reduced yields (food, fuel, fodder and fibre production) due to sedimentation
	Energy	Sedimentation affecting capacity of hydroelectric reservoirs Sediment causing abrasion to water turbines
Regulation	Drainage / discharge of water	Siltation of water courses
	Flood regulation	Siltation of water courses which affects their water holding storage capacity, increasing the risk of flood events (exceeding bankfull discharges)
	Provision of drinking water	Water treatment costs to remove pollutants & sediments
		Reservoir capacity
	Water quality	Water pollution from chemicals adsorbed onto eroded soil (especially phosphorus) Eutrophication of lakes
Supporting	Infrastructure	Obstruction of roads, culverts, drainage ditches etc. due to sedimentation
	Wetland habitat	Degradation of riverine / wetland habitats due to siltation and pollution Sediments affecting wetland biodiversity Increased water turbidity of receiving waters, affecting aquatic habitats such as salmon spawning beds and freshwater pearl mussels
Cultural	Recreation	Siltation of waterbodies affecting fish habitat (angling) and navigable waterways (boating, tourism).
	Health	Air pollution by soil particles (wind erosion)

4.3. Mitigation of soil erosion

The Scottish Soil Framework identifies six policies protecting soils, including planning, conservation and biodiversity, water quality and flooding, pollution, land use and management and cultural heritage. However, finding the evidence related to the uptake, use (and effectiveness) of soil erosion mitigation measures in Scotland is challenging. Whilst the current review has found only limited evidence of the use of erosion mitigation measures in Scotland, this should not be interpreted to mean that they are not necessarily being used: it could be their use is simply under-reported. The Committee on Climate Change (2019) call for better metrics on the uptake of soil conservation measures by farmers. Examples of mitigation measures from elsewhere are discussed below in terms of their suitability in Scotland.

While cover crops are often put forward as an option to control soil erosion during winter months in England, over-winter ground cover is often difficult to achieve in Scotland. This is because of late harvesting and subsequent late sowing leading to poor establishment (Vinten et al., 2004), although a well-established cover crop may provide a more complete cover than a poorly established winter cereal. Cover cropping may also have low uptake because their residues are also slow to anaerobically decompose in the spring in Scotland (Vinten et al., 2004).

The Demonstration Test Catchments (DTCs) were established by the Department for Food and Rural Affairs (Defra) to gather data on the effectiveness of options to mitigate diffuse agricultural pollution from a farmed landscape. Outputs from this scheme are beginning to provide important evidence. Whilst it is recognised that the environmental conditions of the DTC catchments are very different to Scotland, some principles of soil erosion mitigation are transferable. For example, in the Wissey DTC, observations have shown that fragmented mitigation is less likely to be effective at reducing diffuse pollution (usually associated with soil erosion). This requires most farmers in any catchment or landscape to sign up to a range of mitigation options in order to effectively reduce the off-site impact of soil erosion. Boardman et al. (2019) suggest that because off-site damage may not be caused by high rates of soil erosion from fields, mitigation methods should also focus on interrupting the flow of runoff, encouraging infiltration and diverting flows from sensitive receiving areas. A long-term study in north Norfolk, UK, corroborated the effectiveness of interrupting connectivity on reducing soil erosion (Evans, 2006).

Soil erosion mitigation methods used in the UK to reduce erosion rates on-site and reduce offsite sediment loads are listed in Table 59. Posthumus et al. (2015) estimated the costeffectiveness of some of these measures (see below). However, few of these measures are mentioned in the reviewed literature concerning Scotland specifically. It is uncertain whether this is because the measures are not used, or are simply not reported. This represents an evidence gap in estimating the total costs of soil erosion (and its mitigation) in Scotland.

Table 59. Mitigation methods to control on-site soil erosion and off-site sediment damage (adapted from Cuttle *et al*., 2007)

Category	Mitigation method
Land use	Convert arable land to extensive grassland Grow crops less damaging to the soil at time of harvest (avoid sugar beet and potatoes)
Soil management	Establish cover crops in the autumn
	Cultivate land for crop establishment in spring rather than autumn
	Adopt minimal cultivation systems
	Cultivate compacted tillage soils
	Cultivate and drill across the slope
	Leave autumn seedbeds rough
	Avoid tramlines over winter
	Establish in-field grass buffer strips
	Loosen compacted soil layers in grassland fields
	Maintain and enhance soil organic matter levels
	Allow field drainage systems to deteriorate Better timeliness of cultivation, drilling and harvesting
Livestock management	Reduce overall stocking rates on livestock farms
	Reduce the length of the grazing day or grazing season
	Reduce field stocking rates when soils are wet
	Move feed and water troughs at regular intervals
Farm infrastructure	Fence off rivers and streams from livestock
	Construct bridges for livestock crossing rivers and streams
	Re-site gateways away from high-risk areas
	Establish new hedges
	Establish riparian buffer strips
	Establish and maintain artificial (constructed) wetlands Construct retention ponds Silt fences, straw bales and filter socks Grass waterways

Several studies have looked at the effective of mitigation measures in controlling runoff, soil erosion and loss of phosphorus (P) (e.g. Posthumus et al., 2015; Table 60). Different mitigation measures were assessed to have different effectiveness (expressed as % reduction). These results will reflect the reduction in soil erosion rates and associated impacts. For example, infield buffer strips were estimated to reduce runoff, soil erosion and phosphorus loss by 50%, 25% and 25% respectively, compared with having no buffer strip installed in the field.

Table 60. Effectiveness of soil erosion mitigation options in terms of % reduction in runoff, soil erosion and P loss (after Posthumus et al., 2015)

Mitigation measure	Reduction of runoff	Reduction of soil loss	Reduction of P loss
Cover crops (winter)	10%	10%	25%
Cover crops (under sown maize)	10%	10%	25%
Geo-textiles	50%	25%	25%
Mulching	25%	50%	50%
In-field buffer strips	50%	25%	25%
Riparian buffer strips	50%	50%	50%
High density planting	50%	25%	25%
Crop rotation (spring crops)	2%	2%	50%
Timeliness	2%	2%	50%
Land use change (arable to pasture)	50%	50%	25%
Agro-forestry	50%	50%	50%
Shelterbelts	10%	10%	25%
Subsoiling	2%	2%	25%
Drainage	2%	2%	25%
Reduced tillage	2%	25%	25%
Zero tillage	10%	25%	50%
Tramline management	80%	80%	80%
Coarser seedbeds	2%	25%	25%
Stocking density	10%	10%	25%
Contour ploughing	50%	50%	50%
Swales	50%	25%	25%
Earth banks	50%	25%	25%

4.4. Costs of soil erosion

The ‘on-site’ and ‘off-site’ costs of soil erosion are incurred in many different ways, affecting a diverse range of ecosystems services and benefits to people, over a range of spatial and temporal scales. This makes estimating the costs of soil erosion particularly challenging. This may explain the limited quantified evidence on soil erosion costs in Scotland.

4.4.1. On-site costs of soil erosion

a) Costs of reduced crop yields due to soil erosion

Davidson and Harrison (1995) discuss the impact of soil erosion on Scottish crop yields (and therefore farm income). Studies from elsewhere have found that yield reductions are typically between 0.03 and 0.05% per tonne soil lost (e.g. Biot and Lu, 1995; Hodges and Arden-Clarke, 1988; Owens et al., 2006). Evans (1996) estimated that loss of productivity from loss of soils and nutrients amounts to £9 million for England and Wales. The degree of yield loss depends upon the soil profile characteristics, the crop grown, soil management, and the microclimate (Lal, 1985; Posthumus and Stroosnijder, 2009). Impact of soil erosion on soil productivity depends on the quality and quantity (i.e. depth) of remaining soil and is thus location-specific.

The effect of soil erosion on crop yields is frequently given in relation to a change in soil depth (Pimentel et al., 1995; Lal, 1998). Observed reductions show wide variation, depending on the crop grown (e.g. rooting character), soil profile characteristics (e.g. nutrient storage and availability; water holding capacity), existing soil and crop management, and the site's weather and microclimate (Pimentel et al., 1995; Lal, 1998). Since erosion induced yield declines are of considerable importance, especially in low input agriculture, modelling tools such as EPIC (EPIC: Erosion-Productivity Impact Calculator; http://epicapex.brc.tamus.edu/) have been developed to examine long-term effects of various components of soil erosion on crop production.

Based on a variety of measured data, Pimentel et al. (1995) found that as a result of soil erosion, crop yields declined by 20% over a period of 20 years. Graves et al (2011) developed a simplified approach, using the relationships developed by Pimentel et al. (1995) to predict erosion induced yield penalties (Table 61; Appendix C). The total yield penalty was calculated to be £5.4 million per year for England and Wales, much of this associated with silts and sands, especially where under arable and horticultural use.

Table 61. Soil erosion induced yield penalties as developed from Pimentel et al. (1995).

	Yield penalty (%)		
	Over 20 years	Average annual	per mm loss of soil depth due to erosion
Water runoff	7	0.35	0.3
Nitrogen Phosphorus Potassium	8	0.4	0.3
Soil depth	7	0.35	0.3
Organic matter	4	0.2	0.1
Water holding capacity	2	0.1	0.1
Soil biota	1	0.05	0.0
Total on-site	20	1	0.74

b) Erosion induced losses in soil carbon (C) and nutrients (N, P and K)

The literature review found no economic data on these losses specifically for Scottish soils. Theoretically, the costs of erosion induced losses of soil carbon and nutrients (N, P and K) can be estimated from the following information:

- the content of C and nutrients in the soil (that may be lost through soil erosion processes);
- the degree of soil loss, with associated C and nutrients within the eroded soil;
- the economic cost of the C and nutrient losses, in terms of the cost of replacing them.

c) on-site expenditure on soil erosion mitigation measures

Despite the work by Lilly et al. (2018) and Frost and Ramsay (1996), the evidence for on-site expenditure on soil erosion mitigation measures in Scotland is sparse. Frost and Spiers (1984) discuss the additional field operations (and their costs) needed to rectify any damage done by soil erosion, including addition of organic matter to replace that carried away in the eroded soil.
Information that is missing on mitigation measures in Scotland includes:

- investment costs (materials and implementation costs)
- maintenance costs
- hindrance of farming operations
- loss of productive land; and
- loss of high value land use in case of land use change.

These costs, however, may vary from field to field, depending on soil type, land use, and skills of the farmer. Some mitigation measures will be easier to implement, less costly and have a greater effectiveness than others. Table 62 contains an example of the different types of onsite costs of mitigation measures and an average annual cost per hectare (taken from Posthumus *et al.*, 2015). Dividing the investment costs by the lifetime of the mitigation measures, and adding the annual maintenance costs gives the average annual cost.

Table 62. An example of on-site costs of soil erosion mitigation measures (taken from Posthumus et al., 2015)

Mitigation measure	Investment costs (£ ha^{-1})	Maintenance costs (£ ha^{-1})	Hindrance to farming operations	Loss of agricultural production	Total annual cost (£ ha^{-1})
Cover crops (winter cover)	148	25	None	Switch from winter cereals to spring cereals : £175	348

Cover crops (under sown)	75	25	None	None	100
Geotextiles	257	5	Negligible	£27 (cereals) to £47 (general cropping)	80 to 100
Mulching	100	0	None	None	50
In-field buffer strips (6m)	32	1.5	Some	£32 (cereals) to £56 (general cropping)	40 to 64
Riparian buffer strips (6m)	32	1.5	None	£32 (cereals) to £56 (general cropping)	40 to 64
High density planting	5	None	None	None	5
Crop rotation	None	25	None	Change in value of agricultural production	-6 to 306
Timeliness	None	70	Potentially high	Potentially high	70

Table 63. An example of on-site costs of soil erosion mitigation measures (taken from Posthumus et al., 2015)…continued

Mitigation measure	Investment costs (£ ha^{-1})	Maintenance costs (£ ha^{-1})	Hindrance to farming operations	Loss of agricultural production	Total annual cost (£ ha^{-1})
Land use change (arable to grass)	Potentially very high if change in agricultural enterprise	None	None	Cereals to pasture: £281; General cropping to pasture: £607	281 to 607
Agro-forestry	503	Variable	Huge hindrance	Potentially high: major change in land use	25
Shelterbelts	670	0	Low	£11 (cereals) to £19 (general cropping)	44 to 52
Subsoiling	48	None	None	None	16
Drainage	2,000	Negligible	None	None	80
Reduced tillage	None	50	None	£32 (cereals)	82

Zero tillage	Possibly purchase of specialist machinery	67	None	£32 (cereals)	99
Tramline management	None	20	None	None	20
Coarser seedbeds	None	34	None	None	34
Stocking density	None	40	None	£85 ha^{-1} for dairy (RPA 2003)	125
Contour ploughing	None	32	not suitable for slopes > 10%	None	32
Swales	212	Negligible	May cause some hindrance	Dependent on size swale & land use	14
Earth banks	218	Negligible	Potentially high	£11 (cereals) to £19 (general cropping)	55 to 63

These costs of soil erosion mitigation measures can be off-set by the benefits these options bring. Examples of these are given in Table 64 (Posthumus et al., 2015). These include savings in field operations (labour and fuel), positive impacts on yield / productivity, financial benefits of ‘by-products’, and any applicable agri-environment payment schemes (Table 64). Knowing the costs and benefits of different soil erosion mitigation measures allows for cost benefit analysis of the different options (Table 66; Posthumus et al., 2015).

Table 64. An example of on-site benefits of soil erosion mitigation measures (from Posthumus et al., 2015)

Mitigation measure	Cost savings in field operations	Impacts on yield	Resulting byproducts	Agrienvironment payments (if applicable)	Total annual benefit (£ ha^{-1})
Cover crops (during winter)				Higher Level Scheme (HLS): £200 ha-1	200
Cover crops (under sowing maize)	None	Retain status quo		HLS: £18 ha^{-1}	18
Geotextiles	None	Retain status quo	None	None	0
Mulching	None	Increase	None	None	0

In-field buffer strips (6m)	None	Retain status quo		HLS: £400 ha-1	24
Riparian buffer strips (6m)	None	None		HLS: £400 ha-1	24
High density planting	None	Increase (due to crop density) +10%?	None	None	
Crop rotation	None	None	Depending on changes	None	0
Timeliness	None	None	None	None	0
Land use change (arable to extensive grass)	None	N/A		HLS: £210 ha^{-1}	210
Agro-forestry	None	Retain status quo	Depending on tree species	HLS: £190 ha^{1} (creating orchards); £95 ha^{-1} (managing orchards)	105
Shelterbelts	None	Retain status quo	None	HLS: £5 m^{-1} (for planting); £0.27 m^{-1} (maintenance)	52
Subsoiling	None	Increase?	None	None	0
Drainage	None	Increase?	None	None	0
Reduced tillage	Cuttle *et al*. 2007: £40 ha^{-1}	Retain status quo	None	None	40

…….continued

Table 65. An example of on-site benefits of soil erosion mitigation measures (from Posthumus et al., 2015)...continued

Mitigation measure	Cost savings in field operations	Impacts on yield	Resulting byproducts	Agrienvironment payments (if applicable)	Total annual benefit (£ ha^{-1})
Zero tillage		Retain status quo	None	HLS: 70	70
Tramline management	None	None	None	None	0
Coarser seedbeds	Rolling: £26 ha^{-1} (Nix 2009)	Retain status quo	None	None	26
Stocking density	None	Retain status quo	None	HLS: 40	40
Contour ploughing	None	Potential yield increase (16%) cereals (Quinton and Catt, 2004)	None	None	85
Swales / sediment traps	None	None	None	CSF: £6 m^{-2} (investment costs)	1
Earth banks	None	None	None	HLS: £3 m^{-1}	60

Table 66. An example of on-site costs and benefits analysis (£ ha^{-1}) of soil erosion mitigation measures (from Posthumus et al., 2015)

Mitigation measure	Lifetime of the measure (years)	Annual financial costs (£ ha^{-1})	Annual financial benefits (£ ha^{-1})	Net annual benefit (£ ha^{-1})	Benefit-cost ratio (for 5 year period)
Cover crops (during winter)	1	315	200	-115	0.64
Cover crops (under sowing maize)	1	100	18	-82	0.18
Geotextiles	5	80 to 100	0	-99 to -79	0
Mulching	2	50	0	-50	0
In-field buffer strips (6m)	5	40 to 64	24	-40 to -16	0.38 to 0.60

Riparian buffer strips (6m)	5	40 to 64	24	-40 to -16	0.38 to 0.60
High density planting	1	5	0	-5	0
Crop rotation	1	-6 to 306	0	-306 to 6	0.02 to 7.0
Timeliness	1	70	0	-70	0
Land use change (arable to extensive grass)	1	281 to 607	210	-397 to -71	0.35 to 0.75
Agro-forestry	20	25	105	80	1.32
Shelterbelts	20	44 to 52	52	0 to 8	0.83 to 0.88
Subsoiling	3	16	0	-16	0
Drainage	25	80	0	-80	0
Reduced tillage	1	82	40	-42	0.49
Zero tillage	1	99	70	-29	0.71
Tramline management	1	20	0	-20	0
Coarser seedbeds	1	34	26	-8	0.78
Stocking density	1	125	40	-85	0.47
Contour ploughing	1	32	85	54	2.13
Swales / sediment traps	15	14	1	-13	0.07
Earth banks	5	55 to 63	60	-2 to 6	0.98 to 1.12

4.4.2. Off-site costs of soil erosion

Few studies quantified the wider, off-site costs of soil erosion in Scotland. Watson and Evans (2007) and Wade et al. (1998) recorded the costs of erosion linked to clearing sediment from roads and Halcrow Water (2001) reported damage to turbines caused by sediment accumulations near power intakes, leading to increased sediment loads in the water passing through the turbines, which accelerated turbine wear.

There is little data on the impacts on water quality from eroded soil reaching watercourses. This represents a significant evidence gap, but studies from elsewhere can be used to estimate the likely off-site costs of soil erosion in Scotland. For example, the damage caused in waterbodies by nutrients carried on eroded sediments was estimated for England and Wales by Graves et al (2011; Table **67**). Specifically, the off-site damage cost associated with N in the eroded soil in rivers and canals was estimated to be £2.9 million. The off-site damage cost associated with the P in eroded soil in lakes (e.g. through processes such as eutrophication) was estimated to be £6.8 million (Table 70).

Table 67. Summary of economic data used to estimate off-site cost of soil erosion in the water environment (from Graves et al., 2011 and Anthony et al. 2009).

Source		Pollutant	Cost	Unit
Environmental water quality	Rivers, canals	NO_3-N Nitrate	161	£ t^{-1}
	Freshwater lakes	P	1,407	£ t^{-1}
	Transitional water	NO_3-N Nitrate	8.9	£ t^{-1}
Drinking water quality		NO_3-N Nitrate	172	£ t^{-1}
		Soil / sediment	15.4	£ t $soil^{-1}$

However, data on the proportion of C in eroded material that is released to the atmosphere to form CO_2 is lacking. Lal (2003) proposes that approximately 20% of the soil C that is eroded each year is emitted to the atmosphere as CO_2. The ratio of organic C in the soil to CO_2 in the atmosphere is given as 3.67 (Williams, Audsley and Sandars, 2006), and the assumed quantity of eroded C emitted to the atmosphere was multiplied by this ratio to obtain its Global Warming Potential (t CO_2e). Using these assumptions, the cost of GHG emissions from eroded soils in England and Wales was estimated by Graves et al. (2011) to be £8.5 million (Table 70).

There are also few studies that quantify the costs of defensive or remedial measures that reverse the off-site damage caused by soil erosion in Scotland. Other studies (e.g. (Anthony et al., 2009) have derived a 'per unit' cost (£ 172 t^{-1} NO_3-N) for removal of nitrate from drinking water. Anthony et al. (2009) also derived a 'per unit' cost of £15.4 t^{-1} to remove sediment from drinking water. From these estimates, Graves et al. (2011) estimated the costs of removing sediment from drinking water to be £45 million for England and Wales.

Although no data was found for Scotland, the off-site costs of dredging sediment from water courses was estimated for England and Wales as £9.9 million, with an agricultural apportionment of 95%, giving a total cost (adjusted to 2009) of £9.8 million (Graves *et al*., 2011).

4.4.3. Overview of soil erosion costs

The literature review reveals that evidence on soil erosion costs in Scotland has not expanded significantly since Glenk et al's work in 2010. There are difficulties in gathering data on costs of soil erosion and often the figures reported are not specific to Scotland (e.g. Alam, 2018). The paucity of direct data for Scotland meant that figures not specifically developed for Scotland had to be used by Glenk et al. (2010), namely for England and Wales. Transfers of soil related costs were made to Scotland, on the basis of rough apportionments from England and Wales' estimates and relative agricultural activity. Glenk et al. (2010) admit that transferring these generic estimates of soil erosion costs to Scotland "may not be valid beyond giving the broad range of potential values". This is because of:

- Differences in soil erosion rates and frequencies;
- Differences in soil types;
- Crop types: some may not be relevant to Scotland;
- Crop yield, as affected by environmental conditions and year of study, which reflects trends in yield over time;
- Crop price; this may be related to crop attributes (quality) or year of study (reflecting fluctuations in market prices); and
- Input prices; these will vary according to the system being used or year of study.

Another example of this approach is given in the Environmental Accounts for Agriculture (Jacobs and SAC, 2008; as further developed by Defra), which bases soil erosion costs on channel dredging costs in England and applies these to Scotland on the basis of the relative area of arable land. This calculation gives a damage cost estimate for Scotland of £1.3m in 2008 for example.

The present study will improve on Glenk et al.'s (2010) methodology by taking these issues into account specifically for each of the identified case study catchments (Work Package 3). This approach is recommended by Glenk et al (2010), who "suggest that soil erosion costs estimates for Scotland could be obtained by a case study approach in a small number of representative catchments where there is an identified risk of soil erosion". Where possible, actual measured / observed rates of erosion in those catchments, their associated impacts and mitigation measures will be used to estimate total costs of soil erosion. However, where data are missing, 'proxy' data from elsewhere may have to be used to produce an estimate of soil erosion costs in Scotland (see Section 4.5).

4.5. Data gaps and how to address them

As presented above, the evidence on soil erosion rates in Scotland, their impacts, mitigation measures and associated costs is currently limited. The following section will propose a methodology that will allow the costs of soil erosion to be estimated for the study catchments, where there are gaps in the information.

4.5.1. Estimating soil erosion rates in the study catchments

Where observed data on soil erosion rates is not available for the chosen case study catchments in Scotland, these could be estimated from a 'look up' table that presents typical erosion rates from similar sites in Scotland where data is available.

The look up table is populated with actual erosion rates observed for a combination of factors affecting erosion (e.g. soil type, slope and land use). This approach was used by Graves et al. (2010) who found similar gaps in the evidence on soil erosion rates in England and Wales. Here, observed erosion rates for soil texture / land use combinations were used to populate the table (**Table 68**). It was assumed that wherever the same combination of factors occurred, similar erosion rates would be expected. It should be noted that rainfall was not taken into account. This is because land use was deemed more influential on erosion rates than annual precipitation (Evans, 1990b). A similar table could be created using Scottish data where available.

It should be noted that erosion occurs only on a proportion of the total land area in each category each year. The method developed by Graves et al (2011) necessitates an estimate of these proportions across the defined soil type / land use / slope steepness categories. This can be based on the soil erosion risk map (Lilly and Baggaley, 2018) and land cover to assess the actual percentage.

Table 68. 'Look up table' of soil erosion severity (H = High; M = Medium; L = Low) and measured soil erosion rates in England and Wales by soil type (texture)/ land use combinations (from Graves et al., 2011)

Land use	Soilscapes							
	Clay	Typical rate* (t ha-1 yr-1	Silt	Typical rate* (t ha^{-1} yr^{-1})	Sand	Typical rate* (t ha^{-1} yr^{-1})	Peat	Typical rate* (t ha-1 yr^{1})
Urban	L	0	H	10	H	5	n/a	n/a
Horticulture	L	2	H	20	H	5.08 (Evans, 2002)	H	15
Arable intensive	L	1.92 (Evans, 2002)	H	22.1 (Morgan et al., 1987) 22.7 (Robinson and Boardman, 1988)	H	16 (Reed, 1983; 1986) 22.1 (Morgan et al., 1987) 22.7 (Robinson and Boardman, 1988)	H	20
Arable extensive	L	0.9 (Deasy et al., 2008; 2009) < 2 (Cooper, 2006)	M	3.2 (Deasy et al., 2008; 2009) 4.5 (Brazier, 2004) 11.2 (Fullen, 1992)	H	0.4 (Deasy et al., 2008; 2009); 0.75 (Quinton and Catt, 2004); 1.48 (Brazier, 2004) 3.47 (Cooper, 2006) 11.2 (Fullen, 1992)	H	10
Grassland improved	L	0.36 (Brazier, 2004)	M	4.09 (Evans, 2002) 4.89 (Brazier, 2004)	M	4.09 (Evans, 2002)	H	7
Grassland unimproved	L	1.29 (Brazier, 2004)	M	2.07 (Brazier, 2004)	M	1.5	H	10

Rough grassland	L	0.05	M		M	0.22 (Brazier, 2004)	H	10
Forestry	L	0.01	L	0.5	L	0.05	M	0.7
Woodland	L	0.01	L	0.5	L	0.05	M	0.7
Wildscape	L	0.01	L	0.5	L	0.05	M	0.7

*Notes:

Data from Evans (2002) do not specify soil type, but do specify crop / land use. Reasoned assumptions have been made as to which soil type is used for various crops (e.g. oilseed rape on heavy (clay) soil).
Data from Brazier (2004) derives from Evans (1988, 1993) and Skinner and Chambers (1996). These erosion rates relate to soil types only: No land use data are given. Reasoned assumptions have been made regarding likely land use for different soil types and resulting erosion rates as presented in Brazier (2004).
Data on arable soil erosion rates have been split between intensive and extensive arable: highest rates have been assumed to apply to intensive arable; lowest rates are assumed to apply to extensive arable.

This information can then be used to calculate an estimated gross erosion (t) for each land use/soil type/slope category, and; b) an estimated mean erosion (t ha^{-1}) for each land use/soil type/slope category at the local, regional and national scale. Using this approach for land use and soil type alone, Graves et al (2011) estimated soil erosion rates in England and Wales to be 2.9 Mt yr^{-1}, which is similar to the 2.2 Mt yr^{-1} estimate given by the Environment Agency.

Where soil erosion mitigation measures are used in the study catchments, their effectiveness in controlling erosion (Table 60) can be used to reduce expected soil erosion rates.

4.5.2. Estimating the impacts of soil erosion in the study catchments

Simple soil erosion / yield penalty models (e.g. Pimentel et al., 2015) can be used to predict the impact of soil erosion on yields (Table 61), taking account of the soil erosion rates in the study catchments (see Section 4.5.1).

To calculate the losses in soil carbon and nutrients due to soil erosion processes, a similar approach to Graves et al. (2011) can be used. The National Soil Inventory topsoil dataset was used to obtain the mean soil carbon (C), phosphorus (P) and potassium (K) content of each of the land use/soil type categories (and associated erosion rates as shown in **Table 68**. The results are given in Appendix C . Whilst this approach estimates the quantity of C, N, P and K in the soil, it is worth noting that erosion selectively takes the most important components of the soil first and eroded soil can typically contain three times more nutrients than the soil left behind (Sharpley, 1980; Lal, 1998; Ali I, Khan and Bhatti, 2006). Enrichment ratios measure the relative concentrations of carbon and nutrients in the deposited material (sediment) and in the soil from which that eroded material came. The range of enrichment ratios used by Graves et al (2010) to estimate nutrients and carbon lost in eroded soil are shown in Table 69.

Table 69. A range of enrichment ratios to show the proportion of nutrients in eroded soil (sediment) relative to the parent (uneroded) soils and the enrichment ratios used by Graves et al. (2011).

Nutrient	Range of enrichment ratios	Mean Enrichment Ratio (ER)
Total P	1.32 – 3.04 (Zheng et al., 2005) 1.47 (Sharpley, 1985) 2.79 (Ali et al., 2006)	2.15
OC / OMC	1.08 – 1.4(Zheng et al., 2005) 0.9 – 2.6 (Schiettecatte et al.,) 2.00 (Sharpley, 1985) 1.23 (Ali et al., 2006)	1.56
Total N	0.89 – 1.26 (Zheng et al., 2005) 1.61(Sharpley, 1985) 1.43 (Ali et al., 2006)	1.37
Total K	2.90 (Ali et al., 2006)	2.90

4.5.3. Estimating the costs of soil erosion in the study catchments

Many of the impact costs can be derived from the Scottish Farm Management Handbook (2018/19). For example, the loss of crop yields due to erosion will affect gross margin data. Whilst outputs will be affected by the yield penalties, variable costs (seed, fertiliser, sprays, etc.) for growing the crop will remain the same. As a result, economic margins are likely to be reduced.

The on-site economic cost of losing nutrients and C through soil erosion (i.e. adsorbed on eroded soil) can be quantified by investigating the costs of replacing them. Estimates of N, P, K losses associated with soil erosion (see Appendix) can be multiplied by the fertiliser price of N, P and K, (£ kg^{-1}) obtained from the Farm Management Handbook (2018/19). In 2018/19, this was £0.0.67 / kg N; £0.68 / kg P_2O_5 and £0.45 / kg K2O for N, P and K respectively (SAC Consulting, 2018).

For soil carbon, the benefits of soil organic matter (a proxy for soil carbon) (such as ease of tillage, crop germination, feasibility of minimum tillage, better yields, and resistance to compaction) were used to calculate the impact of its loss through soil erosion. The calculations gave the benefit / costs as £0.3 to 0.5 t^{-1} OM yr^{-1} or £0.5 to 0.83 t^{-1} C yr^{-1}. The mean of these estimates was assumed to be the net benefit of carbon in the soil (£0.67 t^{-1} C yr^{-1}).
Regarding off-site costs of soil erosion, Graves et al. (2011) assumed that all eroded material was removed from the fields and discharged into water bodies. (In reality, sediment delivery from the eroded hillside to adjacent watercourses is highly dynamic in space and time as it is dependent on complex relationships between sediment characteristics and availability; erosion, transport and deposition processes; weather events; the nature of natural and artificial pathways linking sediment sources to the river network; slope length and gradient; land use and management practices; and the spatial distribution and density of the receiving watercourses (Rickson, 2014)).

The off-site costs of dredging sediment from water courses was estimated for England and Wales (Graves et al., 2011). A given value of £9.9 million was used, with an agricultural apportionment of 95%, giving a total cost (adjusted to 2009) of £9.8 million This was then divided by the sediment load 1,906,260 t yr^{-1} given for England and Wales by Anthony et al, (2009) to give a unit cost of £5.15 t^{-1} of eroded soil. Knowing the total rates of soil erosion meant the off-site damage cost associated with soil removal from rivers and canals in England and Wales was estimated to be £15 million (Table 70).

4.5.4. Summary of the total costs of soil erosion: a case study from England and Wales

Graves et al (2010) summed all the costs of soil erosion to estimate the total cost of soil erosion for England and Wales (Table 70). Overall, the estimated on-site impacts (£47m) were substantially less than the estimated off-site costs of £81 million. The loss associated with lost productivity was relatively minor (£5.4 million) and it is primarily the replacement value of the stock of nutrients that are removed in the eroded material that comprise the majority of the on-site costs. The off-site costs are primarily associated with the cost of removing sediment, both from drinking water (£45 million) and from watercourses (£15 million).

Table 70. Summary of soil erosion costs for England and Wales (from Graves et al., 2011).

Physical data	Total areas at risk within categories (ha)	1,022,459
	National soil erosion (t yr^{-1})	2,920,626
	Average national soil erosion (t ha^{-1} yr^{-1})	0.21
	Soil N loss (t yr^{-1})	18,026
	Soil P loss (t yr^{-1})	4,830
	Soil K loss (t yr^{-1})	38,280
	Soil C loss (t yr^{-1})	225,787
On-site costs	Total E&W productivity loss due to erosion (£)	5,357,516
	E&W productivity loss due to erosion in risk area (£ ha^{-1})	5.2
	Total E&W productivity loss due to erosion in total area (£ ha^{-1})	0.4
	Total E&W N loss cost due to erosion (£)	11,176,177
	Average E&W N loss cost due to erosion (£ ha^{-1} risk area)	10.9
	Average E&W N loss cost due to erosion (£ ha^{-1} category area)	0.8
	Total E&W P loss cost due to erosion (£)	3,284,425
	Average E&W P loss cost due to erosion (£ ha^{-1} risk area)	3.21
	Average E&W P loss cost due to erosion (£ ha^{-1} category area)	0.24
	Total E&W K loss cost due to erosion (£)	19,905,772
	Average E&W K loss cost due to erosion (£ ha^{-1} risk area)	19
	Average E&W P loss cost due to erosion (£ ha^{-1} category area)	1.43
	Total E&W C loss cost due to erosion (£)	7,902,534
	Average E&W C loss cost due to erosion (£ ha^{-1} risk area)	8
	Average E&W C loss cost due to erosion (£ ha^{-1} category area)	0.57
Off-site costs	Cost of N in drinking water (£)	3,100,488
	Cost of sediment removal in drinking water (£)	44,977,637
	Cost of N in rivers and lakes (£)	2,902,201
	Cost of N in transitional waters (£)	160,43
	Cost of P in freshwater lakes (£)	6,795,861
	Cost of sediment removal in rivers & canals (£)	15,041,223
	GHG cost of soil C loss (£)	8,452,098
Total costs	Total onsite cost	47,626,423
	Total offsite cost	81,429,940

5. Conclusion

Comprehensive, quantitative data on the spatial and temporal extent of soil erosion in Scotland is currently limited (Lilly and Baggaley, 2014b). This finding is supported by the Committee on Climate Change (2019), who report that “there are insufficient data and metrics to assess the vulnerability of soils to climate impacts” and “appropriate metrics have not yet been identified or measured for rates of soil erosion, including the uptake of soil conservation measures by farmers”. Much of what is known about soil erosion rates in Scotland comes from a few, individual studies of erosion events, often gathered in response to a severe erosion event. The main focus of much of this work has been on the form of erosion and the magnitude of the erosion event, with the majority of observations focused on agricultural (often arable) land. Soil erosion will continue, especially if winter cereals remain a dominant crop in the Scottish landscape (Lilly and Baggaley, 2014b). Rates will increase under the climate change projections for Scotland of heavier rainfall and an increase in winter rainfall (Committee on Climate Change, 2019).

Compared to information on soil erosion rates in Scotland, the reviewed evidence suggests less attention has been paid to the on- and off-site economic and environmental impacts and associated costs of erosion. This might be because the assessment of costs of soil erosion (and its mitigation) is not a simple process. The costs of soil erosion cannot be judged simply by what soil erosion has cost the producer and the consumer, as it also incurs costs that are not paid for by either, termed ‘externalities’ by Pretty et al. (2000). Externalities include costs for example of cleaning up roads, polluting the environment and/or producing water fit for consumption. Pretty et al. (2000) defined five features of externalities relating to the agricultural sector that are also relevant to soil erosion: 1) externality costs are often neglected; 2) they often occur with time lags; 3) they often damage groups whose interests are not represented; 4) the identity of the producer of the externality is not always known; and 5) they result in sub-optimal economic and policy solutions.

Because of its diffuse nature, it is difficult to quantify soil erosion induced externalities for a particular farm field / site. Not all soil erosion will lead to off-site damage. In addition to the challenges of identifying all the costs of soil erosion, assigning an economic value to these costs is also complicated, as these values can be subjective. The OECD (2003) report that “Off-site costs of erosion and sediment redistribution are probably at least an order of magnitude greater than on-site (private costs). It should be noted that there is considerable ambiguity in quantification of off-site costs, and especially in how to quantify the impact of agriculture on soil and other natural resources (air and water). This ambiguity needs to be addressed”. Furthermore, it is unlikely that the impact of soil erosion on ecosystem services follows a linear relationship (i.e. as erosion rates accelerate, the impact on ecosystem goods and services may be amplified).

Whilst the literature review demonstrates that evidence on soil erosion rates, impacts, mitigation and costs in Scotland tends to be anecdotal rather than quantitative, there are proven approaches that can estimate these parameters in a logical and justified manner. These estimates may have some uncertainty, given the paucity of data. Even so, this information can then be used to calculate an estimated mean soil erosion rate for different combinations of land use/ soil type/ slope at the local, regional and national scale (along with likely impacts and associated costs).

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7. Literature review appendices

Appendix A. Systematic review matrix (with example below)

Reference (Authors, title, date, source)	
Type of data (e.g. modelled, experimental, observational)	
Erosion type (water, wind, plough or co-extracted)	
Area of observation (e.g. field, farm or catchment), if possible give an indication of the area over which the erosion occurred (e.g. 10% of field).	
Number of sites (e.g. fields, farms or catchments) mentioned	
Number of erosion events data relates to (e.g. single rainfall event, annual erosion)	
Erosion rate (ideally as t ha^{-1} yr^{-1} otherwise make clear how rate is expressed)	
Land use and/or crop at time when soil erosion occurred (e.g. arable/maize, permanent pasture/grass, bare soil)	
Land management practices that may increase or mitigate soil erosion (e.g. drainage, reduced tillage, cross slope cultivations)	
Slope angle (degrees or %)	
Slope length (m)	
Soil texture (and/or soil type if given)	
Organic matter content of soil	
On-site costs (e.g. loss in yield/t ha^{-1} yr^{-1}, change in fertiliser use/t ha^{-1} yr^{-1}, cost of mitigation measures)	
Off-site costs (e.g. dredging/£ yr^{-1}, water treatment/£ yr^{-1})	
Impact on provisioning services (anything not covered in on-site costs)	
Impact on regulating services (e.g. change in carbon storage, change in water storage)	
Impact on supporting services (e.g. change in soil depth)	
Impact on cultural services (e.g. change in landscape characteristics)	
Additional notes (anything that you think may be helpful but not included above e.g. field rotation information)	
Useful references cited (to follow up)	

Example (over next 7 pages):

Reference (Authors, title, date, source)	Carling, P.A. et al., 2001. Reducing sediment inputs to Scottish streams: A review of the efficacy of soil conservation practices in upland forestry. Science of the Total Environment, 265(1–3), pp.209–227.
Type of data (e.g. modelled, experimental, observational)	Secondary (review paper), mostly observational
Erosion type (water, wind, plough or co-extracted)	Water
Area of observation (e.g. field, farm or catchment), if possible give an indication of the area over which the erosion occurred (e.g. 10% of field).	Soil erosion is usually very localised, such that even if soil loss per unit area is less than the natural rate of renewal, local damage can occur to the resource.
Number of sites (e.g. fields, farms or catchments) mentioned	Numerous (review paper)
Number of erosion events data relates to (e.g. single rainfall event, annual erosion)	Numerous (review paper)

Erosion rate (ideally as t ha^{-1} yr^{-1} otherwise make clear how rate is expressed)	Moffat (1988) reported maximum soil losses of 1.3 t ha−1 year−1 immediately after ploughing or harvesting. Subsequently, this reduced to less than 0.25 t ha−1 year−1. This latter value is approximately equivalent to the rate at which soil is formed naturally (Worrell and Hampson, 1997) A debate ensued (Moffat, 1989, Moffat, 1988, Soutar, 1989a, Soutar, 1989b, Stott, 1989), concerning the actual extent of the soil erosion problem (Moffat, 1991). Soil loss was typically 40 kg m−1 of furrow length for all soil types — in particular sandy or loamy soils were found to be at risk. Given well-designed drainage networks, soil loss recorded as suspended load or bed load ranges between 32 and 1331 kg ha−1 year−1 (Soutar, 1989a, Soutar, 1989b). The furrows were excessively long (195 m) and this resulted in an initial soil yield of 29.76 t ha−1 for 1 year. Ninety-five percent of this sediment was entrapped in a dolloped buffer strip at the end of the furrows. In contrast, the mole system lost most sediment during February snowmelt events in each of the first 2 years after the initial ploughing whereas the furrows by this time had been stabilised by vegetation. The initial yield from the mole runs was much less than from the furrows, between 0.56 and.72 t ha−1 for 1 year. Given the receiving drain emptied firstly into a catch pit, and then subsequently into a dolloped buffer strip, only some 36 kg ha−1 year−1 of sediment is likely to have entered the stream network. Johnson and Brondson (1995b) monitored suspended sediment yields from road surfaces within Kirkton forest, Balquhidder, Scotland. The sediment yields from a heavily trafficked forest road, both before and after regrading, were between two and 10 times greater than from a little-used old road.

	However, there was no evidence that this sediment reached any watercourses.
Land use and/or crop at time when soil erosion occurred (e.g. arable/maize, permanent pasture/grass, bare soil)	Upland forestry

Land management practices that may increase or mitigate soil erosion (e.g. drainage, reduced tillage, cross slope cultivations)	Furrows Ploughing Vegetated buffer strips Cross drains Worrell (1996) identifies ten cultivation techniques ranging from ploughing to direct planting — 'notch-planting' — the later technique involves zero cultivation. Mounding, dolloping, scarifying, hand turfing and screefing are increasingly being used, often in association with second rotations, where the presence of roots and stumps largely preclude ploughing. Of these techniques, to date, only moling has been considered in terms of potential soil loss. A study of the effect of the revised 'Guidelines' showed that between 1996 and 1997 cultivation of the Halladale catchment in Scotland for afforestation led to no significant increase in soil erosion and no damage to aquatic ecology (Forest Research, 1997). Similar reports were received from studies in Kintyre, Scotland, and at Waun Maenllwyd in mid-Wales (see Nisbet, 1996). Francis (1987) speculated that moling should result in less soil loss than the use of furrows. Preliminary data comparing mole drains and furrows on the same site in Glen Skibble, near Skipness in Kintyre, showed that soil losses might be comparable (Carling et al., 1993). Additional research has been conducted by the authors near Newcastleton in the Southern Uplands.

Slope angle (degrees or %)	Various
Slope length (m)	Various
Soil texture (and/or soil type if given)	Various
Organic matter content of soil	Various
On-site costs (e.g. loss in yield/t ha^{-1} yr^{-1}, change in fertiliser use/t ha^{-1} yr^{-1}, cost of mitigation measures)	n/a

Off-site costs (e.g. dredging/£ yr^{-1}, water treatment/£ yr^{-1})	In some reviewed cases off-site impacts were reported. Specifically, in a few instances potable water-supplies were affected (Austin and Brown, 1982, Stretton, 1984) and claims were made that aquatic habitats were damaged (e.g. Maitland et al., 1990). In contrast, Carling and Orr (1990) could not identify any in-stream impacts on invertebrates in a Scottish salmon and trout stream.
Impact on provisioning services (anything not covered in on-site costs)	n/a
Impact on regulating services (e.g. change in carbon storage, change in water storage)	Fine sediment in watercourses Sedimentation Raised water tables
Impact on supporting services (e.g. change in soil depth)	Waterlogged soils
Impact on cultural services (e.g. change in landscape characteristics)	n/a
Additional notes (anything that you think may be helpful but not included above e.g. field rotation information)	Firstly much greater emphasis needs to be given to the significance of impacts rather than overall magnitude. Secondly, greater emphasis needs placing on developing practical solutions to problems rather than reporting the magnitude of the disturbance. In other words prevention is possible, eliminating the need for remedial action.
Useful references cited (to follow up)	• Carling and Orr, 1990. Response of benthic macroinvertebrates and salmonid fish in a Scottish stream to preafforestation drainage. Unpublished Report to the Atlantic Salmon Trust, 1990:30. • Duck, R.W. 1985. The effect of road construction on sediment deposition in Loch Earn, Scotland. Earth Surf Process Landforms, 10 (1985), pp. 401-406 • Ferguson RI, Stott TA. 1987a Forestry and sediment yields in upland Scotland. In: Beschta et al., editors. Erosion and sedimentation in Pacific rim steeplands. Proc Corvallis Symposium, Int Assoc Sci Publ, 1987a;165:499–500.

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	Scotland. Earth Surf Process Landforms, 22 (1997), pp. 383-399 • T.A. Stott, R.I. Ferguson, R.C. Johnson, M.D. Newson, 1986. Sediment budgets in forested and unforested basins in upland Scotland. IAHS Publ, 159. (1986), pp. 57-68 • Swift and Norton, 1993. Measures for protecting upland water quality: assessment of forestry buffer strips. Unpublished Report No. SR 3442/1 produced for the Scottish and Northern Ireland Forum for Environmental Research (SNIFFER) by Wrc plc, Medmenham, 1993. • R. Worrell. 1996. The environmental impacts and effectiveness of different ground preparation practices • Scott Nat Heritage Res Surv Monit Rep, 52 (1996), p. 55

Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water Winter 1994-5 and Winter 1995-6 (Nov to June)	Brown earths (Sourhope series) NO3653224945 Noncalcareous gleys (Mountboy Series) Brown earths (Macmerry series) Noncalcareous gleys (Winton Series)	3-13 degrees		Wormit farm (NO367247); North Callange Farm (NO 42081 12232); North Fife in general	Obs and data	Field; and area 6 fields, 2 on each farm in 1994-5. One on each farm 1995-6 Cereal at farm monitoring sites, some arable and grassland at observational sites With-slope cultivation and wheelings	Field 1: Wormit: 7.7 t km-2 yr-1 Field 2: Wormit: 32.2 t km^{-2} yr-1 Field 3: North Callange: 531.4 t km^{-2} yr-1 Field 4: North Callange: 548.1 t km^{-2} yr-1 Field 5: Wormit: 283.1 t km^{-2} yr-1 Field 6: North Callange: 101.2 t km^{-2} yr-1	Wade (1998)

Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water, Annual observation of erosion events (midMarch, 1985-2007)	Sandy loams or loams, freely or imperfectly drained	1.9-2.7% (rills <1 cm) 7.7% (rills 10-25 cm)		Mearns near Stonehaven	Observational	>136 fields, Winter cereal, winter oilseed rape, ploughed fields and other fields with much bare ground (e.g. turnips, potatoes and bulbs).	% of fields with erosion 59% erosion from winter cereals with rills of <1 cm 9% erosion from winter cereals with rills of 1-10 cm 4% erosion from winter cereals rills of 10-25 cm 12% oilseed rape with rills of <1 cm 1% oilseed rape with rills of 1-10 cm	Watson and Evans (2007)

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Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water, multiple events Winter 1985-1956				Kincardine and Angus	Observational	11 fields, cereal, ploughed, oilseed rape, reseeded grass, potatoes	The mean value between 1982 and 1984 was 6.7 $m^3\ ha^{-1}$	Watson and Evans (1991)
Rainfall on snow, 2 x snowmelt events (1993 and 1996)	Light textured and stony and underlain by compact till or fluvioglacial sand and gravel below a depth of 30-50 cm.	RM = 8.3º over 350m EP = 10.0º over 230m WK = 9.5º over 170m All fields convex-concave in form Precedent		Rumgally Mains (RM; NO 4014), Easter Pitscottie (EP; NO 4113) and Wester Kilmany (WK; NO 3821)	Observational	3 fields 1993, All fields were drilled up- and downslope and seeded to winter cereals.	A total of $214m^3$ of soil was removed from the three main gullies, excluding small feeder rills of which 127 m^3 was lost from one channel in a field at Rumgally Mains. RM soil loss (1993) 127 m^3,	

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Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
							sediment yield 12.7 t ha^{-1} EP soil loss (1993) 76 m^3, sediment yield 10.1 t ha^{-1} WK soil loss (1993) 12 m^3, sediment yield 0.8 t ha^{-1} Erosion rate in 1996 was <7% of the total estimated loss experienced in the 1993 event.	Wade and Kirkbride (1998)

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Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water	Aldbar series (freely drained podzols, with glacial till parent material derived from Old Red Sandstone) In lower lying area either side of the Baldardo burn there is a band of Forfar series (imperfectly drained cambisol, with water sorted parent material overlying glacial till derived from Old Red Sandstone sediments)	0 to 18%, concave slope.		Baldardo Farm, Angus eastern Scotland	Experimental	2 fields Potatoes Tine cultivation after potato harvest along approx. contours Full grubbing (tine cultivation) up and down Slope. Partial grubbing using 3 m widths every 40 m approx. along field contours Non-cultivated treatment	230 m^3 ha^{-1} or 345 t ha^{-1} at packing density of 1.5 t m^{-3}	Vinten et al. (2014)

Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water, multiple events				Lunan Water	Observational	Catchment	Suspended sediment range between 1167 mg l^{-1} for 3 storm events (Dec 08 to Feb 09)	Vinten et al. (2009)
Water, multiple erosion events				Greens Burn (GB), near Kinross, to the north of Loch Leven Cessnock Water (CW), Ayrshire	Observational	Field GB arable CW grass	For GB 48.1 tonnes in four months (?) 18.1, 20.2 and 755.2 kg suspended sediment – 8 Jan 04 (5.8mm rainfall) 1497.8, 156.7 and 994.4 kg suspended sediment	Vinten et al. (2004)

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Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
							– 29-30 Nov 03 (11.6 mm rainfall) Before installation on buffer strip suspended sediment 233 mg/l +-115 and 94+-62mg/l after	
Water				Lambieletham Reservoir (LR) Dunoon No. 3 Reservoir, Argull (D3R) Glen Ogle, deposited in L. Earn (GO)	Observational	Reservoir catchment area LR 1941-45 'bare-earth', after World War II, post 1960 government and EEC subsidy policy D3R Forestry	2-3 mm p.a. (1900-1920) 3-4 mm p.a. (1920-1940) 1.3-2 mm p.a. (19401970) 1.3-2.7 mm p.a. (19701985)	McManus and Duck (1988)

Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
							D3R 9100m3 capacity filled within 15 years (1960-70s) GO 4cm deposit over 4.6ha	
Water	Coyle: brown earths with gleying and noncalcaeous gles with slowly permeable subsoils and some alluvial soils. East Pow: larger component of permeable soils compared with the Coyle, but also a large proportion of alluvial soils.	<2º 2º-4.9º 5º-9.9º 10º-17.9º 18º-30º >30º		The Coyle (NS395214) Ayrshire and the East Pow (NO069256) Perthshire, both sub-catchments of SEPA's designated priority catchments	Modelled	2 catchments Coyle predominantly grassland East Pow predominantly arable	Erosion risk for specific soil textures categorised into Low, Medium and High based on slope and runoff	Lilly and Baggaley (2014a)

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Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water, single extreme event				Ugie and South Esk catchments.		439 fields	Observed erosion in 17 of the 439 fields (4% of fields) 16 fields in South Esk	Baggaley et al. (2017)
Water over multiple years	Sandy loam	6º to 9º		Balruddery Farm, Perthshire (NO305329)	Observations and data collection	Field, arable	Over 2 years ranged between 117 to 417 kg ha^{-1}	Lilly et al. (2018)
Water, singles rainfall event (50 mm of rainfall in 24 hours, 31 March 1992)	Sandy loams and sandy clay loams of the closely related Forfar and Balrownie associations D, S=33 Z=43 C=24 (%) H, S=39 Z=47 C=14 (%) K, S=54 Z=35 C=11 (%)	Generally less than 10 degrees, but locally up to 15 degrees	LOI D = 6.08 (%) H = 5.79 (%) K = 7.36 (%)	Douglastown (D; NO 418474), Hatton (H; NO 463430) and Kincaldrum (K; NO 430457) around the villages of Douglastown and Inverarity in Angus	Observations	20 km^2, 195 x Fields, ranging from 4-12 ha, many >8ha, 176 fields that hadn't been ploughed were assessed for erosion Mixed arable, sheep and dairy	30% of fields experienced some erosion 19% of fields rills developed 1.17 to 2.2 t ha^{-1}	Kirkbride and Reeves (1993)

Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
						68 field were bare (57 of these worked up and down slope) 62 were partially vegetated with young spring cereals (49 aligned up and down slope) 46 were grazed.	At D 1.73 t ha-1 At K 1.17 t ha-1 At H 2.22 t ha-1	

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate	* Reference
Water, Single event	Fields 1&2: USDA Sandy loam, Hobkirk Series (Brown earth). High proportion of fine sand. Field 1: clay = 12; silt =14 fs (up to 200 microns) 52; remainder 22% Field 2: clay = 10; silt =14 fine sand (up to 200 microns) 55; remainder 21%	Field1: 410 degrees, approx. 500m in length Field 2: 2 to <10 (*x*=5.5) degrees, approx. 400m in length	Field 1: 1.7% Field 2: 1.5%	Nr Kelso; farm name not given	Observational	Field: (approx. 10 ha): whole field affected but just 2 fields reported on Field 1: Winter barley Field 2: Peas	Field 1: 800 t so 80 t ha^{-1} in a single event, 4.7% of the area eroded Field 2: 48 t ha^{-1} in a single event. Estimate of > 6 t ha^{-1} yr1	Frost and Spiers (1984)

Water, Single rainfall event (1 in 20 yr event)	Winton, Kilmarnock, Humbie, Yester: fine textured tills with 24% clay, fs/z up to 50% - low to moderate erodibility Macmerry & Moreham: water modified tills with 20% (or less) clay and s/z of 40% - Erodibility greater than heavy glacial tills Hobkirk and Presmennan: 15-20% clay, vfs/z 60-65% ('coarse tills') – highly erodible Darvel: 5-15% clay but high medium – coarse sand. (glaciofluvial deposits) – moderately erodible	Flat to <20°, modal slope between 5-10%, LS factors between 0-16, with highest % (33% area) in 2-4 category. Slopes of >100m included		Between Haddington and Gifford, East Lothian. Colstoun Water, sub catchment of the Tyne.	Observational	565 fields, 36km^2 rectangular block (4x9km). Field size 1-48 ha (5-10 ha most common), arable crops and bare soil 75% arable 16% grass	1 to >100 t lost from fields Soil loss per hectare was not calculated and is not particularly meaningful, as in general soil loss did not occur uniformly over the whole field.	Frost and Spiers (1996)

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Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water, single rainfall event	Fluvioglacial ms and some gravel	3.8º , >70m long		Woodhill House Farm, Barry (NO523342)	Observational	Single field (6 ha), winter barley (newly sown). Adjacent potato field did not erode	70m gully (1.7m at deepest and 4.4 width), sediment 55 m^3 15 rills 10-20cm wide and 5 cm deep, sediment 10 m^3 Assuming Db of 1.6 g/cm^3 Implies 14.7 t ha^{-1}	Duck and McManus (1987)
Water	Mean diameter 2026µm, Caprington Series,Noncalcareous gley/Brown earth with gleying	Low relief		Lambieletham reservoir (NO502134)	Measured Depth of sediment accumulated between 1900-1984 (84 yrs)	Catchment (2.29 km^2), mixed arable with sporadic periods of increased intensification. During single observed storm event land sown to oil seed rape	0.021 t ha-1 yr-1 Single storm event of 0.45 t ha^{-1}	Duck and McManus (1988)

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Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water	Till and peat			Glenfarg (NO016110) and Glenquey (NN 980027) Reservoirs	Sediment core data from 2 catchments, Glenfarg 56 years, Glenquey 73 years	Glenfarg catchment (Σ $23.50 km^2$), arable with some woodland Glenquey catchment ($5.58\ km^2$), Moorland		Duck and McManus (1984)
Water				Glenfarg (NO016110) and Glenquey (NN 980027) Reservoirs	Sediment core data from 2 catchments	Catchment	$31.3\ t\ km^{-2}\ yr^{-1}$ for Glenfarg, and 9.0 t km–2 yr–1 for Glenquey	Duck and McManus (1990)
Water (singles erosions event 1992)	Predominantly freely drained brown forest soil of low base status (Sourhope Series_			West of Town Yetholm (NT 813282)	Observational	Field, arable	$105\ m^3$ or 5 mm from the field	Davidson and Harrison (1995)

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Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water (rainfall and snow melt over 18 days)	Balrownie (an imperfectly drained brown earth developed on water-sorted till with loam/sandy loam with sandy clay loam subsoil); Lour (a poorly drained noncalcareous gley with similar textures) Buchanyhill (a freely drained brown earth loam/sandy loam).			Strath Earn; Gask Ridge between the Earn and Pow Water	Observational	Ca. 44km^2, 208 fields	No rate of erosion given, only occurrence of erosion noted.	Davidson and Harrison (1995)
Tillage	Loamy sand or sand	Ca. 2^o, 180m		Littleour (NO17344024)	137 Cs technique	Field (6ha), one site, 24 observations Land in setaside (arable)	-2 mm yr^{-1} (top of the field) +2 mm yr^{-1} (bottom of the field)	Davidson et al. (1998)

…continued over

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water	Used data from European Soil Portal	Profile DTM LiDAR		River Tweed catchment	Modelled using PESERA	Catchment	Section 1 0.42 t ha^{-1} yr-1 Section 2 1.38 t ha^{-1} yr-1 Section 3 1.90 t ha^{-1} yr-1	Grabowski et al. (2014)
Water		slopes of 25-35º.			Observational	Forest with	136 kg ha^{-1} yr-1	Lewis and Neustein (1971)
Water, single event	Sandy or loamy soils Stagno-orthic gley soil with up to 30 cm peat, sandy loam texture.	10º-12.5º		Kintyre (NGR 896605)	Experimental observation	200 m long furrows under afforestation	40 kg m^{-1} yr-1	Carling et al. (1993)

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water and wind	Peat			Mid-Kame (HU 409596) Ward of Scousburgh (HU 387190), Shetland Islands	Observational, along transects, on four dates between 1982 and 1987	Hillside	Average surface losses ranged from 1.6 cm yr^{-1} to 3.3 cm yr^{-1}. Average over 4 yrs was 2.3 cm yr^{-1}.	Birnie (1993)

…continued over

Appendix B. Collation of evidence for rate and type of erosion experienced in Scotland…continued from previous page

Type of erosion	Soil type	Slope	Organic matter	Georeference	Type of data	Area of observation	Erosion rate*	Reference
Water and tillage				Loanleven, Blairhall and Littlelour	Observational, changes in ^{137}Cs along transects	Field	Mean net erosion Loanleven,1.18 kg m^{-2} yr^{-1}; Blairhall -0.27 kg m^{-2} yr^{-1}; Leadketty 2.30 kg m^{-2} yr^{-1} ; Littlelour 0.42 kg m^{-2} yr-1	Bowes (2002)

*+ve values indicate deposition and –ve values indicate erosion

Appendix C. Converting soil erosion rates to loss in soil depth

Graves et al. (2011) used the relationships given by Pimental et al. (1995) in Table 61 to provide a broad assessment of how erosion in England and Wales might potentially contribute to crop yield reductions and lost economic revenue for a series of soilscape categories, which they termed “soilscapes”. The soilscapes defined by Graves et al. (2011) included: i) urban, ii) horticultural production, iii) intensive arable production, iv) extensive arable production, v) improved grassland, vi) unimproved grassland, vii) rough grassland, viii) forestry, ix) woodland, and x) wildscape land uses. The soil type classes included: i) clay, ii) silt, iii) sand, and iv) peat soil types. The 40 soilscape categories that this combination produced were judged to be sufficiently different from each other, as to make treating them separately worthwhile for the purpose of estimating the economic costs of soil degradation. However, in order to estimate how soil depth loss would affect crop productivity in each soilscape, the various effects of soil erosion in reducing crop yield identified by Pimental et al. (1995) were expressed on a soil depth basis.

The annual soil depth loss (mm yr^{-1}) can be calculated from the mass of soil lost each year (t ha^{-1} yr^{-1}) and the bulk density (Mg m^3) using Equation 3.

$$\text{Depth of soil loss per annum (mm)} = \frac{\text{Mass of soil loss (t ha}^{-1}\ yr^{-1})}{\text{Bulk density of soil (m}^3)} \div 10$$

Equation 3

Over 20 years, the overall mass of soil loss was 340 t ha^{-1}. Given a bulk density of 1.25 Mg m^3, the application of Equation 1 meant that the effects on crop productivity described in Table 61 were associated with a total soil depth loss of 27.2 mm. On an annual basis, assuming that the soil was eroded at a mean rate of 17 t ha^{-1} yr^{-1}, the average annual reductions described in Table 61 were found to be associated with a soil depth loss of 1.36 mm yr^{-1}. Using these data provided by Pimental et al. (1995), the yield reduction associated with each mm of soil loss was calculated by Graves et al. (2011) to be approximately 0.74%.

Appendix D. Estimated contents of soil carbon and major nutrients (from Graves et al., 2011)

Organic C content (% by weight) is provided in NSI topsoil data and is measured either by loss-on-ignition or by dichromate digestion (**Table 71**). Total P and K concentrations (mg kg-1) were determined by inductively coupled plasma emission spectrometry in an aqua regia digest (**Table 73**; **Table 74**). The NSI topsoil database does not contain data on N concentrations, and this was therefore estimated from the C content of the soil. Commonly found ratios of C to N in soils vary from about 8 to 1 to 15 to 1, with 11 to 1 being typical (Brady and Weil, 2008). The 11 to 1 C to N ratio was therefore used to estimate the quantity of N that would typically be in the soil (Table 72).

Table 71. The mean carbon content (kg t^{-1}) calculated from the NSI topsoil dataset. Organic C content (% by weight) is provided in NSI topsoil and is measured either by loss-on-ignition or by dichromate digestion.

	C content (kg/t)			
Land use	Soilscapes			
	Clay	Silt	Sand	Peat
Urban	45	38	42	140
Horticulture	36	41	28	198
Arable intensive	39	44	29	166
Arable extensive	37	38	32	123
Grassland improved	49	40	47	104
Grassland unimproved	67	48	74	210
Rough grassland	63	53	56	141
Forestry	69	45	54	186
Woodland	47	38	47	124
Wildscape	88	51	94	250

Table 72. The mean N content (kg t^{-1}) estimated from the C content (kg t^{-1}) of the NSI topsoil dataset

	N content (kg/t)			
Land use	Soilscapes			
	Clay	Silt	Sand	Peat
Urban	4	3	4	13
Horticulture	3	4	3	18
Arable intensive	4	4	3	15

Arable extensive	3	3	3	11
Grassland improved	4	4	4	9
Grassland unimproved	6	4	7	19
Rough grassland	6	5	5	13
Forestry	6	4	5	17
Woodland	4	3	4	11
Wildscape	8	5	9	23

Table 73. The mean P content (kg t^{-1}) estimated from the NSI topsoil dataset

	P content (kg/t)			
Land use	Soilscapes			
	Clay	Silt	Sand	Peat
Urban	0.82	0.77	0.72	0.85
Horticulture	0.83	0.79	0.61	1.09
Arable intensive	0.84	0.83	0.66	1.06
Arable extensive	0.81	0.80	0.67	0.91
Grassland improved	0.86	0.79	0.69	0.80
Grassland unimproved	0.84	0.79	0.72	0.84
Rough grassland	0.82	0.82	0.71	0.80
Forestry	0.80	0.66	0.54	0.82
Woodland	0.81	0.71	0.65	0.78
Wildscape	0.77	0.73	0.63	0.74

Table 74. The mean K content (kg t^{-1}) estimated from the NSI topsoil dataset

	K content (kg/t)			
Land use	Soilscapes			
	Clay	Silt	Sand	Peat
Urban	5.07	4.63	3.71	3.54
Horticulture	4.88	4.70	2.42	2.79
Arable intensive	5.39	5.42	3.14	3.86
Arable extensive	5.46	5.18	3.55	4.13
Grassland improved	5.33	5.39	3.93	3.77

Grassland unimproved	5.19	5.27	3.68	3.01
Rough grassland	4.83	5.00	3.65	3.67
Forestry	5.12	5.18	2.79	3.31
Woodland	5.17	4.66	3.52	3.39
Wildscape	4.48	4.11	3.20	2.47

Appendix 2. Classifying land use of observed erosion sites (Evans' data) into broad land use types.

A simplification of the land use at the sites with observed erosion was made, depending on the way the soil is managed and disturbed (and thus at risk of erosion).

Land Use	LU_categories	Land Use	LU_categories
Apple_Orchard	Woodland	Onions	Horticulture
Asparagus	Intensive arable	OSR	Extensive arable
Bare_Soil	Extensive arable	Parsley	Intensive arable
Bare_Soil	Intensive arable	Parsnips	Intensive arable
Beetroot	Intensive arable	Peas	Extensive arable
Black_Current	Horticulture	Permanent_Grass	Improved grassland
Brassica	Intensive arable	Potatoes	Intensive arable
Brussell_Sprout	Intensive arable	Potatoes_Parsnips	Intensive arable
Cabbage	Intensive arable	Root_Crop	Intensive arable
Carrots	Intensive arable	Rose_Bush	Horticulture
Cauliflower	Intensive arable	Rye	Extensive arable
Daffodil	Horticulture	Soft_Fruit	Horticulture
Fallow	Extensive arable	Spring_Barley	Extensive arable
Field_Bean	Extensive arable	Spring_Beans	Extensive arable
Field_Vegetable	Horticulture	Spring_Cereals	Extensive arable
Fodder_Crop	Extensive arable	Spring_Crop	Extensive arable
French_Bean	Horticulture	Spring_Oats	Extensive arable
Fruit_Bush	Horticulture	Spring_Wheat	Extensive arable
Garlic	Horticulture	Strawberry	Horticulture
Grass	Improved grassland	Sugarbeet	Intensive arable
Hops	Extensive arable	Swede	Intensive arable

Kale	Extensive arable	Turnips	Intensive arable
Ley_Grass	Improved grassland	Wheat	Extensive arable
Linseed	Extensive arable	Winter_Barley	Extensive arable
Lucerne	Extensive arable	Winter_beans	Extensive arable
Maize	Intensive arable	Winter_Cabbage	Intensive arable
Maize / Carrots	Intensive arable	Winter_Cereals	Extensive arable
Market_Garden	Horticulture	Winter_Oats	Extensive arable
Mustard	Extensive arable	Winter_Wheat	Extensive arable
Oats	Extensive arable	Winter_Wheat_Barley	Extensive arable

Notes: Combinable crops, with soil disturbance only during land preparation, and relatively few field operations, were classified as “extensive”. Other crops that are managed in a similar way (e.g. peas) were classified as “extensive arable”. Whereas root crops, such as potatoes and similar, which require digging up with huge machines and cause a lot of soil disturbance, were classified as “intensive”.

‘Horticulture’ was used for those crops that would be much more based on labour inputs than on machinery, and which were smaller scale, more like market gardening. These include very highly managed land with polytunnels, soft fruit, flowers etc.…

Maize was originally classified as extensive rather than intensive, to reflect the operational management of the systems and in particular, the degree to which soil is disturbed during land preparation and harvest. However, the consensus was that maize is associated with high erosion risk due to: high % bare soil; slow / delayed establishment in cold springs; row crop (often up / down slope orientation); often grown on marginal / sloping ground; late planted; late harvested (often on wet soils, liable to compaction and with no time for overwinter cover crop etc.). Although the area of maize production in Scotland is small, it is generally seen as the most risky crop in terms of erosion vulnerability (see p18 of the Valuing your soils booklet: https://www.farmingforabetterclimate.org/wpcontent/uploads/2018/02/Valuing_Your_Soils_PG.pdf). As a result and for the purposes of this current project, maize is classified as ‘Intensive arable’.

Appendix 3. Input data for economic modelling (soil bulk density) L = Low, M = Medium, H = High erosion risk

Bulk density (Mg ha^{-1})	**L**	**M**	**H**	**Organo-mineral soils and peats**
Ugie				
Urban	-	-	-	-
Horticulture	0.97	0.97		0.30
Arable intensive	1.04	1.03	1.01	0.26
Arable extensive	1.07	1.01	1.00	0.24
Grassland improved	1.07	1.01	1.00	0.23
Grassland unimproved			1.02	0.10
Rough grassland	1.08	1.01	1.02	0.12
Forestry	1.06	0.91	0.83	0.17
Woodland	1.07	0.97	0.85	0.19
Wildscape	1.04	0.97		0.11
Pow				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	1.18	1.23	1.24	0.11
Arable extensive	1.16	1.26	1.23	0.21
Grassland improved	1.11	1.23	1.21	0.20
Grassland unimproved	#N/A	#N/A	#N/A	#N/A
Rough grassland	1.27	1.24	1.17	0.17
Forestry	1.16	0.75	0.65	0.14
Woodland	1.13	0.97	0.74	0.16
Wildscape	1.19	1.23		0.14
Girvan				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	1.19	1.16		
Arable extensive	1.21	1.19	0.73	0.17
Grassland improved	1.23	1.12	0.75	0.12
Grassland unimproved	1.06	0.90	0.70	0.11
Rough grassland	1.17	1.00	0.81	0.12
Forestry	1.12	0.95	0.86	0.12

Woodland	1.17	0.99	0.86	0.15
Wildscape	1.25	0.92	0.77	0.11
Esk				
Urban	-	-	-	-
Horticulture	1.18	1.21	0.00	0.00
Arable intensive	1.10	1.20	1.20	0.21
Arable extensive	1.12	1.19	1.16	0.20
Grassland improved	1.07	1.08	0.94	0.22
Grassland unimproved	1.00	0.93	0.81	0.22
Rough grassland	1.01	0.74	0.61	0.18
Forestry	1.07	0.72	0.75	0.19
Woodland	1.04	0.86	0.90	0.21
Wildscape	1.05	1.02	0.79	0.20
Tweed				
Urban	-	-	-	-
Horticulture	0.00	1.29	0.00	0.00
Arable intensive	1.31	1.23	1.13	0.19
Arable extensive	1.37	1.24	1.05	0.14
Grassland improved	1.17	1.10	0.99	0.18
Grassland unimproved	1.05	0.97	0.85	0.19
Rough grassland	1.07	0.95	0.82	0.16
Forestry	1.10	0.96	0.82	0.16
Woodland	1.14	1.04	0.90	0.17
Wildscape	1.04	0.96	0.85	0.14

Appendix 4. Input data for economic modelling (soil P content) L= Low, M = Medium, H = High erosion risk

P (kg t^{-1})	**L**	**M**	**H**	**Organo-mineral soils and peats**
Ugie				
Urban	-	-	-	-
Horticulture	1.51	1.52		1.44
Arable intensive	1.34	1.42	1.69	1.25
Arable extensive	1.15	1.27	1.60	1.00
Grassland improved	1.15	1.26	1.53	0.95

Grassland unimproved			1.60	0.64
Rough grassland	1.04	1.12	1.60	0.74
Forestry	1.03	1.09	1.17	0.89
Woodland	0.95	1.07	1.26	0.88
Wildscape	0.82	0.94		0.76
Pow				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	1.20	0.98	0.96	0.71
Arable extensive	1.05	1.00	0.96	1.06
Grassland improved	1.06	1.00	0.96	0.94
Grassland unimproved	#N/A	#N/A	#N/A	#N/A
Rough grassland	0.93	0.93	0.94	0.67
Forestry	0.79	0.80	0.78	0.68
Woodland	0.85	0.79	0.81	0.69
Wildscape	0.92	0.94		0.68
Girvan				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	1.30	1.23		
Arable extensive	1.16	1.02	1.35	1.09
Grassland improved	1.01	1.07	1.30	1.06
Grassland unimproved	0.65	0.97	1.32	0.80
Rough grassland	0.90	0.85	1.11	1.04
Forestry	0.73	0.89	0.95	1.01
Woodland	0.85	0.84	0.95	1.06
Wildscape	0.91	1.02	1.14	0.77

Esk				
Urban	-	-	-	-
Horticulture	0.00	0.00	0.00	0.00
Arable intensive	0.97	0.99	0.00	0.65
Arable extensive	0.98	1.00	0.99	0.83
Grassland improved	1.00	1.01	1.00	0.72
Grassland unimproved	1.04	1.19	0.97	0.98
Rough grassland	1.02	0.98	0.77	0.84
Forestry	0.91	0.83	0.95	0.94
Woodland	0.99	0.87	0.88	0.83
Wildscape	1.01	0.97	0.93	1.04
Tweed				
Urban	-	-	-	-
Horticulture	0.00	1.00	0.00	0.00
Arable intensive	1.00	0.98	1.07	1.01
Arable extensive	0.96	0.98	0.96	0.94
Grassland improved	1.15	1.23	1.15	1.10
Grassland unimproved	1.13	1.14	1.16	1.10
Rough grassland	0.95	1.03	1.12	1.06
Forestry	0.87	0.98	1.07	1.08
Woodland	0.96	1.05	1.08	1.14
Wildscape	1.04	1.12	1.10	0.91

Appendix 5. Input data for economic modelling (soil N content) L = low, M = Medium, H = High erosion risk

N (kg t^{-1})	L	M	H	Organo-mineral soils and peats
Ugie				
Urban	-	-	-	-
Horticulture	4.50	4.45		13.60
Arable intensive	3.58	3.57	3.40	14.45
Arable extensive	3.35	3.55	3.51	13.48
Grassland improved	3.36	3.60	3.58	14.04
Grassland unimproved			3.44	19.00
Rough grassland	3.26	3.53	3.44	17.88
Forestry	3.33	4.19	4.72	14.97
Woodland	3.17	3.76	4.61	14.73
Wildscape	3.04	3.71		18.10
Pow				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	2.40	2.29	2.30	18.30
Arable extensive	2.58	2.27	2.33	13.90
Grassland improved	2.92	2.39	2.48	13.53
Grassland unimproved	#N/A	#N/A	#N/A	#N/A
Rough grassland	2.43	2.49	2.72	14.18
Forestry	2.80	5.47	6.11	15.24
Woodland	3.05	4.09	5.45	14.59
Wildscape	2.60	2.59		15.90
Girvan				
Urban	-	-	-	-

Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	2.40	3.20		
Arable extensive	2.57	2.89	6.86	16.28
Grassland improved	2.88	3.46	6.35	21.37
Grassland unimproved	3.90	5.78	7.61	19.95
Rough grassland	3.21	4.56	5.98	20.10
Forestry	3.65	4.60	5.34	20.27
Woodland	3.21	3.71	4.67	19.34
Wildscape	2.97	5.31	6.10	19.34
Esk				
Urban	-	-	-	-
Horticulture	2.80	2.02	0.00	0.00
Arable intensive	3.03	2.32	2.41	12.21
Arable extensive	3.05	2.36	2.49	12.92
Grassland improved	3.23	3.03	3.75	13.43
Grassland unimproved	3.54	4.08	5.22	13.65
Rough grassland	3.56	7.35	6.19	14.58
Forestry	3.32	6.05	6.55	13.76
Woodland	3.33	4.65	4.48	12.74
Wildscape	3.27	3.55	5.99	14.58
Tweed				
Urban	-	-	-	-
Horticulture	0.00	2.10	0.00	0.00
Arable intensive	2.68	2.62	3.24	14.97
Arable extensive	2.39	2.67	3.98	17.43
Grassland improved	3.35	3.77	4.53	16.58

Grassland unimproved	3.86	4.94	6.24	18.17
Rough grassland	4.28	5.28	6.27	17.76
Forestry	3.80	5.42	6.73	18.19
Woodland	3.51	4.30	5.49	18.56
Wildscape	3.96	5.14	5.96	18.46

Appendix 6. Input data for economic modelling (soil K content) L= Low, M= Medium, H = High erosion risk

K (kg t^{-1})	L	M	H	Organo-mineral soils and peats
Ugie				
Urban	-	-	-	-
Horticulture	0.11	0.11		0.13
Arable intensive	0.13	0.13	0.12	0.18
Arable extensive	0.12	0.12	0.13	0.22
Grassland improved	0.12	0.11	0.12	0.25
Grassland unimproved			0.12	0.34
Rough grassland	0.12	0.10	0.12	0.28
Forestry	0.12	0.10	0.13	0.38
Woodland	0.12	0.11	0.12	0.31
Wildscape	0.13	0.10		0.30
Pow				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	0.12	0.10	0.09	0.26
Arable extensive	0.11	0.11	0.09	0.15
Grassland improved	0.11	0.11	0.10	0.23

Grassland unimproved	#N/A	#N/A	#N/A	#N/A
Rough grassland	0.13	0.13	0.10	0.31
Forestry	0.08	0.13	0.14	0.41
Woodland	0.08	0.14	0.14	0.36
Wildscape	0.09	0.10		0.28
Girvan				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	0.14	0.10		
Arable extensive	0.12	0.10	0.19	0.51
Grassland improved	0.11	0.11	0.19	0.41
Grassland unimproved	0.10	0.10	0.17	0.35
Rough grassland	0.11	0.11	0.16	0.44
Forestry	0.10	0.12	0.14	0.42
Woodland	0.10	0.11	0.15	0.43
Wildscape	0.09	0.11	0.16	0.36
Esk				
Urban	-	-	-	-
Horticulture	0.09	0.08	0.00	0.00
Arable intensive	0.10	0.10	0.10	0.48
Arable extensive	0.10	0.10	0.10	0.50
Grassland improved	0.10	0.11	0.11	0.35
Grassland unimproved	0.10	0.12	0.13	0.45
Rough grassland	0.10	0.15	0.14	0.43
Forestry	0.09	0.13	0.15	0.50
Woodland	0.10	0.12	0.12	0.49

Wildscape	0.10	0.10	0.12	0.47
Tweed				
Urban	-	-	-	-
Horticulture	0.00	0.12	0.00	0.00
Arable intensive	0.14	0.11	0.11	0.20
Arable extensive	0.15	0.12	0.15	0.47
Grassland improved	0.13	0.13	0.15	0.43
Grassland unimproved	0.14	0.16	0.19	0.46
Rough grassland	0.14	0.17	0.20	0.48
Forestry	0.15	0.16	0.20	0.47
Woodland	0.15	0.15	0.18	0.46
Wildscape	0.14	0.16	0.20	0.41

Appendix 7. Input data for economic modelling (soil C content) L = Low, M = Medium, H = High erosion risk.

C (kg t^{-1})	L	M	H	Organo-mineral soils and peats
Ugie				
Urban	-	-	-	-
Horticulture	53.90	53.50		175.20
Arable intensive	45.01	46.87	45.60	251.43
Arable extensive	45.12	47.59	47.32	289.92
Grassland improved	45.59	48.21	47.25	318.24
Grassland unimproved			45.83	517.30
Rough grassland	44.69	47.06	45.83	481.52
Forestry	46.63	58.22	65.82	382.27
Woodland	45.51	51.31	64.45	359.05

Wildscape	45.35	48.79		490.71
Pow				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	30.10	29.24	29.40	502.90
Arable extensive	32.65	28.90	30.31	307.01
Grassland improved	37.03	31.02	32.80	323.80
Grassland unimproved	#N/A	#N/A	#N/A	#N/A
Rough grassland	30.52	33.99	36.82	388.48
Forestry	35.74	85.43	96.69	444.26
Woodland	40.16	64.00	87.56	402.37
Wildscape	32.75	35.70		436.33
Girvan				
Urban	-	-	-	-
Horticulture	#N/A	#N/A	#N/A	#N/A
Arable intensive	30.07	38.22		
Arable extensive	31.60	36.71	90.04	375.28
Grassland improved	34.89	43.36	82.95	478.18
Grassland unimproved	57.20	68.86	95.91	499.70
Rough grassland	41.79	60.29	78.06	470.55
Forestry	49.68	59.85	67.71	481.58
Woodland	42.18	50.31	64.48	427.79
Wildscape	35.51	64.09	81.38	501.07
Esk				
Urban	-	-	-	-
Horticulture	39.70	28.23	0.00	0.00

Arable intensive	40.69	31.28	31.65	360.30
Arable extensive	41.09	31.74	33.94	336.69
Grassland improved	42.23	41.64	54.57	343.24
Grassland unimproved	44.33	55.53	79.70	335.34
Rough grassland	46.15	116.06	109.09	382.57
Forestry	42.66	98.15	109.76	356.91
Woodland	42.34	70.50	66.84	332.65
Wildscape	42.01	48.91	82.41	363.75
Tweed				
Urban	-	-	-	-
Horticulture	0.00	27.20	0.00	0.00
Arable intensive	32.00	32.68	41.69	336.84
Arable extensive	28.08	33.21	52.98	438.32
Grassland improved	40.41	46.11	59.54	379.56
Grassland unimproved	49.44	64.86	85.50	411.25
Rough grassland	54.98	70.11	85.26	410.83
Forestry	51.75	75.11	95.78	416.57
Woodland	46.88	56.78	73.87	420.62
Wildscape	52.43	69.31	80.27	457.33

Appendix 8. Classification of IACS crops into the economic model (and erosion rate class)

Table 75 shows the descriptions of the IACS land use classes (and their associated erosion rate class) and how these have been classified for the economic model.

Table 75 Descriptions of the IACS classes (RED TEXT) and how we have classified them for erosion risk and for the economics tables.

PREDOM_LU	IACS class	ECONOMICS CLASS	EROSION RATE CLASS
CMIX	Arable silage for stock feed	Improved grass	Improved grass
ARTC	Artichokes	Artichokes	Intensive arable
ASPG	Asparagus	Asparagus	Intensive arable
BEAN	Beans for human consumption	Beans	Extensive arable
BLB	Bilberries (and other fruits of the genus vaccinium)	Soft fruit	Horticulture
BKB	Blackberries	Soft fruit	Horticulture
BLR	Blackcurrants	Soft fruit	Horticulture
BFLO	Bulbs/flowers	Bulbs	Intensive arable
COMM	Common grazing	Rough grazing	Rough grazing
FALW	Fallow	Fallow	Extensive arable
FB	Field beans	Beans	Extensive arable
BSFS	Flower bulbs and cut flowers	Bulbs	Intensive arable
GSB	Gooseberries	Soft fruit	Horticulture
PGRS	Grass over 5 years	Improved grass	Improved grass
TGRS	Grass under 5 years	Improved grass	Improved grass
LLO	Land let out to others	Llo	Extensive arable
LIEM	Lfass ineligible environmental management	Improved grass	Improved grass

LIN	Linseed	Linseed	Extensive arable
MAIZ	Maize	Maize	Intensive arable
MC	Mixed cereals	Cereals	Extensive arable
NF_IB	Non-food setaside - barley for industrial use	Barley	Extensive arable
NF_SRC	Non-food setaside - forest trees short cycle	Woodland	Woodland
NF_HEAR	Non-food setaside - high erucic acid rapeseed	Osr	Extensive arable
NF_IOSR	Non-food setaside - oilseed rape for industrial use	Osr	Extensive arable
NF_TSB	Non-food setaside - trees shrubs and bushes	Woodland	Woodland
NF_IW	Non-food setaside - wheat for industrial use	Wheat	Extensive arable
NS_5S_FWS	Normal setaside - 5 year under fws	Setaside	Extensive arable
NS_5S_WGS	Normal setaside - 5 year under wgs	Setaside	Extensive arable
NS_BF	Normal setaside - bare fallow	Setaside	Extensive arable
NS_GCM	Normal setaside - green cover mixture	Setaside	Extensive arable
NS_MU	Normal setaside - mustard	Mustard	Extensive arable
NS_NRC	Normal setaside - nat regen (after cereals)	Setaside	Extensive arable
NS_NRO	Normal setaside - nat regen (after other crops)	Setaside	Extensive arable
NS_SAS_W	Normal setaside - next to watercourses,hedges,woods,dykes and sssis	Woodland	Woodland
NS_OL	Normal setaside - organic legumes	Legumes	Extensive arable
NS_OWN	Normal setaside - own management plan	Setaside	Extensive arable
NS_P	Normal setaside - phacelia	Phacelia	Extensive arable
NS_G	Normal setaside - sown grass cover	Setaside	Extensive arable

NS_WBC	Normal setaside - wild bird cover	Improved grass	Improved grass
WDG	Open woodland(grazed)	Woodland	Woodland
OCS	Other crops for stock feed	Other	Extensive arable
OVEG	Other vegetables	Vegetables	Intensive arable
PEAS	Peas for human consumption	Peas	Intensive arable
PEM	Positive environmental management	Improved grass	Improved grass
PP	Protein peas	Peas	Intensive arable
RAST	Rape for stock feed	Osr	Extensive arable
RASP	Raspberries	Soft fruit	Horticulture
RRC	Redcurrants	Soft fruit	Horticulture
RHB	Rhubarb	Rhubarb	Horticulture
RGR	Rough grazing	Rough grazing	Rough grazing
RYE	Rye	Rye	Extensive arable
SPOT	Seed potatoes	Potatoes	Intensive arable
AGRI	Sfps being claimed on agri-environmental options	Improved grassland	Improved grassland
STS	Shopping turnips/swedes	Turnips	Intensive arable
SRC_E	Short rotation coppice energy	Woodland	Woodland
SFRT	Soft fruit	Soft fruit	Horticulture
SB	Spring barley	Barley	Extensive arable
SO	Spring oats	Oats	Extensive arable
SOSR	Spring oilseed rape	Osr	Extensive arable
SOSR_E	Spring oilseed rape energy	Osr	Extensive arable
SW	Spring wheat	Wheat	Extensive arable
SS_X5	Structural setaside - ex 5 year still in fws	Improved grass	Improved grass
SS_WP	Structural setaside - wgs, fwps or sfgs	Improved grass	Improved grass

SL	Sweet lupins	Lupins	Intensive arable
SC	Sweetcorn	Sweetcorn	Extensive arable
TFRT	Top fruit	Top fruit	Horticulture
TSB	Trees shrubs & bushes	Other	Woodland
TRIT	Triticale	Triticale	Extensive arable
TURF	Turf production	Turf	Improved grassland
TSWS	Turnips/swedes for stock feed	Turnips	Intensive arable
WPOT	Ware potatoes	Potatoes	Intensive arable
WBS	Wild bird seed	Improved grass	Improved grass
WB	Winter barley	Barley	Extensive arable
WO	Winter oats	Oats	Extensive arable
WOSR	Winter oilseed rape	Osr	Extensive arable
WOSR_E	Winter oilseed rape energy	Osr	Extensive arable
WW	Winter wheat	Wheat	Extensive arable
WAF	Woodland and forestry	Woodland	Woodland

Appendix 9.

Detailed tables of the outputs (costs) from the economic model (Ugie catchment as an illustration)

Appendix 9.1. Physical data by land use and Erosion Risk Class for the Ugie catchment. L = Low, M = Moderate, H = High erosion risk class.

	Total category areas (ha)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	116	183	-	21	320
Horticulture	4	9	-	0	13
Arable intensive	36	138	0	3	177
Arable extensive	3,083	8,283	23	733	12,122
Grassland improved	2,356	7,493	53	1,681	11,583
Grassland unimproved	-	0	0	5	5
Rough grassland	147	568	5	922	1,642
Forestry	139	992	10	1,156	2,297
Woodland	122	667	7	219	1,015
Wildscape	18	53	-	634	705
Total	6,021	18,384	99	5,373	29,878

	Total areas at risk within categories (ha)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	**-**	**-**	**-**	**-**	**-**
Horticulture	0	1	-	0	1
Arable intensive	1	18	0	1	19

Arable extensive	62	1,077	6	154	1,298
Grassland improved	47	974	13	353	1,387
Grassland unimproved	-	0	0	1	1
Rough grassland	3	74	1	194	271
Forestry	3	129	2	243	377
Woodland	2	87	2	46	137
Wildscape	0	7	-	133	140
Total	118	2,366	24	1,124	3,632

…continued

Appendix 9.1. Physical data by land use and Erosion Risk Class for the Ugie catchment (continued)

	Category soil erosion (t yr^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0	4	-	0	5
Arable intensive	3	77	0	7	88
Arable extensive	148	2,584	13	770	3,515
Grassland improved	141	2,922	38	353	3,455
Grassland unimproved	-	0	0	0	1
Rough grassland	2	55	1	75	134
Forestry	2	77	1	32	112
Woodland	1	52	1	6	60
Wildscape	0	4	-	17	22
Total	298	5,777	55	1,261	7,392

	Average Catchment soil erosion (t ha^{-1} yr^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.08	0.49	-	1.47	0.39
Arable intensive	0.09	0.56	1.03	2.10	0.50
Arable extensive	0.05	0.31	0.58	1.05	0.29
Grassland improved	0.06	0.39	0.72	0.21	0.30
Grassland unimproved	-	0.27	0.50	0.08	0.11
Rough grassland	0.02	0.10	0.18	0.08	0.08
Forestry	0.01	0.08	0.14	0.03	0.05
Woodland	0.01	0.08	0.14	0.03	0.06
Wildscape	0.01	0.08	-	0.03	0.03
Total	0.05	0.32	0.56	0.23	0.25

…continued over

Appendix 9.1. Physical data by land use and Erosion Risk Class for the Ugie catchment (continued)

	Soil depth loss (mm yr^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.39	0.39	-	2.31	0.42
Arable intensive	0.41	0.42	0.42	3.90	0.49
Arable extensive	0.23	0.24	0.24	2.05	0.34
Grassland improved	0.28	0.30	0.30	0.44	0.31
Grassland unimproved	-	0.20	0.20	0.40	0.38
Rough grassland	0.07	0.07	0.07	0.33	0.22
Forestry	0.06	0.07	0.07	0.08	0.07
Woodland	0.06	0.06	0.07	0.07	0.06
Wildscape	0.06	0.06	-	0.12	0.11
Total	0.24	0.24	0.24	0.51	0.29

Appendix 9.2. On-site productivity losses and associated costs by land use and Erosion Risk Class for the Ugie catchment

	Catchment soil erosion (t yr^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0	4	-	0	5
Arable intensive	3	77	0	7	88
Arable extensive	148	2,584	13	770	3,515
Grassland improved	141	2,922	38	353	3,455
Grassland unimproved	-	0	0	0	1
Rough grassland	2	55	1	75	134
Forestry	2	77	1	32	112
Woodland	1	52	1	6	60
Wildscape	0	4	-	17	22
Total	298	5,777	55	1,261	7,392

	Total catchment productivity loss due to erosion (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	16	245	-	57	318
Arable intensive	10	251	1	71	333
Arable extensive	150	1,795	9	2,169	4,123
Grassland improved	110	2,387	32	1,217	3,745
Grassland unimproved	-	0	0	2	2

Rough grassland	1	22	0	242	265
Forestry	0	11	0	24	36
Woodland	0	4	0	3	7
Wildscape	-	-	-	-	-
Total	287	4,715	42	3,785	8,829

…continued over

Appendix 9.2. On site productivity losses and associated costs by land use and Erosion Risk Class for the Ugie catchment

	Catchment productivity loss due to erosion in risk area (£ ha^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	216.84	216.38	-	1,281.69	254.5
Arable intensive	14.68	13.99	9.98	98.03	17.1
Arable extensive	2.44	1.67	1.56	14.08	3.2
Grassland improved	2.33	2.45	2.49	3.45	2.7
Grassland unimproved	-	1.14	1.13	2.10	2.0
Rough grassland	0.28	0.30	0.29	1.25	1.0
Forestry	0.07	0.09	0.10	0.10	0.1
Woodland	0.05	0.05	0.06	0.06	0.1
Wildscape	-	-	-	-	-
Total	237	236	16	1,401	281

Appendix 9.2

	Total Catchment productivity loss due to erosion in total area (£ ha^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	4.34	28.13	-	269.16	25.4
Arable intensive	0.29	1.82	2.40	20.59	1.9
Arable extensive	0.05	0.22	0.37	2.96	0.3
Grassland improved	0.05	0.32	0.60	0.72	0.3

Grassland unimproved	-	0.15	0.27	0.44	0.4
Rough grassland	0.01	0.04	0.07	0.26	0.2
Forestry	0.00	0.01	0.02	0.02	0.0
Woodland	0.00	0.01	0.01	0.01	0.0
Wildscape	-	-	-	-	-
Total	0.0	0.3	0.4	0.7	0.3

Appendix 9.3. On-site N losses and associated costs by land use and Erosion Risk Class for the Ugie catchment

	Soil N loss (t yr^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0	0	-	0	0
Arable intensive	0	0	0	0	1
Arable extensive	1	13	0	14	28
Grassland improved	1	14	0	7	22
Grassland unimproved	-	0	0	0	0
Rough grassland	0	0	0	2	2
Forestry	0	0	0	1	1
Woodland	0	0	0	0	0
Wildscape	0	0	-	0	0
Total	1	28	0	24	54

	Total Catchment N loss cost due to erosion (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	1	18	-	4	23
Arable intensive	10	253	1	95	359
Arable extensive	455	8,415	43	9,526	18,439
Grassland improved	436	9,650	126	4,547	14,759
Grassland unimproved	-	0	0	7	7
Rough grassland	7	179	3	1,239	1,428
Forestry	5	297	6	434	743
Woodland	4	179	4	81	268
Wildscape	1	14	-	287	302
Total	919	19,006	184	16,220	36,328

Appendix 9.3. On site N losses and associated costs by land use and Erosion Risk Class for the Ugie catchment (continued)

	Average Catchment N loss cost due to erosion (£ ha^{-1} risk area)				
	Erosion Risk Classes				
Land use	L	M	H	Organomineral soils and Peats	Total
Urban	-	-	-	-	-
Horticulture	15.7	15.5	-	87.4	18.1
Arable intensive	14.1	14.1	13.4	132.6	18.5
Arable extensive	7.4	7.8	7.7	61.9	14.2
Grassland improved	9.3	9.9	9.9	12.9	10.6

Grassland unimproved	-	6.8	6.5	6.8	6.8
Rough grassland	2.2	2.4	2.4	6.4	5.3
Forestry	1.8	2.3	2.6	1.8	2.0
Woodland	1.7	2.1	2.5	1.8	2.0
Wildscape	1.7	2.0	-	2.2	2.2
Total	7.9	8.1	7.8	14.4	10.0

	Average Catchment N loss cost due to erosion (£ ha^{-1} category area)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.3	2.0	-	18.4	1.8
Arable intensive	0.3	1.8	3.2	27.8	2.0
Arable extensive	0.1	1.0	1.9	13.0	1.5
Grassland improved	0.2	1.3	2.4	2.7	1.3
Grassland unimproved	-	0.9	1.6	1.4	1.4
Rough grassland	0.0	0.3	0.6	1.3	0.9
Forestry	0.0	0.3	0.6	0.4	0.3
Woodland	0.0	0.3	0.6	0.4	0.3
Wildscape	0.0	0.3	-	0.5	0.4
Total	0.2	1.1	1.9	3.0	1.2

Appendix 9.4. On site P losses and associated costs by land use and Erosion Risk Class for the Ugie catchment. L = low, M – Moderate, H = High erosion risk.

	Soil P loss (t yr^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.00	0.01	-	0.00	0.02
Arable intensive	0.01	0.23	0.00	0.02	0.26
Arable extensive	0.37	7.07	0.05	1.65	9.14
Grassland improved	0.35	7.93	0.13	0.72	9.12
Grassland unimproved	-	0.00	0.00	0.00	0.00
Rough grassland	0.00	0.13	0.00	0.12	0.26
Forestry	0.00	0.18	0.00	0.06	0.25
Woodland	0.00	0.12	0.00	0.01	0.14
Wildscape	0.00	0.01	-	0.03	0.04
Total	0.74	15.69	0.18	2.62	19.23

	Total Catchment P loss cost due to erosion (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	1	10	-	1	11
Arable intensive	6	159	1	13	180
Arable extensive	249	4,811	31	1,125	6,215
Grassland improved	238	5,391	86	490	6,205
Grassland unimproved	-	0	0	0	1

Rough grassland	3	91	2	81	178
Forestry	3	124	3	41	170
Woodland	2	81	2	8	93
Wildscape	0	6	-	19	25
Total	501	10,672	125	1,778	13,076

…continued

Appendix 9.4. On site P losses and associated costs by land use and Erosion Risk Class for the Ugie catchment (continued)

	Average Catchment P loss cost due to erosion (£ ha^{-1} risk area)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	8.41	8.46	-	14.72	8.68
Arable intensive	8.41	8.90	10.65	18.34	9.24
Arable extensive	4.04	4.47	5.62	7.30	4.79
Grassland improved	5.04	5.53	6.72	1.39	4.47
Grassland unimproved	-	3.61	4.84	0.36	0.68
Rough grassland	1.15	1.23	1.75	0.42	0.65
Forestry	0.90	0.96	1.03	0.17	0.45
Woodland	0.83	0.94	1.10	0.17	0.68
Wildscape	0.72	0.83	-	0.14	0.18
Total	4.33	4.55	5.26	1.58	3.63

	Average Catchment P loss cost due to erosion (£ ha^{-1} category area)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**

Urban	-	-	-	-	-
Horticulture	0.17	1.10	-	3.09	0.86
Arable intensive	0.17	1.16	2.56	3.85	1.01
Arable extensive	0.08	0.58	1.35	1.53	0.51
Grassland improved	0.10	0.72	1.61	0.29	0.54
Grassland unimproved	-	0.47	1.16	0.08	0.14
Rough grassland	0.02	0.16	0.42	0.09	0.11
Forestry	0.02	0.12	0.25	0.04	0.07
Woodland	0.02	0.12	0.26	0.04	0.09
Wildscape	0.01	0.11	-	0.03	0.04
Total	0.09	0.59	1.26	0.33	0.45

Appendix 9.5. On site K losses and associated costs by land use and Erosion Risk Class for the Ugie catchment

	Soil K loss (t yr^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.00	0.00	-	0.00	0.00
Arable intensive	0.00	0.03	0.00	0.00	0.03
Arable extensive	0.05	0.90	0.00	0.50	1.46
Grassland improved	0.05	0.95	0.01	0.26	1.28
Grassland unimproved	-	0.00	0.00	0.00	0.00
Rough grassland	0.00	0.02	0.00	0.06	0.08
Forestry	0.00	0.02	0.00	0.03	0.06
Woodland	0.00	0.02	0.00	0.01	0.02
Wildscape	0.00	0.00	-	0.01	0.02
Total	0.10	1.95	0.02	0.88	2.95

	Total Catchment K loss cost due to erosion (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0	1	-	0	1
Arable intensive	1	13	0	2	15
Arable extensive	23	407	2	226	658
Grassland improved	22	430	6	117	575
Grassland unimproved	-	0	0	0	0
Rough grassland	0	8	0	28	36
Forestry	0	11	0	16	27
Woodland	0	7	0	2	10
Wildscape	0	1	-	7	7
Total	46	876	9	398	1,329

…continued

Appendix 9.5. On site K losses and associated costs by land use and Erosion Risk Class for the Ugie catchment (continued)

	Average Catchment K loss cost due to erosion (£ ha^{-1} risk area)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.54	0.55	-	1.18	0.57
Arable intensive	0.72	0.73	0.70	2.34	0.79
Arable extensive	0.37	0.38	0.40	1.47	0.51
Grassland improved	0.47	0.44	0.48	0.33	0.41
Grassland unimproved	-	0.29	0.32	0.17	0.18
Rough grassland	0.11	0.10	0.12	0.14	0.13
Forestry	0.09	0.08	0.10	0.06	0.07
Woodland	0.09	0.08	0.10	0.05	0.07
Wildscape	0.10	0.08	-	0.05	0.05
Total	0.40	0.37	0.38	0.35	0.37

	Average Catchment K loss cost due to erosion (£ ha^{-1} category area)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.01	0.07	-	0.25	0.06
Arable intensive	0.01	0.09	0.17	0.49	0.09
Arable extensive	0.01	0.05	0.09	0.31	0.05

Grassland improved	0.01	0.06	0.11	0.07	0.05
Grassland unimproved	-	0.04	0.08	0.04	0.04
Rough grassland	0.00	0.01	0.03	0.03	0.02
Forestry	0.00	0.01	0.02	0.01	0.01
Woodland	0.00	0.01	0.02	0.01	0.01
Wildscape	0.00	0.01	-	0.01	0.01
Total	0.01	0.05	0.09	0.07	0.05

Appendix 9.6. On site C losses and associated costs by land use and Erosion Risk Class for the Ugie catchment

	Soil C loss (t yr^{-1})				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.02	0.36	-	0.09	0
Arable intensive	0.21	5.63	0.03	2.82	9
Arable extensive	10.42	191.87	0.99	348.19	551
Grassland improved	10.05	219.80	2.82	175.22	408
Grassland unimproved	-	0.00	0.01	0.31	0
Rough grassland	0.15	4.06	0.06	56.71	61
Forestry	0.12	7.03	0.15	18.82	26
Woodland	0.10	4.16	0.10	3.34	8
Wildscape	0.02	0.31	-	13.24	14
Total	21	433	4	619	1,077

	Total Catchment C loss cost due to erosion (£) Erosion Risk Classes				
Land use	L	M	H	Organomineral soils and Peats	Total
Urban	-	-	-	-	-
Horticulture	0	0	-	0	0
Arable intensive	0	4	0	2	6
Arable extensive	7	128	1	232	368
Grassland improved	7	147	2	117	272
Grassland unimproved	-	0	0	0	0
Rough grassland	0	3	0	38	41
Forestry	0	5	0	13	17
Woodland	0	3	0	2	5
Wildscape	0	0	-	9	9
Total	14	289	3	412	718

…continued

Appendix 9.6. On site C losses and associated costs by land use and Erosion Risk Class for the Ugie catchment (continued over)

	Average Catchment C loss cost due to erosion (£ ha^{-1} risk area) Erosion Risk Classes				
Land use	L	M	H	Organomineral soils and Peats	Total
Urban	-	-	-	-	-
Horticulture	0.21	0.21	-	1.28	0.25
Arable intensive	0.20	0.21	0.20	2.61	0.30
Arable extensive	0.11	0.12	0.12	1.51	0.28
Grassland improved	0.14	0.15	0.15	0.33	0.20

Grassland unimproved	-	0.10	0.10	0.21	0.20
Rough grassland	0.03	0.04	0.04	0.20	0.15
Forestry	0.03	0.04	0.04	0.05	0.05
Woodland	0.03	0.03	0.04	0.05	0.04
Wildscape	0.03	0.03	-	0.07	0.06
Total	0.21	0.21	-	1.28	

	Average Catchment C loss cost due to erosion (£ ha^{-1} category area)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.00	0.03	-	0.27	0.02
Arable intensive	0.00	0.03	0.05	0.55	0.03
Arable extensive	0.00	0.02	0.03	0.32	0.03
Grassland improved	0.00	0.02	0.04	0.07	0.02
Grassland unimproved	-	0.01	0.02	0.04	0.04
Rough grassland	0.00	0.00	0.01	0.04	0.02
Forestry	0.00	0.00	0.01	0.01	0.01
Woodland	0.00	0.00	0.01	0.01	0.01
Wildscape	0.00	0.00	-	0.01	0.01
Total	0.00	0.02	0.03	0.08	0.02

Appendix 9.7. Off site costs of sediment removal in rivers and canals, and in drinking water by land use and Erosion Risk Class for the Ugie catchment

	Cost of sediment removal in rivers & canals (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	1.41	22.17	-	1.61	25
Arable intensive	15.74	396.83	2.28	37.04	452
Arable extensive	762.22	13,308.59	68.78	3,964.82	18,104
Grassland improved	727.94	15,049.96	197.12	1,817.66	17,793
Grassland unimproved	-	0.31	0.58	1.99	3
Rough grassland	11.37	285.05	4.55	388.79	690
Forestry	8.59	398.47	7.63	162.55	577
Woodland	7.57	267.85	4.88	30.74	311
Wildscape	1.13	21.09	-	89.10	111
Total	1,536	29,750	286	6,494	38,066

	Cost of sediment removal in drinking water (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	5	77	-	6	88
Arable intensive	55	1,387	8	129	1,579
Arable extensive	2,664	46,515	240	13,858	63,278

Grassland improved	2,544	52,602	689	6,353	62,188
Grassland unimproved	-	1	2	7	10
Rough grassland	40	996	16	1,359	2,411
Forestry	30	1,393	27	568	2,018
Woodland	26	936	17	107	1,087
Wildscape	4	74	-	311	389
Total	5,368	103,982	999	22,699	133,048

Appendix 9.8. Off site costs of N losses and associated costs by land use and Erosion Risk Class for the Ugie catchment

	Cost of N in rivers and lakes (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.32	4.98	-	1.11	6
Arable intensive	2.84	71.62	0.39	27.04	102
Arable extensive	129.13	2,386.34	12.20	2,701.39	5,229
Grassland improved	123.60	2,736.61	35.66	1,289.51	4,185
Grassland unimproved	-	0.06	0.10	1.91	2
Rough grassland	1.88	50.89	0.79	351.27	405
Forestry	1.45	84.32	1.82	122.99	211
Woodland	1.21	50.89	1.14	22.88	76
Wildscape	0.17	3.96	-	81.52	86
Total	261	5,390	52	4,600	10,302

Appendix 9.8 (continued)

	Cost of N in transitional waters (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.02	0.26	-	0.06	0
Arable intensive	0.15	3.77	0.02	1.42	5
Arable extensive	6.80	125.60	0.64	142.18	275
Grassland improved	6.51	144.03	1.88	67.87	220
Grassland unimproved	-	0.00	0.01	0.10	0
Rough grassland	0.10	2.68	0.04	18.49	21
Forestry	0.08	4.44	0.10	6.47	11
Woodland	0.06	2.68	0.06	1.20	4
Wildscape	0.01	0.21	-	4.29	5
Total	14	284	3	242	542

Appendix 9.8. Off site costs of N losses and associated costs by land use and Erosion Risk Class for the Ugie catchment (continued)

	Cost of N in drinking water (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	0.34	5.32	-	1.18	7
Arable intensive	3.04	76.53	0.42	28.89	109
Arable extensive	137.97	2,549.62	13.04	2,886.22	5,587

Grassland improved	132.06	2,923.85	38.10	1,377.74	4,472
Grassland unimproved	-	0.06	0.11	2.04	2
Rough grassland	2.00	54.38	0.84	375.31	433
Forestry	1.54	90.09	1.94	131.41	225
Woodland	1.29	54.38	1.21	24.45	81
Wildscape	0.19	4.23	-	87.10	92
Total	278	5,758	56	4,914	11,007

Appendix 9.9. Off site costs of P in freshwater lakes by land use and Erosion Risk Class for the Ugie catchment

	Cost of P in freshwater lakes (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	1.48	23.37	-	1.60	26
Arable intensive	14.58	388.92	2.67	32.18	438
Arable extensive	607.11	11,736.30	76.34	2,743.90	15,164
Grassland improved	579.81	13,151.80	209.30	1,196.29	15,137
Grassland unimproved	-	0.26	0.64	0.88	2
Rough grassland	8.22	221.84	5.04	198.63	434
Forestry	6.11	301.66	6.19	100.01	414
Woodland	4.98	197.91	4.24	18.84	226
Wildscape	0.64	13.79	-	46.62	61
Total	1,223	26,036	304	4,339	31,902

Appendix 9.10 Off-site costs of GHG losses and associated costs for the Ugie catchment

	GHG cost of soil C loss (£)				
	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	1.15	17.93	-	4.26	23
Arable intensive	10.71	281.22	1.57	140.79	434
Arable extensive	519.92	9,576.68	49.20	17,378.80	27,525
Grassland improved	501.71	10,970.45	140.82	8,745.66	20,359
Grassland unimproved	-	0.22	0.40	15.59	16
Rough grassland	7.68	202.81	3.15	2,830.48	3,044
Forestry	6.05	350.75	7.60	939.47	1,304
Woodland	5.21	207.79	4.75	166.87	385
Wildscape	0.77	15.56	-	661.05	677
Total	1,053	21,623	207	30,883	53,767

Appendix 9.11 Total Onsite costs by land use and Erosion Risk Class for the Ugie catchment

	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	17	273	-	62	352
Arable intensive	27	679	4	183	893
Arable extensive	884	15,555	86	13,277	29,803

Grassland improved	812	18,004	251	6,489	25,556
Grassland unimproved	-	0	1	10	11
Rough grassland	11	302	5	1,628	1,947
Forestry	8	447	10	527	992
Woodland	7	275	6	96	384
Wildscape	1	20	-	322	343
Total	1,768	35,557	362	22,594	60,281

Appendix 9.12. Total Offsite costs by land use and Erosion Risk Class for the Ugie catchment (including drinking water treatment)

	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	10	151	-	15	177
Arable intensive	102	2,606	15	397	3,120
Arable extensive	4,827	86,199	461	43,675	135,161
Grassland improved	4,616	97,578	1,312	20,848	124,354
Grassland unimproved	-	2	4	29	35
Rough grassland	71	1,814	30	5,522	7,437
Forestry	54	2,622	52	2,031	4,759
Woodland	47	1,718	33	372	2,170
Wildscape	7	133	-	1,281	1,421
Total	9,733	192,823	1,907	74,171	278,634

Appendix 9.13. Total costs by land use and Erosion Risk Class for the Ugie catchment

	Erosion Risk Classes				
Land use	**L**	**M**	**H**	**Organomineral soils and Peats**	**Total**
Urban	-	-	-	-	-
Horticulture	27	425	-	77	529
Arable intensive	129	3,285	19	579	4,013
Arable extensive	5,712	101,754	546	56,952	164,964
Grassland improved	5,428	115,582	1,563	27,337	149,910
Grassland unimproved	-	2	5	39	46
Rough grassland	82	2,116	36	7,150	9,384
Forestry	62	3,070	61	2,558	5,752
Woodland	54	1,993	39	468	2,554
Wildscape	8	153	-	1,603	1,764
Total	11,501	228,380	2,270	96,764	338,915

Appendix 9

Appendix 10. Scottish policy instruments related to soil erosion (after McKee, 2018**)**

Table 76. Links between Scottish policy instruments and soil erosion (after McKee 2018). On or offsite impacts relate to the focus of the policy instrument. Potential areas affected by the policy have been related to the landscapes/ land uses used in the cost of soil erosion method.

Policy instrument	**Overall objective**	**Example relationship to soil erosion**	**On or offsite impacts**	**Potential areas affected by the policy**
Scottish Soil Framework	The main aim of the Scottish Soil Framework is to promote the sustainable management and protection of soils it is not a delivery instrument.	No implementation instrument	n/a	n/a
Common Agricultural Policy (Cross-Compliance) (Scotland) Regulations 2014	Cross compliance is delivered through the implementation of Good Agricultural and Environmental Conditions (GAECs)	GAECs to address soil erosion Minimum soil cover (GAEC 4) Minimum land management reflecting site specific conditions to limit erosion (GAEC 5) [eg fencing around water courses and interventions such as sediment traps]	Onsite (with indirect offsite benefits)	
Environmental Protection Act (1990)	Authorisations granted (and revoked) by enforcing body to ensure best techniques used to prevent release of substances (including controlled waste) into the	Sediment discharged into water courses that may illicit harm (water quality, fish etc). Depends on definition of sediment (eroded soil) as harmful substance’	Offsite	High risk areas* (where significant erosion causes ‘harm’)

	environment without 'rendering harmless'.			
The Environmental Liability Regulations (Scotland) (2009)	An application of the 'polluter pays principle', requiring preventative measures to be taken by operators to remove the threat of/remediate any environmental damage, i.e. removing, controlling, containing or diminishing potential land contaminants, as well as risk-assessment procedures taking into account the characteristic and function of the soil, the type and concentration of the harmful substances, preparations, organisms or micro-organisms, their risk and the possibility of their dispersion.	Depends on the definition of eroded soil (sediment) as a contaminant or erosion of contaminated soil – specifically relates to the contamination of soil not as soil as a contaminant	Offsite	Depends on definition. Could be applicable in urban areas or industrial sites (eg mines) where contaminated soil is eroded (low likelihood and area)
Wildlife and Natural Environment (Scotland) Act (2011)	There is no mention of soil, but the Act includes requirements regarding muirburn (i.e. season length and licensing), and the management of	Soil erosion measures could be part of management measures for SSSI	Onsite (wildscape)	Low risk areas

	Sites of Special Scientific Interest (i.e. including geology and geomorphology, which could include soil features.			
The Conservation of Habitats and Species Regulations 2010	The appropriate nature conservation body may make byelaws for the protection of a European site that can prohibit/restrict any activity that will 'interfere with the soil'.	Soil protection through restricting activity (eg access) to prevent soil erosion	Onsite (wildscape)	Low risk areas
Nature Conservation Scotland (Act) (2004)	The legislation makes "further provision in relation to the conservation and enhancement of Scotland's natural features" (Act, page 1); the 'natural features' of land are any flora, fauna, geological, or geomorphological features, i.e. that could include soil.	Soil protection through restricting activity (eg access) to prevent soil erosion	Onsite (wildscape)	Low risk areas
Conservation (Natural Habitats, &c.) Regulations (1994)	As in later Conservation of Habitats and Species Regulations 2010, byelaws can be made to prohibit/restrict any activity that will 'interfere with the soil	Soil protection through restricting activity (eg access) to prevent soil erosion	Onsite (wildscape)	Low risk areas
Water Environment	Part 1 aims to protect the water	Links with soil erosion in RBMPs	Onsite/offsite	Variable

and Water Services (Scotland) Act (2003)	environment, including reducing/preventing pollution of groundwater (i.e. water in direct contact with subsoil). This includes the requirement for responsible institutions (SEPA) to produce River Basin Management Plans (RBMPs) and to enforce control of regulated activities (Scottish Ministers) (e.g. activities that might result in water pollution, the impounding of water, and water abstraction).	include 'maintaining good environmental practice' such as implementing agricultural land management.		
The Water Environment (Controlled Activities) (Scotland) Regulations (2011)	The General Binding Rules include those regarding the area of exposed soil from which water drains into a surface water drainage system (and time period of drainage), the storage of fertiliser on land with a minimum soil depth, and the application of organic/inorganic fertilisers according to soil depth, as well as those relating to livestock, and land cultivation.	Mentions exposed (bare) soil and runoff. P linked to soil erosion and movement to water sources?	Onsite/offsite	Arable Horticulture Grassland

The Water Environment (Miscellaneous) (Scotland) Regulations (2017)	The amendment to the General Binding Rules within these regulations include the types of materials that cannot be disposed of into a surface water drainage system (e.g. oil, paint, paint thinners, pesticides, disinfectants, or other pollutants), the maximum period for exposed soil to be authorised for surface water run-off, that no fertiliser can be stored on land (e.g. in a mobile tank or bowser) on land without a minimum soil depth and specific underlying geology; plus rules regarding fertiliser application to regain agronomic status, the run-off from land where livestock gather; plus location of trees to prevent exposed soil run-off into a river or ditch, and the revegetation of exposed soil to minimise soil erosion. Run-off must be intercepted to prevent soil (or other sediment) entering a water course.	Specifically mentions run off and livestock, and protection of ditches /runoff and revegetation of bare soil to minimise risk.	Onsite/Offsite	Grassland arable

Action Programme for Nitrate Vulnerable Zones (Scotland) Regulations (2008)	Regulations have direct measures for reducing water pollution (and therefore indirectly with regard to soil protection and land), to be undertaken by landowners/managers in designated 'Nitrate Vulnerable Zones'. These measures include restrictions on the amount of manure spread on land, time of spreading, and location, to avoid run-off and water-course [and soil] pollution.	Relates to reduction of input and risk (eg. nitrates and timing of application) rather than reducing runoff /erosion per se.	Onsite	Arable Horticulture grassland
The Contaminated Land(Scotland) Regulations (2005) & Statutory Guidance SE/2006/44	The Regulations do not mention soil specifically, but amends the Environmental Protection Act 1990 with regard to contaminated land in Scotland, requiring local authorities to: "identify and secure the remediation of contaminated land in their area" (Regulations pg. 6).	Only relevant if contaminated soil is at risk from erosion	Onsite	Very specific areas (outside scope of this study)
Environmental Assessment (Scotland) Act (2005)	The legislation "ensures that all public plans, programmes, and strategies that are likely to have significant environmental effects, if implemented, are subject to environmental	Environmental assessments could include the likelihood of accelerated soil erosion after planning implementation. However, development will likely cover soils	onsite	Specific to land under development (outside scope of this study)

	assessment…The likely impacts on soils are a consideration” (from: SEPA’s position statement on land protection, pg. 10).	reducing risk of erosion.		
The Electricity Works (Environmental Impact Assessment) (Scotland) Regulations 2017	Environmental impact assessment (including the ‘Carbon Calculator’) must be used to identify, describe and assess the direct and indirect significant effects of the proposed development on land, soil, water, air and climate, amongst other factors.	Preventing soil erosion during installation of electricity works could be a consideration.	Onsite	Very localised areas specific to land under development (outside scope of this study)

Land Reform (Scotland) Act (2016)	The legislation does not explicitly mention soil. However, the Act requires the publication of a Land Rights and Responsibilities Statement, which must have regard for "furthering the achievement of sustainable development in relation to land" (Part 1(3)g, Act, page 2). The Act also requires Scottish Ministers to provide a complete database of controlling interests in land; knowing who owns and manages land is important in ensuring soil protection measures are undertaken/successful. Part 5 gives rights to community bodies to acquire land where it is: "the transfer of land is likely to further the achievement of sustainable development in relation to the land, [and] the transfer of land is in the public interest" (Part 56 (2)a, Act, page 38). It may be that soil protection could be considered necessary for the sustainable development of land and in	Preventing soil erosion will further the achievement of the SDGs. Tenancies can be terminated if there is poor land husbandry (eg soil erosion)	onsite	variable

	the public interest [NB. Different provisions with regard to mineral rights – how does this untangle from soil?]. Part 10 of the Act details the new ‘modern limited duration tenancies’ and explains that the landlord may end the tenancy after 5 years if the tenant is “(a) is not using the land in accordance with the rules of good husbandry, or (b) is otherwise failing to comply with any other provision of the lease” (Section 8D(6), Act, page 68). Good husbandry is defined in the Agriculture (Scotland) Act 1948 and may be related to soil management (as could be detailed in the lease).			

Climate Change (Scotland) Act (2009)	The Act does not specifically mention soil, but it requires Scottish Ministers to produce a Land Use Strategy (and Action Plan), and to review the Strategy every 5 years (Section 57, pg. 30). Also includes provisions to vary permitted times for muirburn (Section 58, pg. 30).	The Land Use Strategy sets several out principles for sustainable land use under which soil erosion control could be implicated eg 'Greenhouse gas emissions associated with land use should be reduced'. The strategy details 'Farming for a Better Climate' and 'Future Proofing Scotland's Farming' initiatives that promote the uptake of adaptation measures (e.g. soil erosion mitigation measures'), that help to increase the resilience of agriculture to climate change.	Onsite/offsite	Variable – but focus on agricultural land under farming initiatives
Forestry and Land Management (Scotland) Act (2018)	The Act does not mention soil, but makes provisions "in relation to the management of forested land and other land". Part 2 requires Scottish Ministers	Soil erosion control within forestry can be part of 'sustainable forest management'.	onsite	Woodland -Low risk areas

	to “promote sustainable forest management” and produce a forestry strategy, which must include “priorities and policies with respect to— (a) the creation of woodland, (b) economic development of forestry, (c) targets for planting of trees, (d) the conservation and enhancement of the environment by means of sustainable forest management” The Act also requires Scottish Ministers to “… manage land …for the purpose of furthering the achievement of sustainable development”.			

The UK Forestry Standard (Forestry Commission)	The UKFS Requirements are divided into legal requirements (e.g. statutory requirements that can lead to prosecution if contravened) and good forestry practice requirements (often linked to international agreed criteria and provide the framework for regulatory powers of the forestry authority and can be linked to grant payment).	Guidance (non-statutory) in general forest guidance #28 Design road surfaces, drainage and harvesting machine access points to avoid erosion and other adverse impacts on soils, watercourses and water quality. #31 Minimise compaction, rutting and erosion during forest operations by selecting the most appropriate working method for site conditions; monitor operations and modify, postpone or stop procedures if degradation starts to occur. #33 On sites vulnerable to compaction and erosion, consider the weather and aim to carry out operations during dry periods; plan ahead for changes in the weather that	Onsite (Forestry)	Forestry

		could affect site conditions. Specific guidance related to soil erosion: #16 Address the risks of soil erosion as part of the forest and operational planning processes. #17 Aim for a mix of shaded and lightly shaded habitat within the riparian zone – around 50% canopy cover on average but guided by local circumstances and the requirements of priority species. #18 On steep slopes where there is a risk of slope failure or serious erosion, consider alternatives to clearfelling. #19 Consider planting woodland to protect erosion-prone soils and intercept sediment-laden run-off.		

Legislation found in Defra Project SP1318B:

Agricultural –Non SPS	Erosion	The Rural Stewardship Scheme (Scotland) Regulations 2001	Scotland	Direct	Low	Erosion damage must be repaired on sites of archaeological/historic interest.

Agricultural –Non SPS	Erosion	The Rural Development Contracts (Rural Priorities) (Scotland) Regulations 2008	Scotland	Direct	High	A 5 year programme eligible for payment whereby areas/fields at risk of erosion have been identified through a specialist Diffuse Pollution Audit or Soil Water Management Plan have been converted from arable to grassland.
Agricultural –Non SPS	Erosion	The Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2013; The Water Environment (Diffuse Pollution) (Scotland) Regulations 2008 (relevant to poaching only)	Scotland	Direct	Moderate	Works carried out to construct and maintain surface drainage, ditches and to control bank erosion must not cause a significant increase in erosion.
			Scotland	Direct	Low	Prevention of significant erosion must be avoided by minimising poaching on any land within 5m of any river/ditch or wetland.
Agricultural –Non SPS	Erosion	The Agriculture Improvement Scheme 1985; The Farm and Conservation Grant Scheme 1989	UK; Scotland	Direct	Moderate	Specifically in Scotland a grant is given for erosion mitigation works on water-course banks/channels or agricultural flood protection work.

Cutting peat	Erosion	The Rural Development Contracts (Rural Priorities) (Scotland) Regulations 2008	Scotland	Direct	Moderate	Aid payments for the implementation of management plans to:
						not carry out peat-cutting on lowland raised bogs (£40 - £83 ha-1 yr-1)
						address impacts including peatcutting on erosion-sensitive upland and peat land sites (£0.70 ha^{-1} yr^{-1}).

A. Current Scottish national policy instruments with soil erosion focus (implicit or explicit)

All government departments, bodies and policies must align with the National Performance Framework. Scottish environmental policy is embedded in the National Performance Framework which sets out the Governments Purpose, Strategic Outcomes and Targets, as well as a list of indicators by which to monitor progress.

It is difficult to define and bound Scottish environmental policies (Prager et al., in press), specifically those that relate to soil. It is not always clear how to map the parent policy to an Act and a delivery mechanism; sometimes the parent policies or delivery instruments are nested. For example, the Common Agricultural Policy does not have an associated Act, but is implemented via a series of regulations including the CrossCompliance (Scotland) Regulations 2014 that relate to the agri-environment policy instruments such as GAEC. Two GAEC instruments link specifically to soil erosion, however they have limited applicability to all risk scenarios. GAEC 5 (Minimum land management reflecting site specific conditions to limit erosion) only protects soil in certain situations (e.g. to minimise direct bank erosion or additional measures (e.g. grubbing, sediment traps) or where crop or cover is not sown due to adverse conditions. GAEC 4 (minimum soil cover) protects soil against erosion after harvest until the end of winter by leaving stubble, sowing covers or grass. However this might not be possible after late harvested crops due to adverse weather conditions. Agricultural areas not claiming a single farm payment (SFP) would not be covered by these instruments and thus the policies alone would offer no protection against erosion incidence or impacts. In any case, it is estimated that agricultural land not receiving SFP in Scotland amounts to only 3.2% of the land area (Defra Project SP1318B). Whilst this is small, it can be problematic if the area is under high erosion risk. However there is no spatial context to the analysis (i.e. where the areas are located) so this cannot be determined at present.

The Land Use Strategy 2016-2021 is a requirement under the Climate Change (Scotland) Act (2009) and details principles for sustainable land use. Initiatives under the strategy such as 'Farming for a better climate' https://www.farmingforabetterclimate.org/soil-regenerative-agriculturegroup/ provide advice and resources. These include various guides on: 'valuing your soils'/ soil management'/'improving soil quality'/ 'cover crops', that promote mitigation measures for soil erosion control in agricultural areas. These are guidance documents rather than regulatory requirements.

The instruments with the strongest influence on soil (and soil erosion) tend to focus on incentives and voluntary initiatives (e.g. GAEC and 'Farming for a better climate') rather than regulations.

Policies designed for water resource protection also have relevance for soil erosion prevention and control. The Water Environment Regulations mention explicitly minimising bare land and runoff, and are related to the protection of offsite water resources (rather than the soil itself).

Under environmental protection, the primary policy instruments relate to the protection of natural areas and the prevention of contamination. These are only applicable to specific land uses (e.g. wildscapes) that have been identified in this study as having low erosion rates (Table 7).

Contamination regulations focus on the prevention of contamination of soil by harmful substances rather than the (eroded) soil being a contaminant itself. Thus the applicability of this policy would depend on the classification of sediment (eroded soil) as a contaminant or a substance that could cause harm.

highlights the soil policy instruments relevant to soil erosion as summarised above. Some policies relate to specific land uses (e.g. for habitat and conservation of 'wildscapes'), or to very specialised or localised areas (e.g. installation of electricity substations or contaminated sites). Other areas that are likely to have high erosion risk (due to vulnerable soil and land use combinations – e.g.

arable, horticulture) have some protection by policy, but this is often limited to specific situations (e.g. implementation of GAEC) or the policy instrument is a guideline or resource (e.g. Farming for Climate), rather than a regulation.

Analysis of the table identifies the following gaps where there is limited policy protection for soil erosion: 1) overarching regulatory framework for soil erosion; 2) grassland systems; and 3) urban areas.

From Defra SP1318B:
The Rural Development Contracts (Rural Priorities) (Scotland) Regulations 2008 is the only item of legislation found to protect against multiple soil degradation processes (i.e. erosion, compaction, loss of organic matter and contamination). This offers direct soil protection, with high impact, as it not only requires a soil water management plan to be generated for each field, but the costs of preparing these reports can be claimed back.

In addition to the soil protection covered by the Set-Aside Regulations 1988 (England and Wales), Scottish soils are further protected from soil erosion by The Rural Stewardship Scheme (Scotland) Regulations 2001; The Rural Development Contracts (Rural Priorities) (Scotland) Regulations 2008; The Rural Development Contracts (Rural Priorities) (Scotland) Amendment Regulations 2010; The Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2013; and The Water Environment (Diffuse Pollution) (Scotland) Regulations 2008. All are considered to have a direct effect on soil protection.

The Rural Stewardship Scheme (Scotland) Regulations 2001 is considered to provide a low degree of protection as it only relates to a specific sites (i.e. of archaeological and historical interest).

The Rural Development Contracts (Rural Priorities) (Scotland) Regulations 2008 is considered to offer a high degree of protection, because it involves payment and thus has a greater likelihood of adoption. Furthermore, being part of a 5 year programme also means that monitoring is likely to take place, ensuring that the measures in place are effective in protecting soils from erosion.

The Rural Development Contracts (Rural Priorities) (Scotland) Amendment Regulations 2010 offers a low degree of protection as it is only relevant to SSSIs. These make up only a small percentage of agricultural land, and it is assumed that the SSSI designation means they are already well protected.

The Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2013 offers a moderate degree of protection against soil erosion as it only applies to a small area of agricultural land (i.e. field margins with ditches and channels). Together with The Water Environment (Diffuse Pollution) (Scotland) Regulations 2008, this also protects against soil erosion caused by poaching. This legislation is considered to provide a low degree of protection to agricultural (non SPS) land as it is only relevant to livestock agriculture on or near wetland or riverine areas.

Finally, in the Agriculture Improvement Scheme 1985 and The Farm and Conservation Grant Scheme 1989, Scottish soils are protected from soil erosion through grants for erosion mitigation works. This is considered to offer a moderate degree of protection as it is only relevant to watercourse banks/channels and agricultural flood protection works.

Some water quality protection is provided by the Action Programme For Nitrate Vulnerable Zones (Scotland) Regulations 2008. This legislation is considered to have an indirect effect, as soil is not explicitly mentioned, however the enforced monitoring of nitrate reducing practices will have some effect on soils. This is considered to have a moderate impact as nitrate is not the only water pollutant that is linked to soil degradation.

B. Options for implementation of local (catchment) soil erosion mitigation practices

The review of current legislation suggests that there is no Scottish policy instrument to implement soil erosion mitigation measures, although many of these measures fall under the GAEC rules. As such, they can be applied under the CAP rules (although new arrangements post-Brexit may affect this link). A recommendation would be that any future subsidy scheme at least replicates the current provisions to ensure continuity and going forward, potentially highlighting key measures in high risk areas that would be most effective. Table 78 in Appendix 11 describes a number of mitigation measures available to control soil erosion (Cuttle et al., 2007; Posthumus et al., 2013b; Rickson et al., 2010).

Table 77 presents the cost-effectiveness of these measures (Posthumus et al., 2013c) and whether they would be relevant / adoptable in Scotland.

Table 77. Cost- effectiveness of soil erosion mitigation measures (after Posthumus (2013c). Description of measures is given in Table 78.

Mitigation measure (erosion control measure)	estimated reduction in soil loss (%)	Annual costs of mitigation (includes costs of investment; maintenance; loss of production; and hindrance to operations	Relevant in Scotland?
		Total (£/ha/yr)	y/n
No mitigation	n/a	-	
Cover crops- Winter cover	10	229	y
Cover crops - Under sown	10	177	unsure
Mulching	50	69	if practical
High density planting	25	6	unsure
Reduced/ minimum tillage	25	50	y
Zero tillage	25	108	y
Cultivate across slope	50	10	if practical
Tramline management	80	21	y
Loosen compacted soils	25	10	y
Leave autumn seedbeds rough	25	36	unsure
Convert arable to grass	50	607	high risk areas only
Agro-forestry	50	27	high risk areas only
Biomass cropping	50	- 150	leads to more erosion??
Field layout	25	no data	y

Early harvesting	2	800	unsure
Timeliness	2	74	y
Crop rotation	2	331	y
Shelterbelts	10	35	y
Establish new hedges	10	70	y
Reduce the length of the grazing day/grazing season	2	44	y
Reduce field stocking rates when soils are wet	10	44	y
Move feeders at regular intervals	10	30	y
Construct troughs with firm but permeable base	10	5	y
Reduce overall stocking rates on livestock farms	10	138	high risk areas only
Fence off rivers and streams from livestock	2	15	y
Construct bridges for livestock crossing rivers/streams	2	30	y
Re-site gateways away from high-risk areas	10	4	y
Farm track management	2	3	y
In-field buffer strips (6m)	25	68	need proper targeting
Riparian buffer strips	50	68	need proper targeting
Geotextiles/ grassed waterway	25	109	y
Lined waterways or swales	25	15	y

Earth banks/physical barriers	25	67	y
Irrigation	25	1,000	??
Establish coarser seedbeds	25	36	if practical
Increase soil organic matter	50	20	y
Furrow press	25	10	??
Addition of clay sized particles	25	no data	unsure, not proven?
Synthetic stabilisers	25	no data	unsure, not proven?
Establish and maintain artificial wetlands	10	15	not useful in erosion situations
Plough late for spring sown crops			
In-field buffer strips (2m)			
Grubbing tramlines			

Appendix 11. Soil erosion mitigation measures

Table 78. Options for the mitigation of soil erosion

Mitigation measure (erosion control measure)	Description
No mitigation	no mitigation applied
Cover crops- Winter cover	Temporary cover is established in-between main crops in order to protect soil. It can also involve under-sowing whilst the main crop canopy establishes.
Cover crops - Under sown	Temporary cover is established in-between main crops in order to protect soil. It can also involve under-sowing whilst the main crop canopy establishes.
Mulching	Crop residues or stubble from harvested crops are left in place to minimise run-off.
High density planting	Increase in seeding rates ensures maximum cover, reducing exposure.
Reduced/ minimum tillage	Soil structure is kept more intact reducing erosion risk. Noninversion techniques also preserve the soil surface by keeping some vegetation in place. Reduces tillage erosion and translocation and prevents water erosion

Zero tillage	Seeds are planted by a drill, avoiding the need for tilling. Previous crop residue is retained and soil structure is maintained. Impact of erosive forces is reduced and no tillage soil translocation occurs
Cultivate across slope	Across slope cultivation reduces run-off erosion.
Tramline management	Cover cropping and physical barriers such as mulch can be used to reduce tramline soil exposure, reducing run-off. Not using tramlines until the spring will also prevent erosion risk.
Loosen compacted soils	Use of shallow spiking, slitting or subsoiling on cultivated compacted or capped soils increases surface roughness and prevents erosion by water run-off by increasing infiltration.
Leave autumn seedbeds rough	Leaving the seedbed rough will increase water infiltration and reduce run-off risk.
Convert arable to grass	Arable land converted to permanent grass, which would reduce wind and water erosion and tillage would no longer occur.
Agro-forestry	Tree planting within arable and grassland systems
Biomass cropping	Arable land converted to biomass cropping, which would reduce wind and water erosion and tillage would no longer occur.
Field layout	Smaller field sizes reduce wind acceleration and slope length reducing erosion. The movement of soil by tillage may also be reduced.
Early harvesting	Crops are harvested in September when the soils are drier rather than October. Reduces compaction, soil structural damage, and surface run-off.
Timeliness	Arable land is cultivated for spring crops rather than autumn, reducing the likelihood of harvesting in wet conditions which increase erosion risk when the soil is bare and increases coextraction.

Crop rotation	Rotation of high erosion risk crops with low erosion risk crops, such as ley grasses, can help to establish organic matter and improve soil structure.
Shelterbelts	Establishing rows of trees or hedgerows to provide shelter from wind and airborne erosion. They also trap sediment and lower surface run-off.
Establish new hedges	Based on new hedge establishment, installing new gateways and back fencing

Reduce the length of the grazing day/grazing season	Requires indoor areas where stock can be kept, increased labour costs of housed animals and due to increase in proportion of grass utilised by cutting.
Reduce field stocking rates when soils are wet	Assumed that no additional slurry storage was needed.
Move feeders at regular intervals	Costs based on moving feeding troughs on a fortnightly basis for dairy/beef cattle during the grazing season and for pigs throughout the year.
Construct troughs with firm but permeable base	Construct firm but permeable base for existing troughs (large round troughs for dairy cattle and conventional troughs for beef, sheep and pigs).
Reduce overall stocking rates on livestock farms	Reduce total number of livestock on the farm
Fence off rivers and streams from livestock	Fence off rivers and streams from livestock.
Construct bridges for livestock crossing rivers/streams	Construct bridges for livestock crossing rivers/streams.
Re-site gateways away from high-risk areas	Move gateways to lower risk areas
Farm track management	Based on digging out a soakaway and installing French drains across farm tracks, plus maintenance and clearing out every four years
In-field buffer strips (6m)	On sloping fields – grass buffer strips are established along the land contour, at the bottom of valleys or on upper slopes to reduce surface water flow.
Riparian buffer strips	Grass or woodland strip act as a natural buffer to reduce the transfer of pollutants from agricultural land to water. They can be used to restrict direct livestock access to watercourses and can trap sediment
Geotextiles/ grassed waterway	Geotextiles are permeable fabrics which can be natural or synthetic. They can be used to protect emerging vegetation, underline swales and waterways to protect bare ground from erosive forces.
Lined waterways or swales	Lining waterways or swales with vegetation (usually grass) increase resistance against overland flow. Geotextiles can be used prior to vegetation establishment. Reduces particle detachment and transport of eroded material.

Earth banks/physical barriers	Earth banks and other physical barriers such as ponding sites may be used to intercept run-off flow. Reduces the impact of overland flow velocity, thus indirectly reducing erosion.
Irrigation	Keeping the soil moist reduces wind erosion.
Establish coarser seedbeds	A coarse seedbed reduces run-off and erosion by maintaining soil structure.
Increase soil organic matter	Increased soil organic matter decreases erosion risk and encourages water infiltration. Fertility is also increased. Cover crops, green manures and mulches can be used.
Furrow press	Light pressing and soil compaction can increase soil cohesion reducing wind erosion.
Addition of clay sized particles	Mixing clay rich soil into the soil improves soil stability reducing erosion by wind and water. Application rates of 4001000t/ha are likely to be needed depending on the soil.
Synthetic stabilisers	Soil stabilisers such as PVA (polyvinyl acetate) emulsions and PAM (polyacrylamides) can be sprayed onto sands after drilling. This provides cohesion and protection against wind and rain erosion.
Establish and maintain artificial wetlands	Construct wetlands with fences and channels to capture runoff and sediment.

Appendix 12. Project dissemination

The project was mentioned in an article in the June issue of the SNH science quarterly newsletters (https://www.nature.scot/snh-science-quarterly-newsletter). The SNH newsletters are uploaded to their website and circulated to a distribution list which includes current and past SAC and Expert panel members, research contacts including past and present PhD supervisors, NGOs and country agency scientists.

“Since the publication of the *2006 State of Scotland Soil* report, research activities under the RESAS program have help understand the process driving soil erosion in Scotland and led to *improved model of soil erosion risk*. However we are still lacking transparent and robust economic analyses costs of soils erosion in Scotland.

Tom and I have been engaged in the steering board of a new Scottish Government CRF funded project looking at developing a method to estimate soil erosion costs in Scotland. The project led by Cranfield University (Prof. Jane Rickson) and the James Hutton Institute (Dr Allan Lilly) is due to be complete in late 2019 and will estimate the costs of soil erosion in Scotland. These costs are incurred by land-based businesses where soil erosion occurs, and by society where soil is deposited ‘off-field’ or in-stream. Understanding the impacts and costs of soil erosion will inform policies designed to value the soil resource.”

This publication is available at **www.gov.scot**

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