Scottish Natural Heritage

Commissioned Report 325

Climate change, land management and erosion in the organic and organo-mineral soils in Scotland and Northern Ireland

COMMISSIONED REPORT

Commissioned Report No.325

Climate change, land management and erosion in the organic and organo-mineral soils in Scotland and Northern Ireland

(ROAME No. F06AC104 - SNIFFER UKCC21)

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SCOTTISH NATURAL HERITAGE

COMMISSIONED REPORT

Summary

Climate change, land management and erosion in the organic and organo-mineral soils in Scotland and Northern Ireland

Commissioned Report No. 325 (ROAME No. F05AC701 – SNIFFER UKCC21)
Contractor The Macaulay Institute, Agrifood and Bioscience Institute, University of Stirling
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Background

Organic and organo-mineral soils make up 50% of the land area of Scotland and Northern Ireland. These soils are mainly associated with semi-natural environments , many of which are covered by a variety of protected areas designation. Erosion and organic matter loss have been identified as two of the major threats faced by soil resources at both a national (UK) and European level.

The degradation of organic and organo-mineral soils and the ecosystems they support is well documented. Evidence of extensive erosion in some upland peat soils is also available and it is believed that this may relate to the documented increase in dissolved organic carbon in upland streams.

This project aims to provide critical analysis of the factors controlling the rate of physical and chemical degradation of organic and organo-mineral soils in Scotland and Northern Ireland. These factors could thereafter be related to potential impacts of erosion on habitats and freshwater quality. It also delivers information at a large scale to support a review of management/policy strategy to protect soil resources and limit the impact of erosion in Scotland and Northern Ireland.

Main findings

1. The evidence from a wide range of studies suggests that erosion of surface organic horizons has had a significant impact on organic and organo-mineral soils in Scotland and Northern Ireland. At the national scale, erosion has impacted on around 14% of peatland in Northern Ireland and some 35% of peatland in Scotland.

2. It is difficult to quantify the specific effects of the major drivers of erosion, as some act to damage surface vegetation cover and thus increase the susceptibility of surface organic soil horizons to erosion, while others control the occurrence and rates of erosion (usually from sites with prior surface damage). In most instances, erosion is the result of multiple drivers.

3. The evidence suggests that overgrazing is probably the major anthropogenic driver, leading to vegetation damage and increased susceptibility of organic surface soil horizons to erosion. The evidence shows that sheep numbers have decreased in recent years but, in Scotland, there is still concern over the numbers of wild deer.

4. Extreme climatic events, including prolonged warm dry periods as well as intense rainfall events, are the most important triggers for specific erosion incidences. The occurrence of these is difficult to predict but most climate change scenarios suggest that the magnitude and/or frequency of extreme precipitation events are likely to increase.

5. In relation to organic soils, there is some evidence that degradation has been taking place for many centuries and that key climatic perturbations over this period may have triggered the development of the current gully systems. Any change in climate that increases desiccation of the ground surface is likely to make that surface more vulnerable to agents such as trampling by animals, rainfall or wind, wildfires and human trampling. Current climate change scenarios suggest that increased risk of desiccation is likely.

6. It is unlikely that drainage, controlled burning or air pollution act as drivers of soil erosion on any significant scale in Scotland or Northern Ireland, while the widespread adoption of the Forests and Water Guidelines has effectively reduced the risk of erosion being caused by forest operations.

7. It is unlikely that the increased losses of carbon from organic and organo-mineral soils, which are reflected in the increased flux of dissolved organic carbon measured in streams draining upland catchments, are driven by changing climate

alone. Much of the increased Dissolved Organic Carbon (DOC) flux represents an adjustment to reduced levels of sulphate deposition following reduced SO_2 emissions over the last two decades. Modelling work would suggest that rainfall rather than temperature changes may be the key climate drivers of DOC flux in the future.

8. Potential new drivers of erosion in upland organic and organo-mineral soils must also be taken into account in modelling. Although there are strict development guidelines in place, the large number of proposed wind farm developments in upland areas with organic and organo-mineral soils is one example of such potential drivers.

9. Two process-based models were selected as being appropriate to investigate soil erosion risk in Scotland and Northern Ireland based on the availability of the required input data, the availability of support and the capability to test the impact of changes in key drivers such as land use and climate. These were PESERA (Pan European Soil Erosion Risk Assessment) and INCA (INtegrated CAtchments).

10. Due to a lack of validation data, PESERA should be used only to determine relative risk of erosion. The model is able to predict changes in sediment yield due to changes in land cover and climate and is sufficiently flexible that both land cover and climate change can be assessed simultaneously if required.

11. INCA is able to reproduce some of the observed dynamics of DOC fluxes from catchments dominated by organo-mineral soils. Fluxes of both particulate and dissolved organic carbon were positively correlated with precipitation so that increased precipitation resulted in greater losses of particulate and dissolved organic carbon from catchments dominated by organo-mineral soils.

12. Estimates of the rate of change of carbon content of Scotland's soils based on published loss rate equations for England and Wales must be treated with some caution; other national studies display different trends. It would be prudent to evaluate other equations and validate against a national soil re-sampling programme currently underway.

13. The most high-risk situations in relation to erosion of organic and organo-mineral soils are considered to be actively eroding peatland systems with existing and extensive areas of bare peat exposed to the on-going effects of the range of drivers of erosion. Those areas considered to be most at-risk are where sheep are present, combined with moderate to high numbers of red deer (>15 deer per square kilometre).

14. Possible methods for reducing the risk of erosion in these areas include confining sheep grazing to the growing season (i.e. avoid year-round grazing or winter stocking of these sites) and where necessary reduce deer numbers to at or below an overall density of 15 deer per square kilometre. It is also necessary to be aware of the potential role of other herbivores, particularly rabbits, in damaging these areas.

15. It would appear that once upland peat erosion is initiated, in many instances, there is an inexorable tendency towards almost complete loss of the accumulated peat over time. There are limited cost-effective options available to redress this trend.

16. It is important to note that what can be currently observed in the landscape may not be related to present-day conditions but rather to historical ones. This is supported both by data from sediment cores and measurements of contemporary erosion rates. The latter show that the erosional processes are of the order of millimetres per annum, indicating that the processes have endured for several centuries. So a geographical coincidence between erosion and present day conditions cannot be assumed, necessarily, to reflect a causal relationship. The likelihood that multiple drivers of erosion are operating in concert, and the fact that erosional features is relate to historical conditions, does limit options for quantitative analyses of the effects of climate change and land management on the organic and organo-mineral soils of Scotland and Northern Ireland.

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CHAPTER 1

INTRODUCTION

1 INTRODUCTION

The principal aim of this project is to provide a critical analysis of the factors controlling the rate of physical and chemical degradation of organic and organo-mineral soils in Scotland and Northern Ireland and to relate these factors to impacts of erosion on habitats and freshwater quality. It review the findings of empirical studies and evaluate predictive models of erosion of organic and organo-mineral soils.

To meet this overall aim, the project team addressed to complete the following objectives:

1. Review evidence-based and quantitative information on the factors, natural and human-induced (including but not limited to soil properties, management practices, land use, grazing, habitats, climate factors), known to influence erosion dynamics in peat and organo-mineral soils in Scotland and Northern Ireland.

2. Review data on evidence of accelerated soil loss (including DOC and impacts on terrestrial habitats) and analyse and correlate data and factors reviewed in objective 1 to determine trends and primary driving factors both in Scotland and Northern Ireland.

3. Using an agreed selection of existing erosion model(s) (1) assess the robustness and sensitivity of erosion driver and factor responses to changes; and (2) evaluate the ability of selected erosion model(s) to inform on potential risk and its regional variability in Scotland and Northern Ireland for both loss of soil and evidence of soil loss such as DOC or habitat changes.

4. Identify means of assessing and quantifying the response of peat and organo-mineral soils under different climate change scenarios (e.g. land use change and change in climatic factors; temperature, precipitation and storm frequency).

5. Evaluate options for land management practices and mitigation techniques which will reduce the risk of erosion, habitat loss and DOC leaching in high risk situations.

Soil erosion is a natural process but it can be exacerbated by inappropriate soil management or extreme weather events. On cultivated mineral soils, erosion can often be easily rectified. On uncultivated organic or organo-mineral soils in the uplands, restoration is much more difficult. The degradation of organic soils is the result of many natural and anthropogenic factors, often with complex interactions between them and operating over long time periods. These factors are reviewed in detail in Chapter 2. Erosion of soils with organic surface horizons has a direct impact on soil quality in terms of its capacity to deliver a number of functions including the storage of organic carbon. Off-site effects, including elevated Dissolved Organic Carbon (DOC) and Particulate Organic Carbon (POC) concentrations in streams, increased Green House Gas (GHG) emissions to the atmosphere and reductions in above-ground biodiversity, are also impacts related to peat erosion. Nevertheless, some severely eroded sites have been designated as Sites of Special Scientific Interest (SSSI) in their own right because of the geomorphological interest and the pool systems that have developed, for example the Knockfin Heights on the Caithness/Sutherland border in Northern Scotland.

Because of their diverse geomorphology and climate, Scotland and Northern Ireland possess a wide variety of different soil types. The diverse topography gives rise to further local-scale variation, and mapping units shown on the 1:50 000 or 1:250 000 soil maps encompass a range of soil types with varying properties linked to local variations in slope and landform (Soil Survey of Scotland Staff (1970-1987); Soil Survey of Scotland Staff (1981); Soil Survey of Scotland Staff (1954-1986); Cruickshank, 1997).

The distribution of the principal soil groups in Scotland and Northern Ireland is shown in Figures 1.1 and 1.2, respectively. Because of the strongly maritime climate, with cool temperatures and rocks which are generally resistant to weathering and base cation deficient, Scottish soils are in general more organic, more leached and wetter than those of most other European countries. Scotland contains greater proportions of podzols (23.7% of the land area), peat (histosols, 22.5%) and gleys (20.6%) than Europe as a whole. Many of these features are also observed in Northern Ireland where gleyed soils predominate. The proportions of podzols, peats and gleys in Northern Ireland as a percentage of land area are 4.1%, 14% and 62%, respectively.

Figure 1.1 also reveals the contrast between soil types in the Midland Valley and those in the Highlands and Southern Uplands of Scotland. The Midland Valley is dominated by mineral soils, whereas the Highlands and Southern Uplands are dominated by peaty soils (peat, peaty gleys and peaty podzols) especially in the west. Similarly, the central lowlands of Northern Ireland (Figure 1.2) are dominated by mineral gleys, while the peripheral uplands are predominantly covered with peaty soils.

This diversity of soil types underlies the wide range of functions associated with soils in Scotland and Northern Ireland. Although almost all soils produce above-ground biomass, the area of semi-natural communities and their underlying soils in both countries provides an indication of the importance of soils for wider environmental functions such as carbon storage, biodiversity or water filtration, rather than agricultural crops or forestry production. Many of these habitats of high conservation value are unique to Scotland and Northern Ireland and the soils that underpin them are rare in a UK, European and, on occasion, a global context.

Compared with many other soil properties, the current status of soil organic carbon can be quantified relatively well, although there are significant limitations due to heterogeneity of soils and lack of measurements of bulk density needed to calculate absolute stocks of carbon (C) in the soil. Soil organic carbon is an attribute common to soil databases held by the Macaulay Institute (MI) and Agri-Food & Biosciences Institute (AFBI) and can be used to give a broad picture of the soil organic carbon status of Scottish and Northern Ireland soils (Figures 1.3 and 1.4). Figure 1.5 illustrates the frequency distribution of soil organic carbon concentrations in the uppermost horizon of the 10 km National Soil Inventory of Scotland (NSIS) data points, and Figure 1.6 illustrates the frequency distribution of soil organic carbon concentrations in the A horizon for 5 km data points in Northern Ireland. The frequency distributions are very similar, with a bimodal distribution in both cases. The peak at around 5% organic carbon represents the bulk of the agricultural soils in Scotland and Northern Ireland, whilst the peak at around 55% represents peat and other organo-mineral soils such as peaty podzols and peaty gleys.

Figure 1.1 Distribution of soil types in Scotland (source Macaulay Institute)

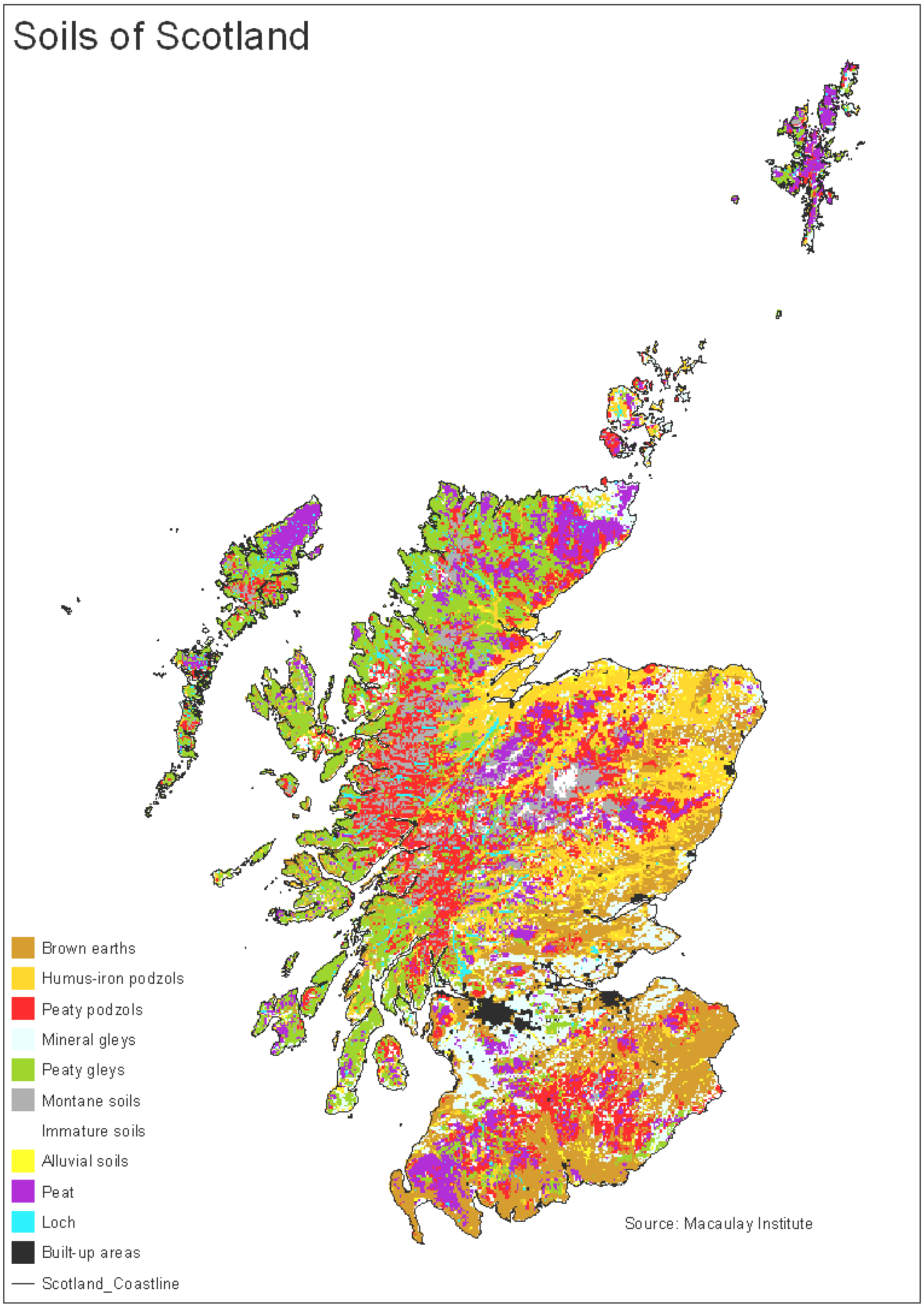


Figure 1.2 Distribution of soil types in Northern Ireland (from AFBI, 2006)

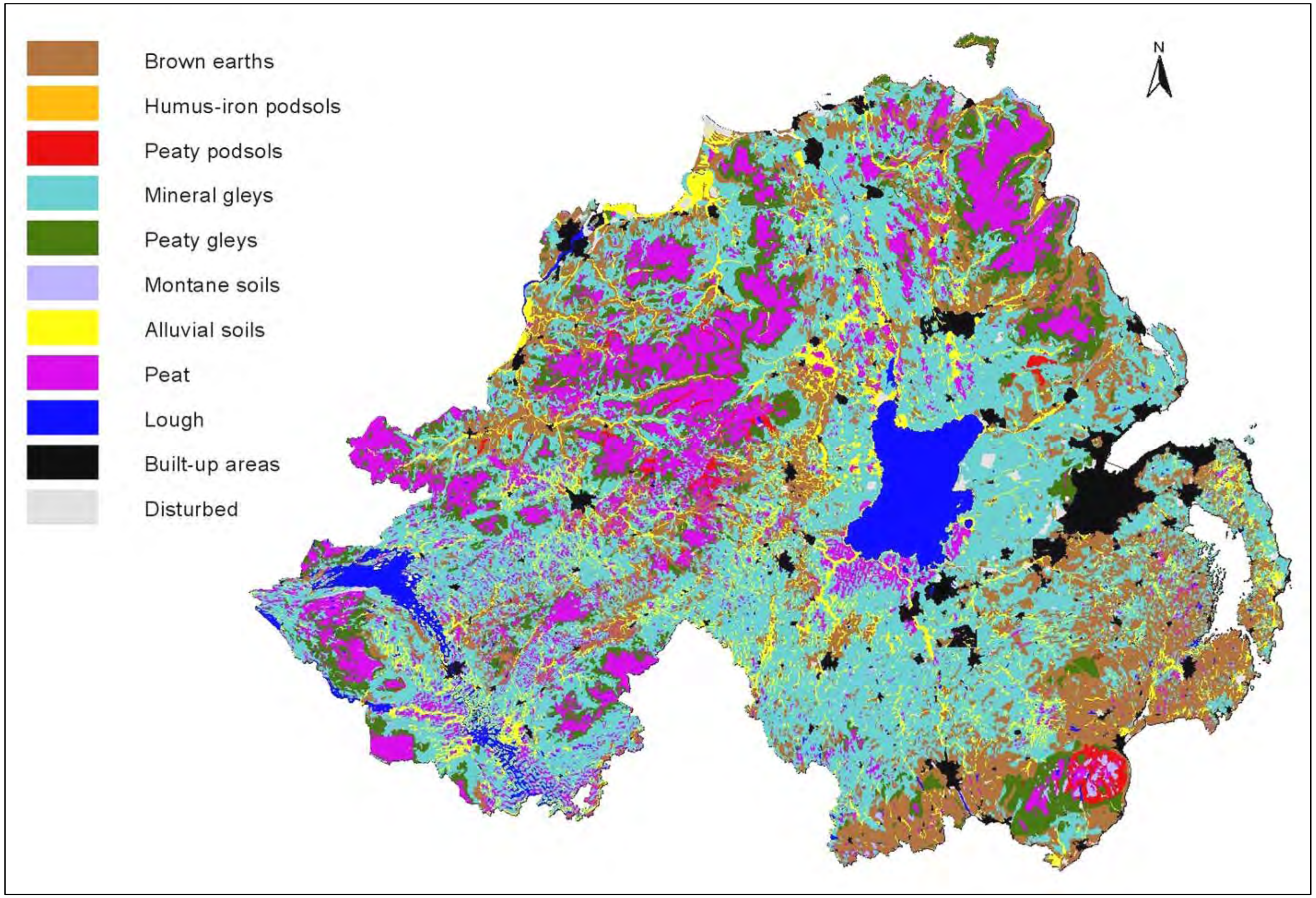


Figure 1.3 Topsoil organic carbon in Scotland, expressed as % total organic carbon of the most extensive soil in each 1km grid square of the 1:250000 soil map

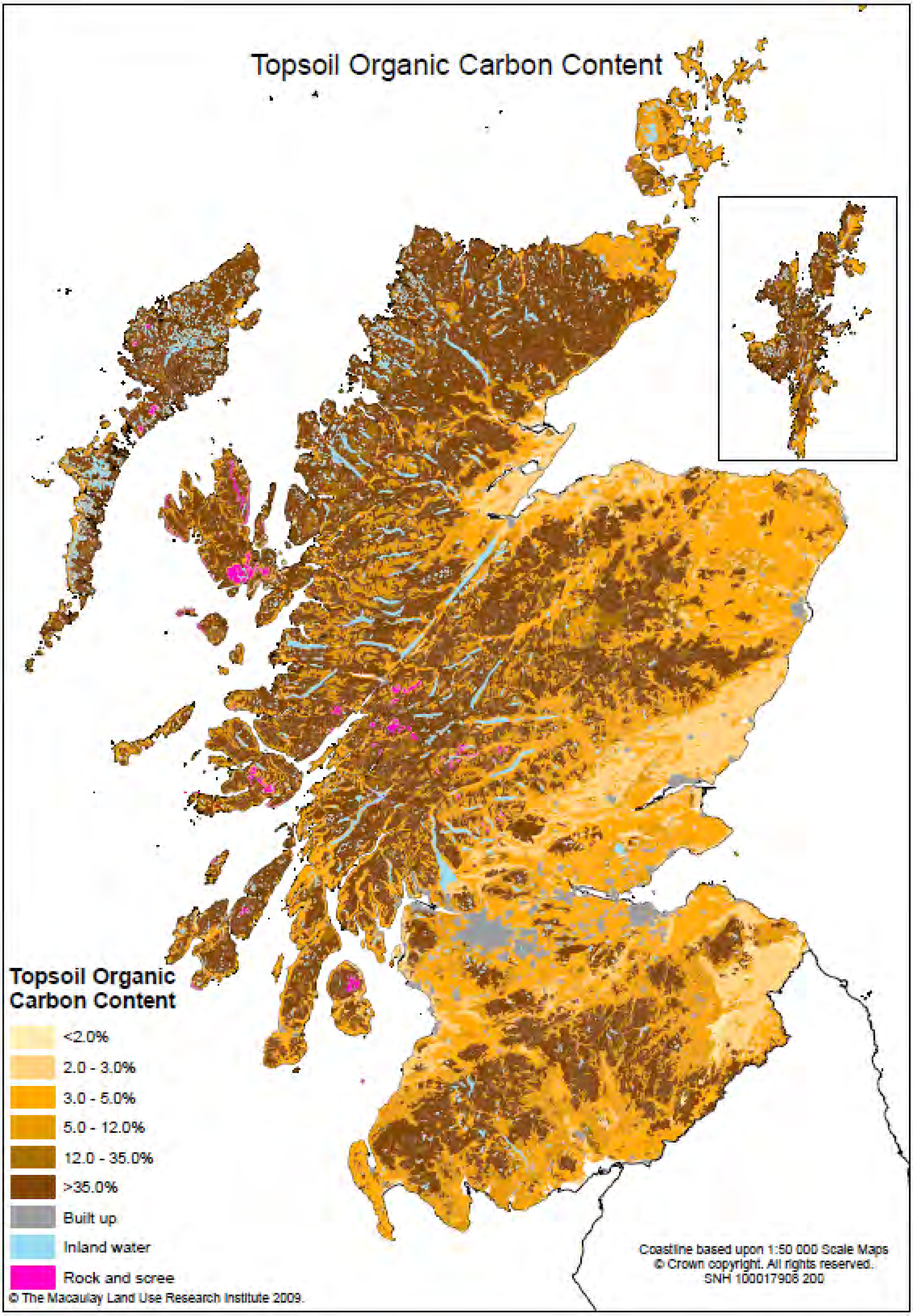


Figure 1.4 Topsoil organic carbon in Northern Ireland (% total organic carbon for each 1:50,000 soil map unit)

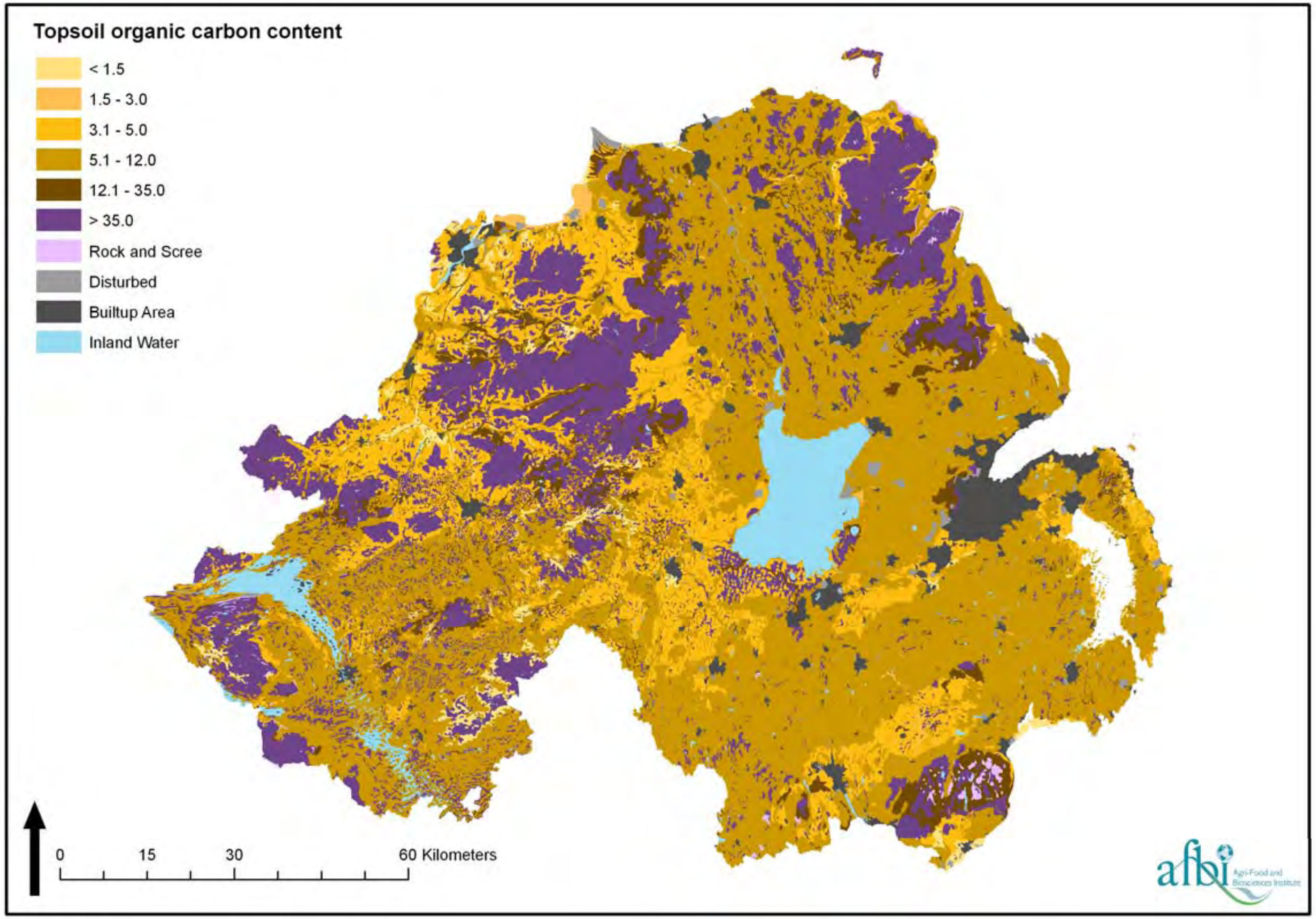


Figure 1.5 Frequency distribution of carbon (mass (wt) %) in the upper horizon of soils at NSIS sites (source Macaulay Institute)

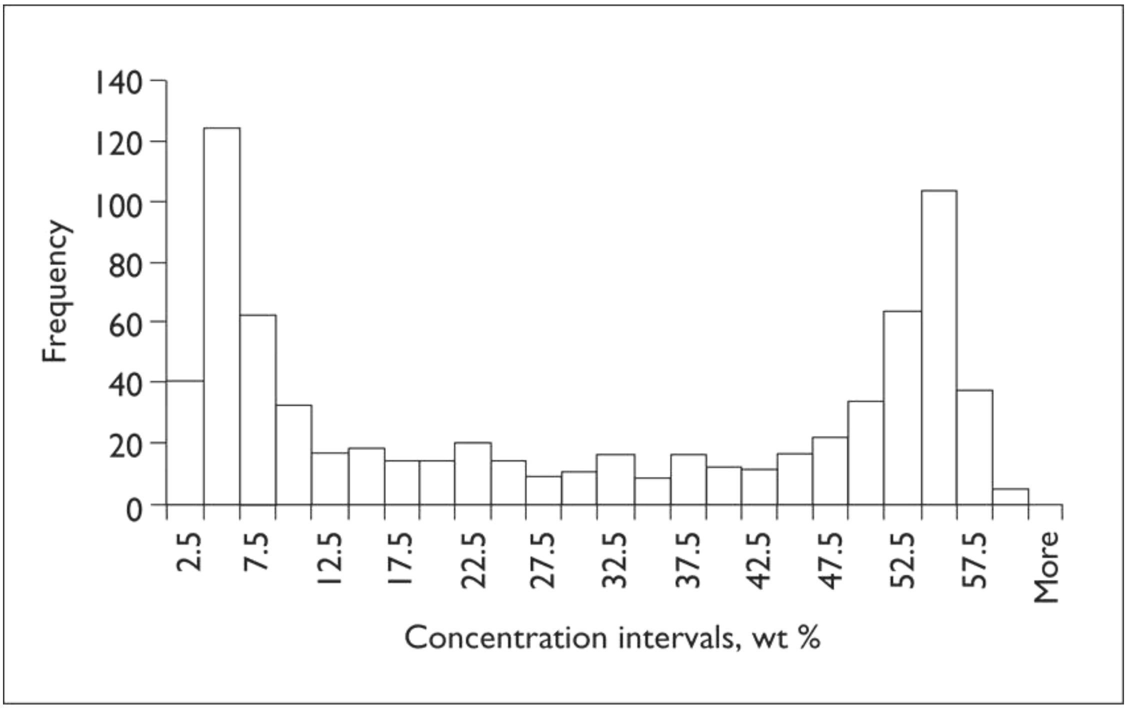
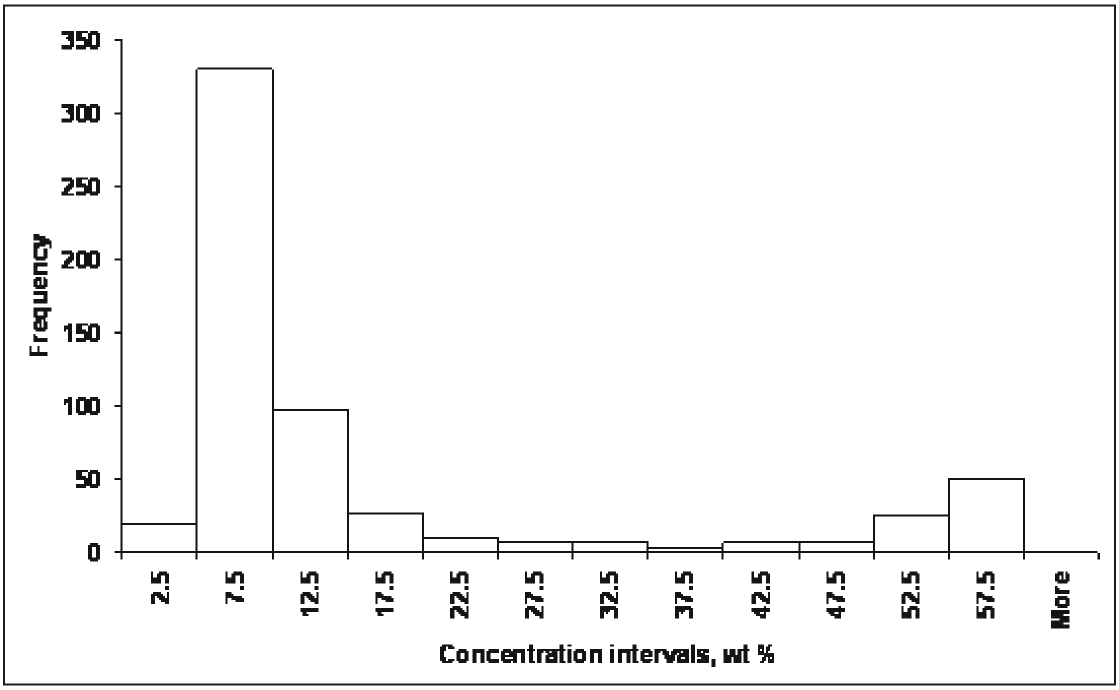


Figure 1.6 Frequency distribution of carbon (mass %) in the upper horizon of soils at NI 5km sample sites (2005) (source AFBI).



High levels of soil organic carbon concentrations exist in the Highlands and Southern Uplands of Scotland, and in upland areas in the north-east and west of Northern Ireland, where the cooler and wetter climate inhibits the decomposition of organic matter in plant material deposited on the soil surface. In such areas, the accumulation of organic carbon is often more rapid than decomposition and an organic surface horizon forms. On level or gently sloping sites, the total accumulation can be as much as 7-8 m.

Although the quality of data on the C concentration in Scottish and Northern Ireland soils is relatively good, it must be remembered that carbon concentrations cannot be translated directly into carbon stock. The bulk density of each soil horizon is also required in order to calculate carbon stocks. Bradley *et al.* (2005) have reported on the development of a database of soil carbon storage and land use. Organic and organo-mineral soils in Scotland and Northern Ireland account for a total carbon storage to a depth of 1 m of almost 1800 Tg C, 40% of the UK's total soil carbon store (Bradley *et al.*, 2005). Estimates of C stocks below 100 cm depth have been determined as part of the ECOSSE project (Scottish Executive, 2007b) and this has added a further 485 Tg C to the Scottish total. In the case of Northern Ireland, estimates of C stocks below 100 cm are computed from the difference between the total soil C stock estimated by Cruickshank *et al.* (1998), (386 Tg C), and soil C stock to 1m given by Bradley *et al.* (2005), (296 Tg C), equating to 90 Tg C.

CHAPTER 2

Review of key drivers of erosion of organic and organo-mineral soils

Objective 1

Review evidence-based and quantitative information on the factors, natural and human-induced (including but not limited to soil properties, management practices, land use, grazing, habitats, climate factors) known to influence erosion dynamics in peat and organo-mineral soils in Scotland and Northern Ireland.

Objective 2

Review data on evidence of accelerated soil loss (including DOC and impacts on terrestrial habitats) and analyse and correlate data and factors reviewed in objective 1 to determine trends and primary driving factors both in Scotland and Northern Ireland.

2 REVIEW OF KEY DATA AND DRIVERS OF EROSION OF ORGANIC AND ORGANO-MINERAL SOILS

The aim of this chapter is to review the information quantifying the extent and rates of erosion of organic and organo-mineral soils and identify the key controlling factors. From previous work we can evaluate evidence of the areal extent of erosion features and of the range of erosion rates in Scotland and Northern Ireland. These studies, together with others from similar upland environments in the UK, can also provide evidence of the effects which factors such as different land use practices, topography and elements of climate have in determining the incidence and rate of erosion of organic and organo-mineral soils. Studies of erosion from areas such as the Pennines in northern England or the uplands of Wales can provide much useful information and act as a proxy for Scotland and Northern Ireland in cases where direct evidence is not available. It should, however, be noted that elements of these latter environments may not be strictly comparable with conditions in Scotland and Northern Ireland, especially for areas such as the southern Pennines where proximity to sources of acid emissions to the atmosphere has led to direct damage to peatland vegetation communities (Tallis, 1997).

2.1 Review of evidence-based and quantitative information on factors known to influence erosion dynamics – Objective 1

Soil erosion is a natural process which occurs in all soils to a greater or lesser extent. Soil erosion at rates exceeding natural background values is termed “accelerated erosion”. In humid temperate climates such as that of Scotland and Northern Ireland, accelerated erosion is often the result of human activities that lead to removal of the protective vegetation cover and thus trigger the inception of erosion. There have been a number of major reviews of degradation of upland soils in the study area in the last 10-15 years, most involving, and some led by, members of this consortium. Similar work has also taken place in England and Wales and these studies provide valuable information on the factors that cause or exacerbate erosion. In addition, there are a significant number of case studies of erosion incidence reported in the scientific literature. Studies relevant to Scotland have been reviewed in the report on ‘*Status of the Threats to Scotland’s Soil Resource’* (Towers *et al.*, 2006). In this section we review this and other evidence from Scotland and Northern Ireland and similar areas in the UK to identify the key drivers of erosion dynamics in organic and organo-mineral soils in

Scotland and Northern Ireland and the evidence available for quantifying rates of erosion.

2.1.1 National Soils Inventory of Scotland (NSIS)

The National Soils Inventory of Scotland (NSIS) is an objective sample of Scottish soils. Soil and site conditions of 3,094 locations throughout Scotland (except for the Orkney Islands) were available and the presence or absence of erosion features was recorded at 2,845 of these points. Erosion features were not observed at the vast majority of sites (86%) at the time of the sampling. Gullying and rill erosion were the most frequently recorded erosional features. Rill erosion was recorded at 100 sites, with either peat soils or organo-mineral soils suggesting that gully erosion was either extending upslope or at an incipient stage.

Wind erosion was primarily found on mountain tops (soils were alpine or oroarctic podzols) or coastal links soils (regosols). The occurrence of erosion features at NSIS points was also compared with the soil type found at each point. Peat covers around 22% of the land area of Scotland and, according to the NSIS, almost a third of the peat sites visited were eroding.

Overall, the NSIS provides an objective sample of 5 main types of erosional features and covers all of Scotland (apart from the Orkney Islands). The regular grid pattern allows areas of erosional features to be determined. However, although the presence or absence of erosion was recorded at each site, the actual area and depth of gullying was not quantified and the severity of erosion cannot therefore be determined. The usefulness of the survey is also constrained by the prolonged period over which the data were collected (around 10 years) and the lack of strict definitions for each erosional feature.

2.1.2 National Soils Inventory of Northern Ireland (NSINI)

The first full survey of Northern Ireland soils was carried out by staff from the Science Service of the Department of Agriculture and Rural Development (DARD) (renamed AFBI from 1st April 2006) over the period 1988-1997. During the survey, the soils of Northern Ireland were systematically sampled, described, analysed and classified into soil series. Soil profiles were located on a 5 km grid across Northern Ireland from each major soil series in the agriculturally important area (equivalent to the area below 200 m altitude) and their physical and chemical properties determined on samples from pedological horizons. The survey identified 308 distinct soil series developed from 97 soil parent materials. The 5 km grid A horizons were resampled to profile depth and 75 mm in winter 2004/05 and the grid extended to include all of Northern Ireland (i.e. uplands and urban soils were sampled systematically for the first time). In the latter survey, a total of 583 soil profiles were sampled, and environmental variables recorded around the immediate sampling site. Of these, 81 soil profiles were classified as peat. These attributes constitute the National Soils Inventory for Northern Ireland. However, only one peat site was indicated as having erosional features (numerous sites were recorded as either having active or historical peat cutting, which may have masked erosional features).

2.1.3 Land Cover of Scotland 1988 (LCS88)

The Land Cover of Scotland 1988 (LCS88) dataset comprises 126 main categories of land cover identified from air photographs of approximately 1:25 000 scale. The photographs were taken primarily in 1988, though a few were taken in 1989. The photographs were interpreted by a team of skilled interpreters who had extensive field experience in matching tonal patterns on air photographs with vegetation communities in the field. Erosional features were identified in only two categories of land cover: eroded blanket bog and eroded montane vegetation.

The LCS88 dataset shows that just under 6% of Scotland was classified as eroding blanket bog which is approximately 34% of the total area of blanket bog identified. This compares with around 7.5% of Scotland or 31% of all peat categories as calculated from the NSIS. The area of erosion in the montane zone is calculated as around 3% of Scotland from the LCS88 but only 0.5% from the NSIS. This may be explained by the fact that all montane land cover classes were defined as having erosional features, which may not always be the case. Given that a map unit of eroded blanket bog will have substantial areas of both bare and vegetated (that is, uneroded) peat, the actual area of eroded and bare peat will be less than 7.5%. This also holds true for calculations based on the NSIS.

2.1.4 Land Cover of Northern Ireland and peatland areas

Erosion of peat in the uplands of Northern Ireland has been reviewed by Tomlinson (1982). In the recent past, the total area of peatland in Northern Ireland has been obtained from different sources (Tomlinson, 1997). There have been four recent attempts to determine this area – the Northern Ireland Peatland Survey (1988), CORINE land cover mapping (1990), the Soil Survey (1997) and the UK Land Cover Map 2000 (LCM2000) – which gave four totals, 1 676, 1 343, 1 931 and 1 837 km^2, respectively. Initially this appears confusing, but it is understandable because each estimate had its own terms of reference and methodology. The Peatland Survey recorded peatland as seen on the most recent readily available air photographs. Most of the photographs dated from the 1970s, but some areas had not been photographed since the mid 1960s. Clearly, soils under forest could not be seen and therefore forest areas were not included in the peatland totals. In addition, no account could be taken of agricultural fields with peat beneath the pasture or other land cover because, as with forest cover, the peat cannot be identified from the air. This applies also to CORINE and LCM2000 mapping - a satellite-borne sensor records reflectance only from surface materials, so that peat occupied by forest or agricultural crops goes undetected. Also, CORINE land cover mapping followed a classification that applies to the EU and this can mean that peatland is over- or under-represented. For example, some poor, upland 'grasslands' with high sedge content have the image appearance of peatland and thus 'inflate' the total. The Soil Survey, in contrast, is not concerned with the cover, but with the material beneath; any 'soil' composed principally of plant remains, and greater than 50 cm depth, is classified as peat. Reclaimed agricultural land and forest areas would be included if they meet the definition. On the other hand, much of the marginal hill-land classified as peat in CORINE or in the Peatland Survey is excluded by the Soil Survey because the thickness of the organic layer is less than 50 cm even though there might be evidence of past cutting and a plant species composition indicative of peatland. A considerable proportion of the marginal hill land therefore is grouped into surface water humic gleys and humic rankers. The Peatland Survey showed that around 14% of the blanket bog in Northern Ireland was affected by erosion. This compares to less than 2% from the NSINI but, as mentioned earlier, this may be due to confusion between erosional features and cut-over peat.

2.1.5 Commissioned surveys of erosion incidence

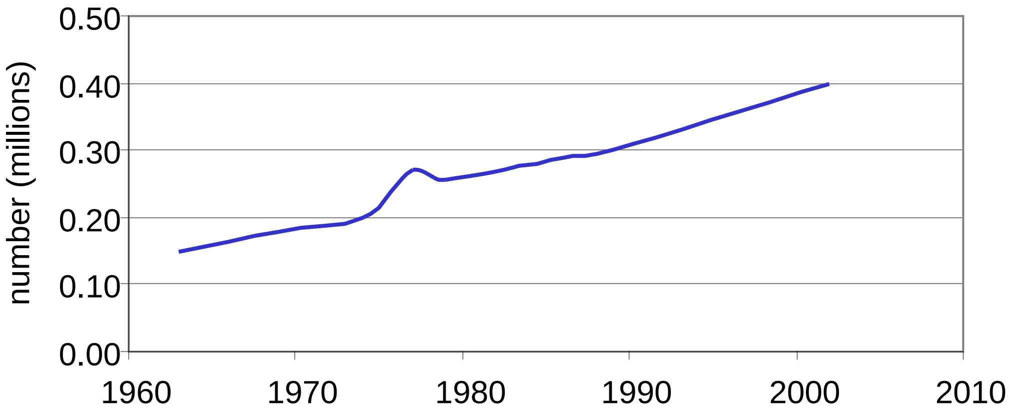
Grieve *et al.* (1994, 1995) quantified the area of erosion from aerial photographs in a 20% sample of the Scottish uplands. In total, just over 12% of the sampled area had erosional features recorded. Of those erosional features, peat erosion accounted for the greatest extent (approximately 50% of the eroded area or 6% of the sample area) and the extent was very similar to that derived from analysis of the LCS88 and NSIS data. It must be emphasized however that these data do not indicate that 6% of the upland area of Scotland has been eroded, but simply that erosion has affected peat soils in 6% of the area. The actual area of eroded peat will be significantly smaller than this.

Tomlinson (1997) reported that in the east of Northern Ireland, the two main areas of blanket peat were on the Antrim plateau and the Mourne Mountains. In Antrim, almost horizontal basalt flows have formed extensive plateaux which have allowed water to accumulate and peat to develop. However, sharp breaks of slope associated with successive lava flows give rise to some steep hillsides and high summits that have encouraged extensive peat erosion. This takes two main forms; on the slopes there is gullying, where sub-parallel, steep-sided channels cut the peatland into large rafts, whereas on flatter surfaces, generally above 360 m and where the peat is deep, a complex pattern of multi-directional channels has developed. Between these freely branching channels there is a myriad of tiny islands of peat. In the most severe examples of this erosion, where the channels have widened, these tiny islands (haggs) are surrounded by bare peat and even bedrock as a result of water, wind and frost action. Peatland has been reduced in Antrim not only through erosion, cutting for fuel (approximately 25% of present peatland has been cut at some time in the past) and reclamation for agriculture, but also by forest planting. This is extensive in some parts, as for example between Glenarrif and Ballycastle. As a consequence of these reductions, pristine peatland is quite rare; the Garron plateau has the largest expanse of pristine peatland and is the area of most interest to conservation. This broad plateau is bounded by steep slopes so that inaccessibility has protected all but the edges from cutting. Erosion is not widespread because of the gently undulating surface and moderate altitude and is confined to short, steep slopes on higher residual summits on the northern side. In the Mournes, the small area of blanket peatland is restricted to high, flat interfluves and almost none has escaped cutting and erosion.

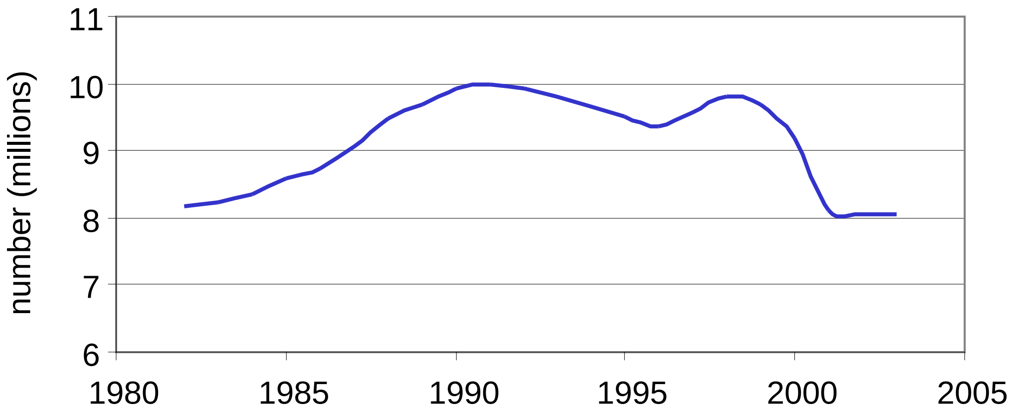
The west of Northern Ireland not only has 73% of its blanket peatland, but also 70% of the intact blanket peatland. In the Sperrins, all the peripheral hills and the lower slopes with blanket peat are affected by hand (spade) cutting. The highest ridges have intensive erosion of freely branching channels and hagging, whereas extensive areas of the upper slopes have gully erosion. Losses of peatland through past cutting and erosion are compounded by afforestation, from both State Forests and private forestry (e.g. Glenlark and Coney Glen). In total, 14% (192 km^2) of the peatland of Northern Ireland is considered to have been affected by erosion to some extent (Tomlinson, 1997).

Figure 2.1. **Variation in a) deer and b) sheep numbers in Scotland and c) sheep numbers in Northern Ireland in recent decades (From Hunt, 2003; Scottish Executive Abstract of Scottish Agricultural Statistics 1982-2003 and DARD Economics and Statistics Division 2007).**
Note that these data refer to different time periods.

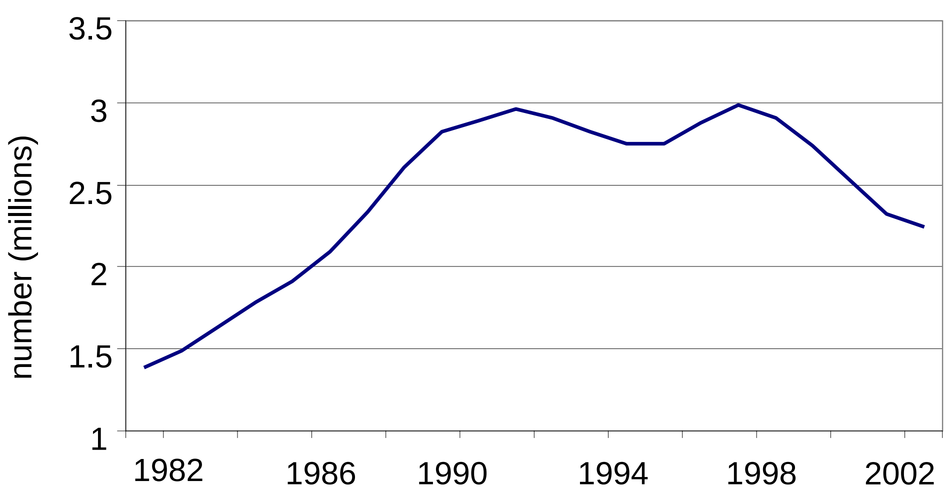
a) Scottish deer population totals.



b) Scottish sheep population totals.



c) Northern Ireland sheep population totals.



The Grieve *et al.* (1994) study provided a preliminary indication of the factors likely to be of importance as erosion drivers, through spatial correlations between areas of erosion and topographic and land use factors. The greatest occurrence of peat erosion (20% of the sample area) was found in the Monadhliath Mountains. However, the extent of the most severe classes of erosion was greatest in eastern parts of the country, particularly the eastern Grampians, where land use and grazing pressures were found to be greatest. This spatial association of erosion and land use pressure, together with the trend of increasing deer numbers in the last four decades (Figure 2.1a) indicates a significant area of concern over erosion in the uplands. Grazing by sheep is also often implicated in soil erosion in the uplands and the number of sheep grazed in Scotland rose by almost 2 000 000 in the 1980s before levelling off, and then more recently declining following the outbreak of Foot and Mouth Disease in 2001 (Figure 2.1b). This decline has continued and the total number of sheep in Scotland is now just less than 7.5 million, a reduction of 25% since the peak in the early 1990s. A very similar trend is evident in the data from Northern Ireland (Figure 2.1c).

A DEFRA-commissioned study of the extent of soil erosion in the upland areas of England and Wales (McHugh *et al.*, 2002) was a ground-based survey measuring similar parameters to those measured in the SNH-commissioned study of upland Scotland (Grieve *et al.*, 1994, 1995). McHugh *et al.* (2002) found that the extent of degraded soil represented around 2.5% of the area surveyed, a smaller percentage than that reported by Grieve *et al.* (1995). McHugh *et al.* (2002) quantified only the area of degraded soil, and thus the results are not directly comparable with the area of soil affected by erosion computed in the Scottish study.

2.1.6 Case studies reported in scientific papers

Case studies reported in the scientific literature supplement the national data sets by providing evidence of the operation of the key drivers of erosion, both through action as triggers and by controlling subsequent evolution of erosion features. Key drivers relevant to objective 1 are summarised here (in alphabetical order) together with some of the key papers which are reviewed. The drivers are responsible for triggering surface disturbance and thus the potential for erosion of surface organic soils or soil layers as described below.

2.1.6.1 Atmospheric pollution

Skeffington *et al.* (1997) suggested that acid deposition since the start of the Industrial Revolution about two centuries ago may be one of the triggers of peat erosion in the

Southern Pennines. Holden *et al.* (2007a) reported that *Sphagnum* has almost completely been eliminated from bogs in areas experiencing high atmospheric deposition of sulphur compounds and there is experimental evidence of a link between sulphur dioxide (SO_2) and damage to *Sphagnum* (Ferguson and Lee, 1983). However, others have commented that the climate of the southern Pennines is also marginal for the growth of blanket mires (Tallis, 1997).

Nitrogen deposition on to organic soils is harmful to them in terms of altering species composition and hence the habitat value of the resource but is unlikely to increase the risk of physical erosion. Indeed the decline in sulphur deposition and increase in N deposition has been linked to revegetation of parts of the North Pennines and hence the provision of a stabilizing influence (Evans and Warburton, 2005).

Reductions in deposition of acid sulphur compounds have also been suggested as a possible contributory factor in the increased concentrations of dissolved organic carbon (DOC) found in streams draining upland catchments during the last two decades. Evans *et al.* (2006b) tested a range of hypotheses to explain the increases in DOC for Acid Waters Monitoring Sites in Britain and concluded that both increasing temperatures and reduced concentrations of non-marine sulphate in streams were contributory factors. The solubility of humic compounds is pH-sensitive and increased acidity and ionic strength have been shown experimentally to reduce DOC concentrations in laboratory experiments. Reductions in acid deposition may, therefore, now be acting to increase the flux of dissolved organic carbon from peatland systems.

2.1.6.2 Burning

Burning is a commonly used tool to manage semi-natural vegetation on heathlands and to a lesser extent on blanket mires. If these fires take place at the appropriate time (October to April), are well managed and not allowed to become too hot and destroy the root mat, they should not expose the peat to erosive forces (Rhodes and Stevenson, 1997). However in some areas, damage is caused by fires as a result of heavy recreational use, often in summer, and these fires are unmanaged (Anderson, 1997).

Burning does affect properties of peat soils which may influence their erosion sensitivity. Worrall *et al.* (2007) reported that burning consistently reduced the depth to the water table, with the greatest decrease for more frequently burnt plots. Rhodes and Stevenson (1997) found that vegetation burning was implicated on only one site out of seven eroded sites studied, although the authors do speculate that the burning may have helped perpetuate and enhance erosion. Imeson (1971) and Yallop *et al.* (2006) also contended that heather burning has been a causal factor in soil erosion. It is likely that accidental or deliberate wildfires (rather than properly managed moorland burning) have the greatest potential to cause serious damage in single events. Holden *et al.* (2007a) expressed some concern over a possible increase in the incidence of wildfires in a changing climate.

Yallop *et al.* (2006) surveyed the areal extent and frequency of managed burning in England and Wales using aerial photograph interpretation. Burning was widespread on moorland dominated by ericaceous plants, with some 17% of the area of this habitat showing evidence of burning within the previous 4 years and a calculated average burn frequency of 20 years. They also found a significant increase in the extent of new burns in the English national parks between the 1970's and 2000. However, they did comment that the burning regime in England and Wales was significantly more intensive that that reported for Scotland.

2.1.6.3 Climate and hydrology

There is still debate about the balance between whether peat erosion is a human-induced process or whether it is also partly a natural process representing the end point of a cycle of accumulation and subsequent loss of organic matter. From analysis of pollen and botanical macrofossils from a partially eroded peat site in north Wales, Ellis and Tallis (2001) dated the initiation of mire development to at least 3,000 years ago and the beginnings of mire degradation to at least 1,350 years ago, possibly related to late Bronze and Iron Age forest clearance. There is some evidence from the Southern Pennines suggesting that climatic perturbations at key points of the last millennium provided the initial trigger for peat erosion and that the much of the present landform stems from that period (Burt *et al.*, 1997). Wishart and Warburton (2001) suggested that some of the gully systems on the Cheviot Hills may be at least 500 years old, although desiccation during the period AD 1050 to 1200 could not be ruled out as a trigger. Presently much of the eroded peat resource is at high altitude and in general terms, the higher the peat is above sea level, the greater is the area of peatland which will be eroded (Grieve *et al.*, 1994; Wishart and Warburton, 2001). This suggests that the current climate, as well as past climates, is also a factor in peat erosion. Analysis of a number of sites from throughout the UK and Ireland also suggests that climatic drivers may be the most important influence in causing erosion (Rhodes and Stevenson, 1997).

Extreme climatic events have also been implicated in triggering erosion. Warburton *et al.* (2004) found that hydrological processes were fundamental in determining the spatial and temporal occurrence of peat slides. Events were most common after summer convective storms, with around 50% occurring during July and August (cf. Dykes and Kirk, 2001; Nolan and Birnie, 2006; Scottish Executive, 2005), although instances of rapid snowmelt and intense winter rainfall also triggered these events. All instabilities occurred in association with distinct drainage features. Slides were initiated along natural drainage lines or in association with artificial drainage often brought about by mining activity or agricultural practices. At the scale of the soil profile, the special hydrological properties of peat, in particular shallow water tables and low soil hydraulic conductivity, offered important clues about failure mechanisms. Pore water pressures were generally low and varied little in the peat profile and throughout the year. It was clear from observations of subsurface flow that significant volumes of runoff reached considerable depths in the soil. Flow in macropores (pores greater than 1 mm diameter) was important in delivering surface runoff to deeper parts of the profile and, in some instances, high soil pipe water pressures developed.

Summer drought has the potential to bring about large and possibly irreversible changes to organic soils through desiccation of the soil surface, leading to cracking and increased vulnerability to erosion (various studies cited in Holden *et al.* 2007a). Such drying also makes the peat more vulnerable to wildfires. The importance of wind in peat erosion has also been highlighted in studies in the Northern Pennines (Warburton, 2003). Wind erosion of peat normally occurs when the peat surface dries and cracks. Surface layers can then become detached and be blown in strong winds. However, Foulds and Warburton (2007) also stressed the role of wind and rain combined in wind-splash erosion, saltation processes associated with rain falling obliquely driven by strong winds. Directionally oriented sediment traps showed windward fluxes of sediment were 2 to 13 times greater than leeward fluxes.

2.1.6.4 Drainage

Much of the effect of grazing on erosion outlined in the previous section can be more correctly attributed to the effects of drainage of hill land to improve the quality of grazings. Holden *et al.* (2007a) reported that around 1,000 km^2 of blanket peat were drained each year in England and Wales during the 1960s and 1970s, with significant impacts on catchment hydrology and soil piping. In Scotland, Bragg (2002) linked drainage of blanket mires to a decrease in runoff response time following precipitation events and more flashy river regimes. Holden *et al.* (2007b) showed that blocking drains could significantly reduce rates of sediment output from drains from 30 to 50 Mg km^{-2} to less than 1 Mg km^{-2} in a Pennine catchment. These latter authors also showed for a number of sites in Scotland and England that where hill drains were not maintained, drains also revegetate and infill naturally on lower angle slopes (less than about 4°). Natural infilling was very rare on slopes greater than 4° (Holden *et al.*, 2007b). In Scotland and Northern Ireland, many areas of eroded peat have not been subjected to artificial drainage; areas which have been drained do not show any significant evidence of erosion, based on visual observation in the field and from air photographs.

2.1.6.5 Forestry

Most erosion from forest areas is linked to disturbance during the planting and harvesting phases (Stott and Mount, 2004), often originating in ditches and stream banks. However, this is temporary and recovery occurs within 4 years as revegetation of exposed banks occurs. Stott (2005) found that erosion rates on the banks and ditches of a forest in mid-Wales increased significantly during felling, but natural revegetation in the post-felling period stabilised the banks to the extent that erosion rates decreased to less than pre-felling rates within 4 years. Carling *et al.* (2001) highlighted several areas where further research is needed, most notably in understanding the long-term sustainability of soil structure through several forest crop rotations. However, several studies have shown that the Forests and Water Guidelines are generally effective in limiting soil damage and minimizing the effects of forest operations on sediment inputs to streams (Nisbet *et al.*, 2002). New forest design in both Scotland and Northern Ireland will follow these guidelines.

2.1.6.6 Evolution of gully systems

Two types of dissection system which are associated with water erosion, but differ in the pattern of gullying produced, were identified by Bower (1960). The key differences in the pattern of gullies produced by the two dissection systems are a function of peat depth and slope angle, which are themselves inter-related. The frequency and complexity of the gully pattern is greatest on high-level, gently sloping (< 5°) upland plateaux. Bower's classification has been widely employed in subsequent studies on peat degradation, albeit with some suggested modifications (e.g. Tomlinson 1982).

Erosion rates within gullies can be high. Evans *et al.* (2006) and Evans and Warburton (2005) reported annual rates of retreat on gully sidewalls of 19 - 34 mm a^{-1}. Hulme and Blyth (1985) observed erosion from the surface layers of erosion channels by water during a severe thunderstorm. The thickness of these layers ranged from 1 to 20 mm and it was reported that almost all were removed during the one hour storm. However, poor connectivity between channels often means that eroded peat does not always find its way to the drainage system but is redistributed within the system (Evans and Warburton, 2005). Evans *et al.* (2006) contrasted this connectivity within an actively eroding catchment in the southern Pennines and a recovering catchment in the northern Pennines, with organic sediment outputs of 195 and 31 Mg km^{-2} a^{-1}, respectively. In the former, sediment derived from high rates of erosion on exposed gully surfaces was transferred rapidly to the stream with little storage within the catchment. In the recovering catchment, sediment eroded from gullies was stored on vegetated gully floors and fans, and inputs to the stream system were dominated by channel processes. The connectivity between these different components can change with time and can thus alter the amount of sediment delivery and extensive revegetation of gully floors seems to be an important check on sediment losses.

2.1.6.7 Grazing

Grazing by domestic (mainly sheep) and wild animals (mainly red deer) can alter the ground vegetation on peat and, in severe cases, create bare patches of peat which are exposed to climatic and other influences to promote further erosion. Sheep grazing has a long history in the UK uplands, with increases in sheep numbers due to various factors from the 1700s onwards. Increases during the 1950s and 1960s have been linked to availability of subsidies for improvement of hill grazing through drainage and during the 1970s and 1980s linked to subsidies under the European Union’s Common Agricultural Policy (CAP; Holden *et al.*, 2007a). McHugh (2007) reported findings from a resurvey of sites sampled during the 1999 upland erosion survey of England and Wales. She found that grazing animals were the greatest single contributor to new and increased erosion between 1999 and 2001.

Heavy grazing by sheep causes a decline in the cover of heather and other ericoids and replacement by tussock forming graminoid species such as *Eriophorum angustifolium*, *Molinia caerulea* and *Nardus stricta*. *Nardus* in particular has short rhizomes and hence has poor soil binding qualities. Thus, peat or other soils with high organic rich surface horizons supporting *Nardus*-dominated vegetation become more prone to erosion (McKee and Skeffington, 1997; Waterhouse *et al.*, 2004). Birnie and Hulme (1990) noted that much of the peatland vegetation in Shetland showed evidence of modification due to grazing and that peat erosion features were widespread. Biologically unsustainable grazing levels have been identified as the cause of the continuing degradation of both the vegetation and the peat resource in Shetland.

The most comprehensive studies of the role of grazing in peat erosion have taken place in the heavily eroded blanket mires of the southern Pennines and Peak District. Evans (2005) reported rapidly eroding slopes during the 1960s in response to the increases in sheep numbers following the Second World War. Reductions in sheep numbers from the 1980s has resulted in some recolonisation, most rapid at lower altitudes, and significant stabilisation of eroded scars. Yeloff *et al.* (2005) reported the changes in erosion rates calculated from reservoir sedimentation rates in a catchment in the southern Pennines. Erosion rates were found to be low during the period from the mid 19th century until the early 1960s, but increased markedly after 1963 and peaked during the late 1970s and early 1980s. Sedimentation rates ranged from 2 to 28 Mg km^{-2} y^{-1}.

The major difficulty in linking severe erosion in the Pennines to contemporary grazing pressures lies in the fact that gully systems in northern England can be many hundreds of years old (e.g. Wishart and Warburton, 2001). The balance of evidence thus suggests that, while contemporary heavy grazing may exacerbate and accelerate peat erosion in the Pennines, the original trigger for initiation of many gully systems probably predates the relatively intensive use of the hills for grazing, around two centuries ago (Rhodes and Stevenson, 1997). Studies from the Pennines have also given an indication of threshold stocking rates required to minimise damage to vegetation and erosion. Working in the Peak District, Evans (2005) considered that stocking rates of up to 5 sheep ha^{-1} could be sustained during the summer, but Holden *et al.* (2007a) suggested that sustainable rates should be lower, with a possible threshold of 2 ha^{-1} and as low as 0.5 ha^{-1} for sensitive northern Pennine blanket bogs. Based on a long-term controlled grazing study on blanket bog vegetation in Scotland, Grant *et al*. (1985) concluded that a year-round stocking rate of 2.2 ha^{-1} was damaging and that stocking rates above one sheep ha^{-1} require careful vigilance if an increase in bare ground is to be avoided. Maximum stocking rates tolerated without loss of plant cover for such vegetation were considered to be 0.4 to 0.8 ha^{-1}.

2.1.6.8 Mechanical harvesting of peat

Cooper *et al.* (2001) and Cooper and McCann (1995) stressed the role of mechanical harvesting in triggering vegetation disturbance and potentially initiating erosion (e.g. Dykes and Kirk, 2001,McGreal and Larmour, 1979). Recovery following light cutting has been shown to occur within 9 years as reflected in increases in *Sphagnum* and other sensitive species, but repeated cutting results in greater loss of peat and much longer recovery times (Cooper *et al.*, 2001). Recovery was also found to be more rapid when sheep were excluded from recovering sites.

2.1.6.9 Recreation

Lowther and Smith (1988) provided evidence of recreation triggers of erosion in the Mourne Mountains in Northern Ireland. Similarly Watson (1984,1985) link footpath development and soil erosion to human pressures associated with mountain walking and skiing in the Cairngorms. In a comparison of aerial photography flown in 1951 and 1983, Wishart and Warburton (2001) found little difference in the extent of erosion features in the high Cheviot Hills other than a marked loss of vegetation and incision along the lines of major paths such as the Pennine Way. Grieve (2000) found that disturbance of peaty upland soils linked to human trampling was associated with a loss of carbon stored in these soils of up to 50%.

2.1.6.10 Other factors

Several other factors linked to climate change may have implications for soil erosion, but the effects on organic and organo-mineral soils has not been determined. Changes in rainfall amount and intensity, occurrence and length of lie of snow, number of frosts etc may increase the sensitivity of surface organic horizons to erosion. For example, decreases in the number of days with lying snow do lessen the time during which the soil is insulated by a snow cover during the winter. The loss of snow cover leads to greater extent of soil freezing and number of freeze-thaw cycles which causes what may be a short-term flush of labile DOC due to disruption of microbial systems and root die-off (unpublished MI data). It may also lead to more physical frost heave disturbance with associated accelerated erosion loss.

2.1.7 Modelling of erosion susceptibility

The risk of soil erosion occurring in Scotland has been modelled following two different procedures. Lilly *et al.* (2002) used a rule-based approach to identify the inherent geomorphological risk of soil erosion by overland flow, whilst Anthony *et al.* (2006) adopted a more process-based approach integrating water balance models with understanding of soil erosion processes at a field scale. The latter approach was designed to predict sediment and phosphate movement to waterbodies as part of a diffuse pollution screening tool. Both approaches relied to varying degrees on national datasets of soil texture, HOST class (Boorman *et al.,* 1995) and digital elevation models (DEM) and produced output at a fairly crude scale (1 km^2 grid cells). Using these same datasets and, to allow for the amelioration effect of land cover on the erosivity of bare soil, the CORINE land cover dataset for Northern Ireland, Jordan *et al.* (pers comm) created a potential soil erosion map for Northern Ireland on a 1 km grid (Figure 2.2) using rules defined in two MAFF documents (MAFF, 1999a, 1999b).

Figure 2.2 shows that the soils predicted to be at greatest risk from erosion in Northern Ireland are found largely in upland areas with steep slopes, especially in the Mourne Mountains (south-east). In Figure 2.2, water and urban areas are shown in white.

The inherent geomorphological risk approach (Lilly *et al.*, 2002) assumes that all soils are bare and that erosion can be modelled using the inherent characteristics of the soil to absorb water from rainfall or snowmelt. The likelihood that a soil would erode was determined according to the erosive power generated by soils becoming saturated and initiating overland flow. The steepness of the slope would determine the erosive potential of this flow. As much of the information available on the mechanisms of soil erosion is for mineral soils, a pragmatic approach to assessing the likelihood of erosion on upland organic and organo-mineral soils had to be adopted. Anecdotal evidence suggested that peats were more susceptible to erosion than peaty soils (peaty gleys, peaty podzols and peaty rankers) even where slope and site conditions were similar. Thus peats (organic soils) were simply assumed to be at high risk (Figure 2.3).

Overall, erosion models provide a useful indication of the geographical variation in erosion susceptibility, highlighting areas potentially at risk and areas where the environmental function provided by soils where rainfall infiltrates may be inadequate to protect surface waters. They also provide a framework for evaluating the effects of changing rainfall or cropping on potential erosion rates. However, the predictions from soil erosion models are often insufficiently verified against field data (Brazier, 2004). There is, thus, a clear need for targeted measurements of actual erosion rates for calibration of model predictions to increase confidence in the outcomes from soil erosion modelling.

Figure 2.2 **Distribution of modelled erosion potential for Northern Ireland soils, derived on a 1 km grid from MAFF 1999a, 1999b erosion rules (Jordan *et al.*, pers. comm., source AFBI; based upon Ordnance Survey of Northern Ireland © Crown copyright NIMA ES&LA201.3 (for Northern Ireland))**

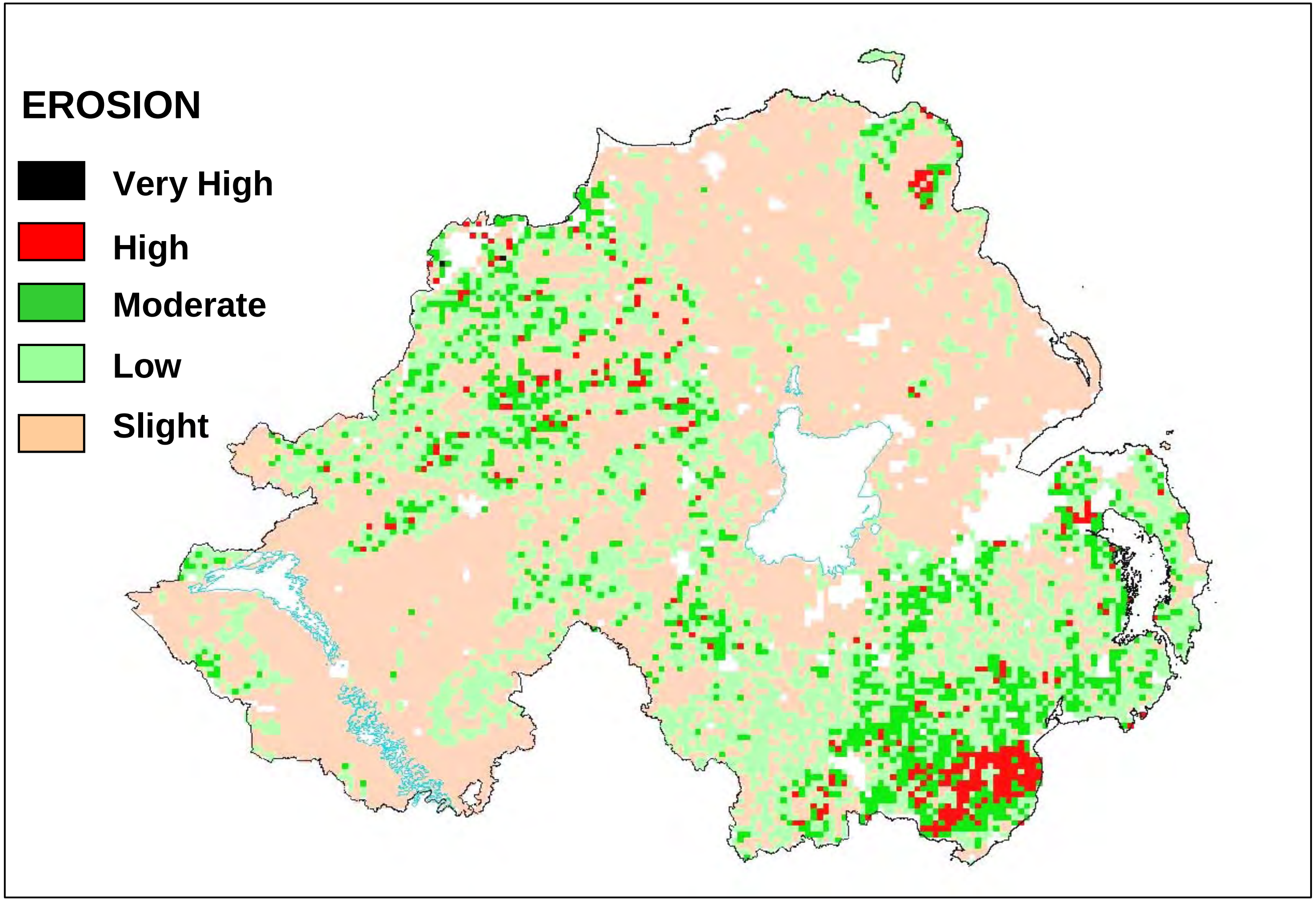
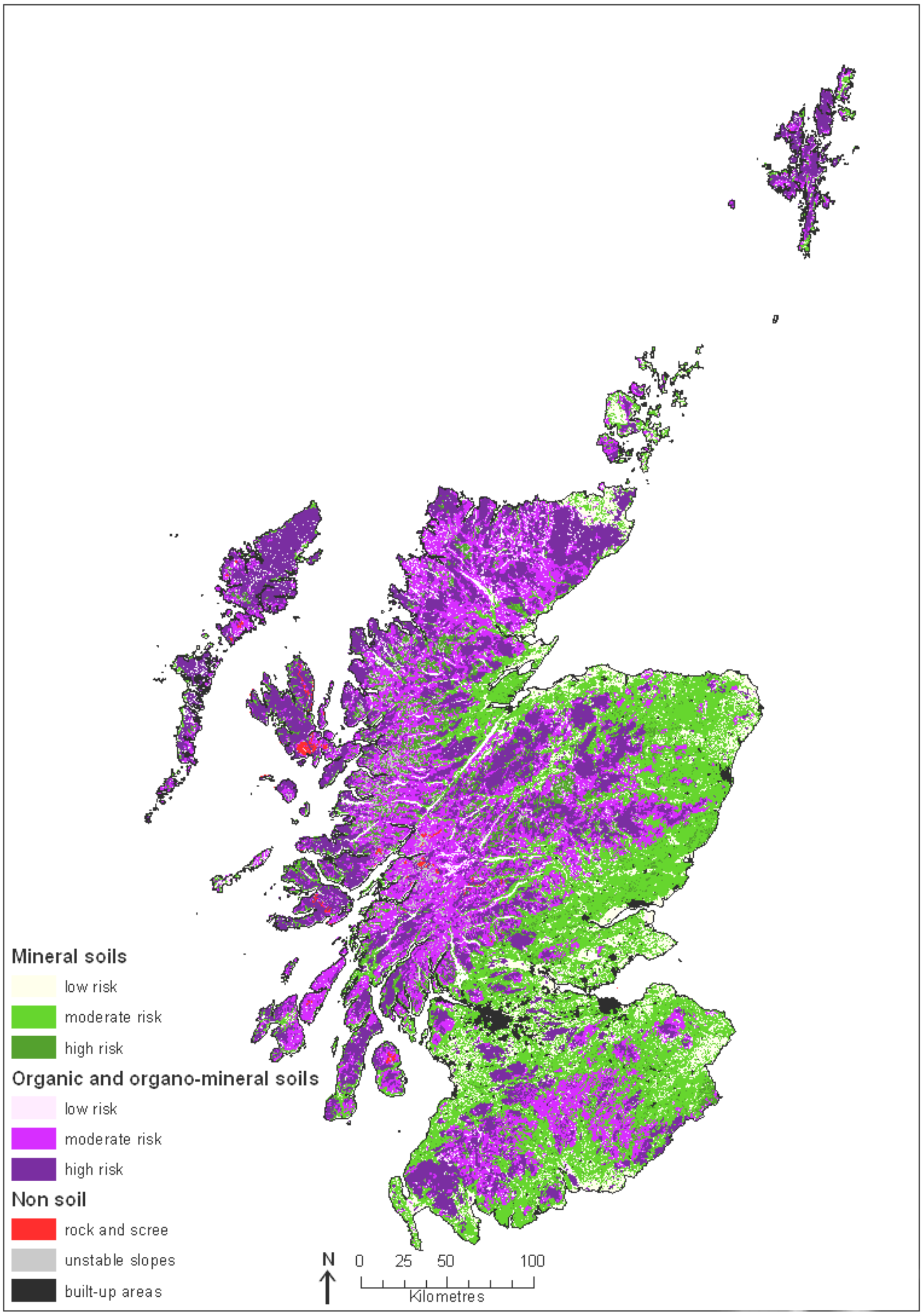


Figure 2.3 **Distribution of modelled inherent erosion susceptibility to overland flow for Scotland (Lilly *et al.*, 2002). Coastline based upon 1:50 000 Scale Maps © Crown copyright. All rights reserved. SNH 100017908 2008**



2.2 Review of evidence of accelerated soil loss

2.2.1 Direct measurement of soil erosion rates

There are few direct measurements of rates of erosion on organic soils in Scotland. Birnie (1993) assessed erosion rates from an exposed hill peat in Shetland using erosion pins driven into the peat surface. Although results were variable and complicated by the loss of pins through trampling by stock, he estimated erosion losses of between 10 and 40 mm year^{-1} due to the effects of trampling and rubbing by sheep as well as geomorphic and weathering processes. These rates are similar to rates reported for bare peat surfaces in the Pennines. Anderson (1997) reported mean annual rates of 92 and 71 mm year^{-1} for winter and summer, respectively. Evans *et al.* (2006b) measured mean erosion rates of 34 mm year^{-1} for bare gully walls in the northern Pennines, and Evans and Warburton (2005) measured a mean rate of 19 mm year^{-1} for bare gully walls in the southern Pennines. All these measured rates are highly variable; for example, rates at individual sites ranged from less than 10 to almost 30 mm year^{-1}, possibly related to aspect (Evans and Warburton, 2005).

2.2.2 Previous estimates of trends in erosion rates from suspended sediment and dissolved organic carbon in rivers

Average erosion rates within river catchment areas may be estimated from the annual load of suspended sediment (as the product of sediment concentration and flow) carried by the stream or river draining that catchment area (Collins and Walling, 2004). River loads provide at best an estimate of the mean annual erosion rate for the whole catchment area. Rates computed from suspended sediment may underestimate the total, depending on the proportion of sediment transported as bedload (Brazier, 2004), although this is more applicable to erosion of mineral soils where proportions of the total sediment load carried as bedload are likely to be greater. Catchment mean values can also mask huge variations in erosion rates within the catchment (Evans *et al*., 2006b). In a similar vein, loads of dissolved and suspended (particulate) organic carbon carried in streams can be used to estimate losses of organic matter from organic soils and horizons within the catchment. Here again caveats apply, as we have a very limited understanding of the in-stream processes that affect the link between the dissolved or particulate carbon lost from a location within the catchment and the point of measurement on the stream. In many studies, the stream sampling point can be many kilometres from the headwater where the erosion occurs and considerable C may be ‘lost’ through in-stream processes such as photolysis, respiration or sedimentation before the sampling point. Such considerations help explain the fact that dissolved and particulate carbon losses expressed on an areal basis decrease with increasing distance downstream (Hope *et al*., 1997) and must be borne in mind in the review which follows.

Indirect evidence of changes in the organic carbon status of upland organic and organo-mineral soils exists in the form of increased concentrations of DOC found in stream waters draining upland catchments where soils are dominantly peaty. There is a greater availability of data on C loads for small upland catchments for time periods of up to 2 years than for trends over longer time periods. Some Scottish river C loads are summarised in Table 2.1.

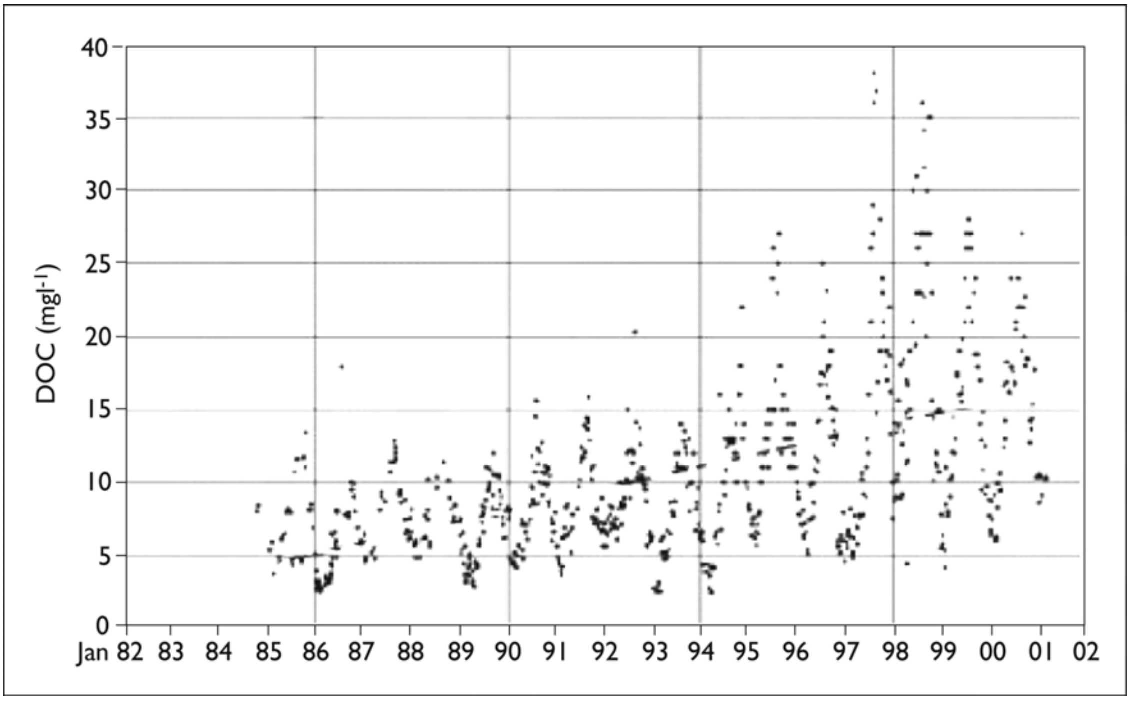
Table 2.1 Values of dissolved (DOC) and particulate organic C (POC) fluxes from literature catchment/regional studies in Scotland

Location	Dominant land use	Catchment size (km^2)	DOC flux (kg ha^{-1} $year^{-1}$)	POC flux (kg ha^{-1} $year^{-1}$)	Ref
River Dee (NE Scotland)	Upland organic headwaters and mixed agriculture in lowlands	1844	50	13	Stutter *et al.*, in press
Regions:					Hope *et al.*, 1997
Caithness			85	3	
Sutherland			65	2	
Ross and Cromaty			65	2	
Inverness			56	3	
North east			25	3	
Brocky Burn (NE Scotland)	Moorland	1.3	169	19	Dawson *et al.*, 2002

Analysis of longer data sets has shown significant trends in DOC concentrations. Data published by McCartney *et al.* (2003) show a clear rising trend in mean DOC concentrations in a stream draining a mature forest catchment near Loch Ard in west-central Scotland, from around 5 mg l^{-1} in the early 1980s to around 16 mg l^{-1} in 2003 (Figure 2.4). There also appears to be a trend towards higher values in extreme events from 1995 onwards.

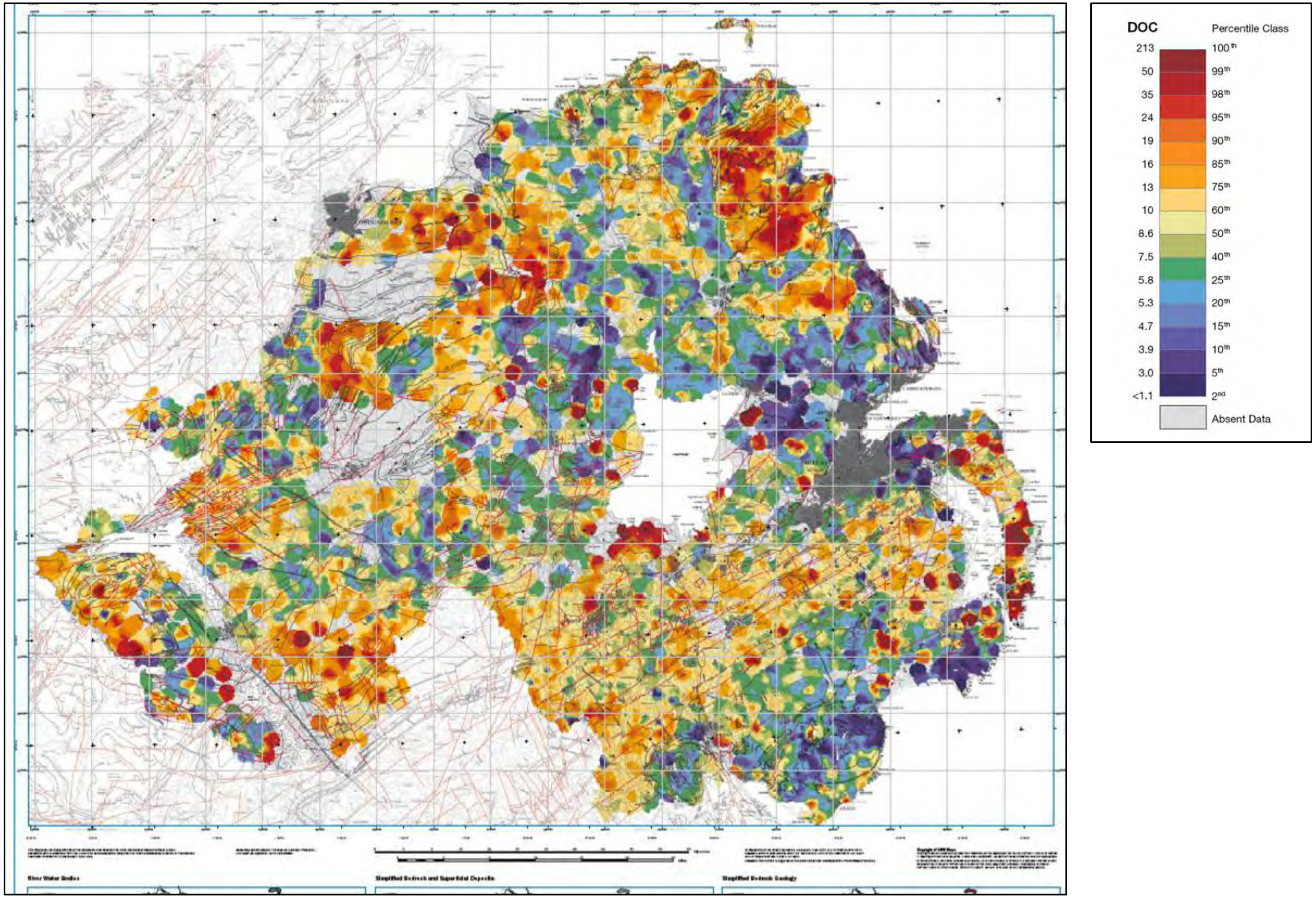
These trends in DOC concentrations appear to be universal in the UK uplands. Worrall *et al.* (2004b) summarised data from 198 streams within the UK (155 in Scotland). These showed a statistically significant increase in DOC concentrations at 77% of the 198 sites. The remaining 23% showed no trend and no sites showed a decrease. The mean annual increase in DOC concentrations was 0.17 mg l^{-1} $year^{-1}$. The trends were independent of regional effects such as differences in rainfall, sulphur and nitrogen deposition and land use change. Further work has investigated whether these changes can be linked to climate change (Worrall *et al.*, 2004a; Freeman *et al.*, 2004) but both these studies cast doubt on whether climate warming on its own offers a satisfactory explanation. Recovery from acidification may be the trigger for these increases in DOC levels (see previous discussion in section 2.1.1).

Figure 2.4 Changes in Dissolved Organic Carbon (DOC) over a 16-year period (Trossachs, west-central Scotland from McCartney *et al.*, 2003)



Summer DOC concentrations have been measured on most 1st and 2nd order streams in Northern Ireland as part of an integrated geophysical and geochemical survey (the Tellus Project) of the Geological Survey of Northern Ireland (GSNI) (see http://www.detini.gov.uk/cgi-bin/get_builder_page?page=1565&site=5&parent=156&prevpage=2817). The western part of Northern Ireland was sampled between June and September 1994-96, while the eastern part was sampled between May and September 2005. The distribution map of DOC in stream waters for Northern Ireland is shown in Figure 2.5 and shows highest DOC concentrations, as expected, in those upland areas with extensive peat cover (the Sperrin Mountains in the west and the Antrim Plateau in the north-east).

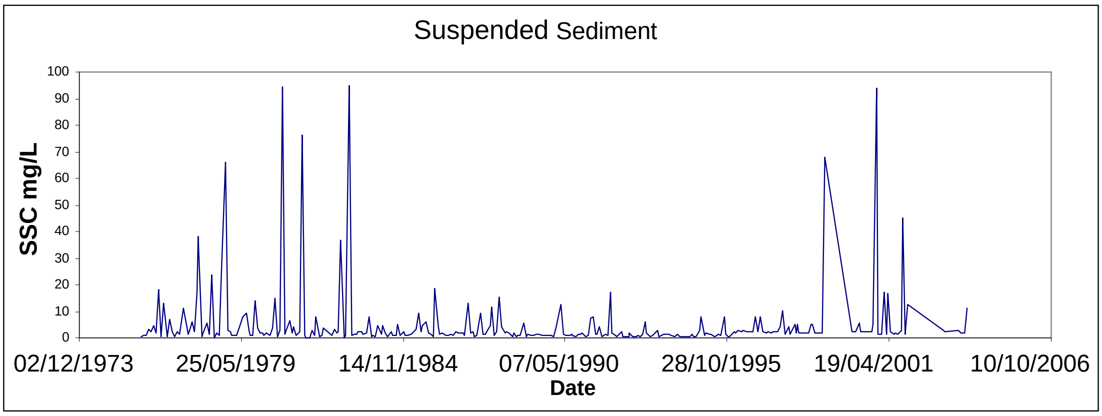
Figure 2.5 Dissolved organic carbon concentrations (mg l^{-1}) in 1st and 2nd order streams across Northern Ireland (copyright GSNI).



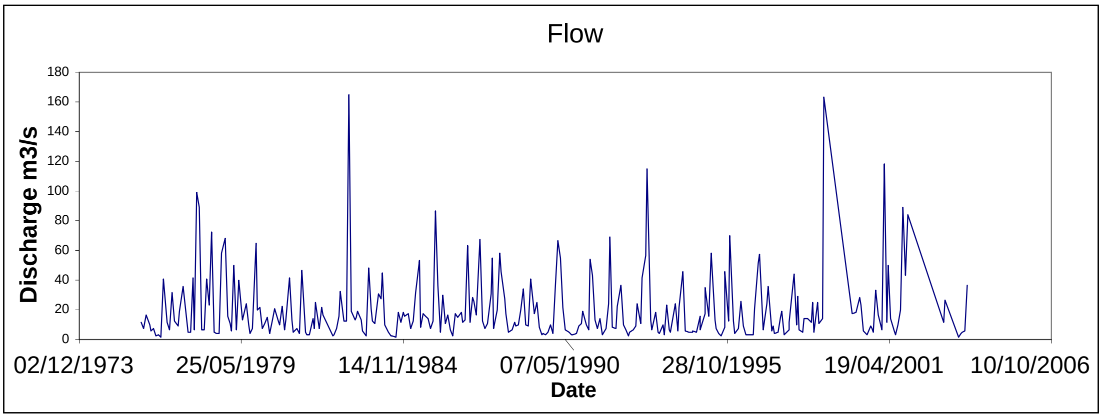
Data from harmonized river monitoring across the UK in support of the EC Freshwater Fish Directive (78/659/EEC) provides some insights from which long-term trends in net soil erosion losses from catchments may be inferred, although the low frequency of sampling (monthly) and gaps in data sets limit the usefulness of these data for assessing sediment fluxes. Towers *et al.* (2006) used suspended sediment concentration data obtained from the UK Harmonized Monitoring Scheme data held by SEPA for rivers draining largely agricultural areas to examine changes in sediment flux through erosion of arable land. In this report we use similar data for upland rivers in Scotland and Northern Ireland to assess long-term changes in erosion of organic soils. Figure 2.6 shows trends in suspended sediment concentrations and discharge since 1975 for one river with a significant percentage of organic and organo-mineral soils within the catchment, the River Findhorn (Towers *et al.* 2006).

Figure 2.6 Trends in (a) suspended sediment concentrations and (b) flow for the River Findhorn, NE Scotland (from Harmonised Monitoring Scheme data)

a)



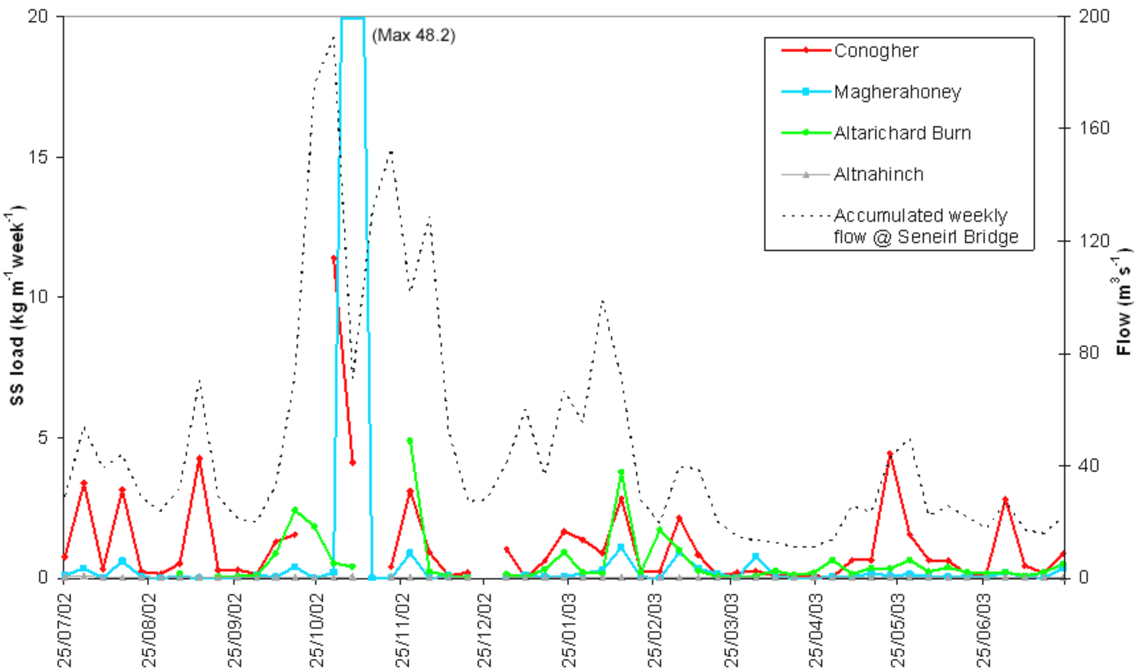
b)



There is no clear evidence of any trend in these graphs and the main limitation of the Harmonised Monitoring data sets is undoubtedly the infrequency of data collection, monthly at best, which is insufficient to capture the detail of variations in erosion events which are highly episodic. More intensively sampled research data sets may provide better data here, although these are often confined to periods of 3 years at most. The River Bush monitoring project in the north-east of Northern Ireland (Evans and Gibson, 2004) monitored suspended solids and flows (and shear stress on the river bed) on a weekly basis at 4 sampling sites during the period July 2002 to July 2003. Evans and Gibson (2004) showed how events in the catchment, including bank erosion, affected the sediment load at each site (Figure 2.7) and its potential impact on salmon spawning.

DOC concentrations (but not suspended solids) have also been monitored throughout 2006/07 on a fortnightly basis by AFBI for rivers inflowing to Lough Melvin whose cross-border catchment is dominated by organo-mineral soils (R. Foy, pers comm).

Figure 2.7 Temporal variation in suspended sediment load transport and flows at four sampling sites along the River Bush, Northern Ireland



2.2.3 Analysis of long term changes in soil carbon losses from Scottish catchments

2.2.3.1 Available data

Data to evaluate temporal trends in factors relating to dissolved and particulate forms of C were available from only a limited number of sources. These were:

(a) Scotland's Harmonised Monitoring Scheme (HMS) catchments (previously described by Ferrier *et al.*, 2001).

The HMS sites (with combined catchments covering 58% of Scotland's land area) comprise long-term records (initiated in 1974 and sampled approximately monthly) of chemistry at the tidal limits of major rivers and have an associated flow gauging station and record. Being large, they encompass mixed land use catchments often with only upland headwaters, significant scope for in-stream processing of C, anthropogenic inputs of C with wastewaters and are therefore not ideal to evaluate erosion in the carbon-dominated soils in upper parts of the systems. Out of a total of 54 catchments where data were available, there are 29 Scottish catchments with a significant (>10%) areas of moorland and/or peatland and analyses were restricted to these (Table 2.2). Due to the large size of the HMS catchments a low threshold of >10% was chosen in order to include catchments which contain quite large areas of peatland/moorland (>20 km^2) even though the proportional areas were small. Given the position of the HMS monitoring sites, generally near to tidal limits, these catchments were largely dominated by agricultural land. Data included discharge, biological oxygen demand, suspended solids (SS, <1.2µm particle diameter) and total organic carbon (TOC).

TOC was principally determined on unfiltered samples but included several sites where DOC (filtered <0.45 µm) was determined; in this analysis these data were combined and collectively termed TOC. It should be noted that the HMS record probably provides a poor representation of SS concentrations due to the limited temporal resolution of the data (fortnightly to monthly) which do not provide good coverage of high flow events. For this reason loads of SS were not calculated and the description of trends against time are restricted to concentrations.

(b) Two catchments, Glensaugh (North East) and Sourhope (South East), of the Environmental Change Network (http://www.ecn.ac.uk/sites.htm).

These smaller upland catchments are much more suited to the purposes of this current investigation but data were limited to weekly discharge and DOC (filtered <0.45 µm) measurements over the period 1994 to 2005.

Table 2.2 Attributes of the study catchments. (a) The 29 HMS sites with significant (>10%) combined areas of peatland + moorland (in decreasing % order), (b) the ECN sites. Land cover data from Land Cover of Scotland 1988

			Catchment % areas							
HMS ID	Site	Area km^2	Arable	Improved Grassland	Rough Grassland	Heather Moorland	Peatland	Montane	Urban	Woodland
(a) HMS sites										
7	Findhorn	787	1	4	7	34	40	2	0	12
29	Carron	149	0	2	4	69	4	8	1	11
3	Conon	1170	3	2	4	61	9	6	1	11
2	Kyle of Sutherland	617	0	3	3	40	28	0	0	18
10	Thurso	479	0	18	8	10	51	0	1	10
12	Spey	2948	2	9	8	39	14	6	1	18
5	Ness	1821	1	3	11	41	12	4	0	19
23	North Esk	740	26	9	11	36	9	0	1	8
17	Dee	2039	10	10	11	37	7	4	1	17
8	Lochy	1325	0	1	20	36	7	12	2	16
20	Tay	5073	14	6	16	30	12	4	1	14
6	Nairn	333	16	10	5	20	18	0	1	27
22	South Esk	503	28	9	17	29	4	0	1	11
19	Earn	738	24	7	22	16	11	3	1	12
27	Teith	514	3	5	30	16	8	3	0	24
44	Water of Luce	169	0	12	48	1	20	0	0	16
26	Allan	222	31	10	22	11	9	0	2	14
36	Whiteadder water	533	26	28	16	20	0	0	1	9
49	Leven	812	0	17	31	14	5	1	2	15
32	Water of Leith	124	18	9	9	16	2	0	34	4
16	Don	1316	39	17	7	15	3	1	2	16
28	Forth	1027	17	8	22	11	7	2	1	27
52	Ayr	586	0	45	19	6	11	0	4	15
48	Black Cart Water	145	3	40	15	5	10	0	15	6
55	Garnock	175	0	56	15	6	9	0	8	5
11	Lossie	374	36	10	5	8	5	0	4	31
45	Clyde	1996	0	40	18	8	6	0	12	13
13	Deveron	1284	45	20	8	6	4	0	1	15
33	Esk	320	26	24	18	7	3	0	10	9
(b) ECN sites										
Glensaugh		0.8	0	0	0	80	20	0	0	0
Sourhope		0.7	0	0	90	10	0	0	0	0

2.2.3.2 Modelling

For the HMS sites the TOC record was initially supplemented by colour data measured as Hazen units. For this a relationship was derived:

$$TOC\ [mg/l] = 0.0856 \times colour\,hazen\,units + 1.0282 \qquad R^2 = 0.83 \quad n = 419$$

A multiple linear regression modelling routine was then written in Genstat (v.10) to model the TOC and SS data:

Observed data (TOC, SS) $_{\text{for a given site}}$ = *month* + *a* × *runoff* + *b* × *date* + *intercept*,

where *month* is a factor (1 to 12); *runoff* and *date* (as days from the start of the HMS data record) are numerical values with gradients of *a* and *b*, respectively.

This model with month, runoff and date as predictors was constructed to separate the effects of month, flow and residual date trend (for example the parameter of date is evaluated once the effects of month and flow have been removed). Runoff was instantaneous discharge scaled by catchment area. Land use data for the catchments were taken from the Land Cover of Scotland map (LCS88; Macaulay Institute, 1993).

2.2.3.3 Results

Where regression models showed overall significance using the predictors of month+runoff+date, then SS and TOC concentrations were positively related to runoff, suggesting that water transport process were implicated in SS and TOC losses. For SS concentrations the strength of runoff as a positive factor was strongly and positively correlated with the proportion of arable land in the catchments (Table 2.3). This suggested erosion of cultivated soils (likely to be relatively low in C content) was prevalent at these sites. Of the fifteen HMS river sites where significant trends against time were observed for SS concentrations, only 6 sites showed increasing SS, whilst 9 showed decreasing SS concentrations (Table 2.4 and locations in Figure 2.8). Sites with rising SS trends are dominantly draining the uplands of NE Scotland and those with decreasing SS draining catchments in the central belt. The weighting of the factor of date in predicting SS concentrations was only weakly correlated to land use factors which did not contain those related to organic soil coverage. However, sites which showed increasing SS concentrations with time were at the top of Table 2.4 (higher proportion of moorland + peatland land cover) and those with decreases were to the bottom of Table 2.4.

There was much poorer resolution of sampling where TOC had been analysed and fewer trends were significant overall. The five sites where trends in TOC concentration against time were significant were located in NE Scotland (Table 2.4; Figure 2.9). The strength of the trend with date was positively but weakly significantly correlated with catchment areas of peatland and with moorland, implicating C loss from organic upland soils in rising TOC exports in NE Scotland rivers.

Table 2.3 Significant correlations (r) between regression estimates from multiple regression modelling and catchment land use. The model estimates are the weightings of factors: (i) runoff and (ii) date, once the effect of season has been removed.

	SS, runoff	SS, date	TOC, runoff	TOC, date
Catchment size		0.48*		0.85*
% Arable	0.60***			-0.85*
% Improved Grassland				
% Rough Grassland		-0.55*		
% Heather Moorland	-0.36*			
% Peatland				0.85*
% Montane	-0.38*			0.83*
% Urban				
% Sum peatland+moorland	-0.41*			

*, **, **** denote significance at p<0.05,<0.01 and <0.001 respectively.

Table 2.4 Regression models of Log SS and Log TOC time series for HMS sites.

		SS data						TOC data						% Land use
HMS ID	Site	Period	n	Runoff		Date		Period	n	Runoff		Date		Peatland +moorland
7	Findhorn	1983-2004	258	0.49	***	35	***	1983-2004	244	0.22	***			74
29	Carron	1976-2005	339	0.37	***	-44	***	2001-2003						73
3	Conon	1983-2005	169	0.19	**	17	*	1993-2001	99			36	***	70
2	Kyle of Sutherland	1983-2006	182	0.21	**			1993-2001						69
10	Thurso	1983-2005	185	0.41	***			1993-2001	92	0.12	***			61
12	Spey	1980-2005	163	0.82	***			1988-2005	86	0.40	***	59	***	54
5	Ness	1983-2005	289	0.07	*	26	***	1983-2001	250	0.06	***			53
23	North Esk	1987-2005	219	0.44	***			2003						45
17	Dee	1980-2005	274	0.28	***	25	***	1988-2003	120	0.29	***	53	***	45
8	Lochy	1983-2006	288	0.18	***			1983-2006	258	0.14	***			43
20	Tay	1987-2005	311	0.47	***			2003	14	0.12	*			42
6	Nairn	1983-2005	272	0.61	***			1983-2004	247	0.38	***			38
22	South Esk	1987-2005	226	0.40	***			2003						33
19	Earn	1987-2005	214	0.41	***			2003						27
27	Teith	1983-2003	224	0.27	***	-40	***	no record						24
44	Water of Luce	1976-2005	354	0.20	***			2002-2004						21
26	Allan	1983-2002	266	0.63	***	-33	***	2001-2002						20
36	Whiteadder water	1986-2005	285	0.67	***			2002-2003	10	0.51	***			20
49	Leven	1976-2006	503	0.19	***	-31	***	2000-2001						19
32	Water of Leith	1976-2003	345	0.76	***	-21	***	2001-2003						18
16	Don	1976-2005	322	0.66	***	-20	***	1988-2002	145	0.23	***	19	*	18
28	Forth	1992-2006	347	0.59	***			2001-2003	48	0.13	**			17
52	Ayr	1976-2006	478	0.55	***			2002-2004	9	0.32	*			17
48	Black Cart Water	1976-2006	501	0.34	***	-37	***	2000-2001						16
55	Garnock	1978-2006	488	0.43	***			2002-2004						15
11	Lossie	1983-2005	252	0.61	***	21	***	1990-2002	103	0.46	***	24	*	13
45	Clyde	1976-2005	557	0.54	***	-31	***	1997-2006						13
13	Deveron	1980-2005	239	0.75	***	20	**	1989-2002	115	0.28	***			11
33	Esk	1978-2002	249	0.75	***	-23	***	2001-2003	14	0.34	**			10

*, **, *** denote significance at $p<0.05$, <0.01, <0.001 levels, respectively.

Figure 2.8 Location of HMS sites showing a significant trend in SS concentrations over time when the effects of month and flow have been removed (data from Table 2.4). Red and blue arrows indicate increasing and decreasing trends, respectively, and black dots indicate no significant trend.

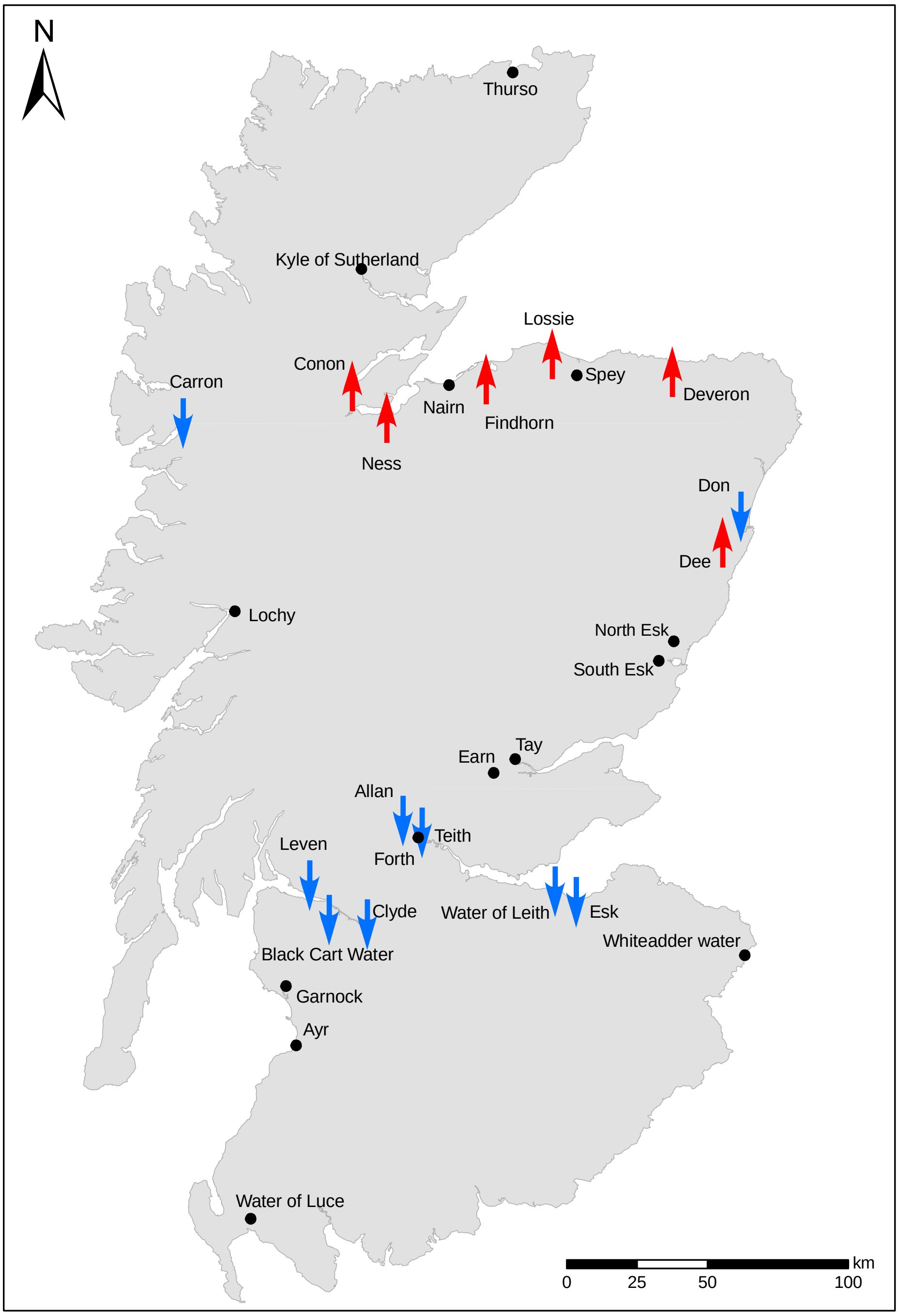
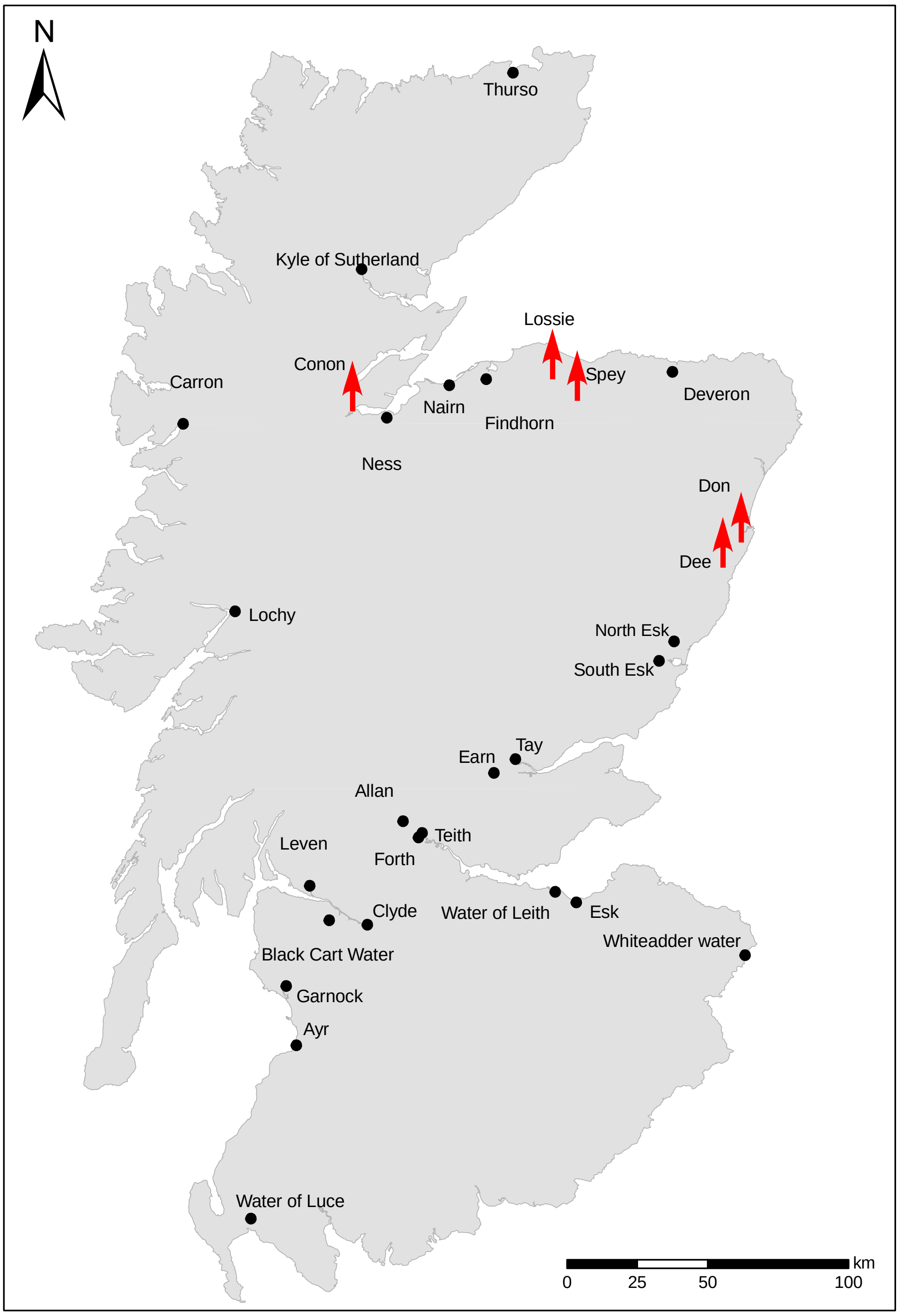


Figure 2.9 Location of HMS sites showing a significant trend in TOC concentrations over time when the effects of month and flow have been removed (data from Table 2.4). Red and blue arrows indicate increasing and decreasing trends, respectively, and black dots indicate no significant trend.



Data from the Environmental Change Network (ECN) sites were available for DOC only but included stream flow and weekly sampling so flux values were available (Unpublished data, Macaulay Institute). At ECN Glensaugh (Aberdeenshire), a mixed acid schist, heather moorland catchment with freely draining podzolic soils grading into peat, there was a significant and strong rise in DOC exports with time (Figure 2.10). However, no rise in DOC was observed for ECN Sourhope (Borders) with rough grassland land use on peaty gleyed podzols over andesitic lavas (Figure 2.11).

Figure 2.10 Temporal change in annual DOC flux from Glensaugh ECN site

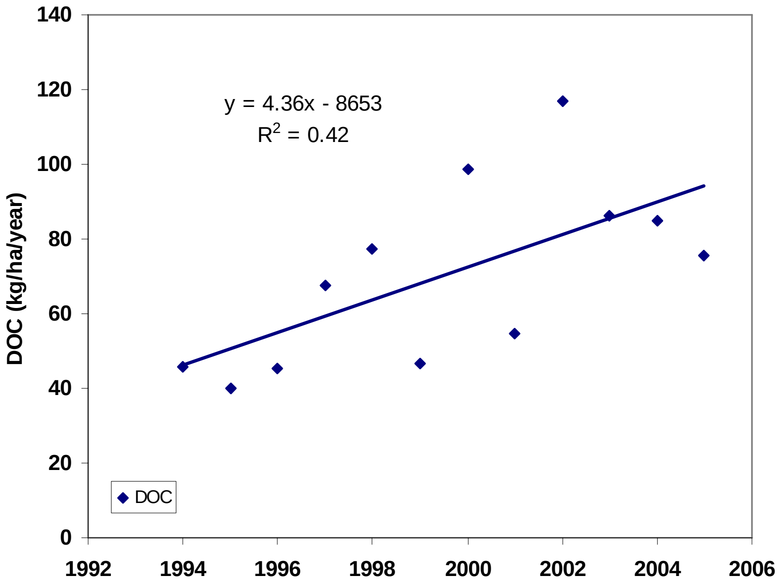
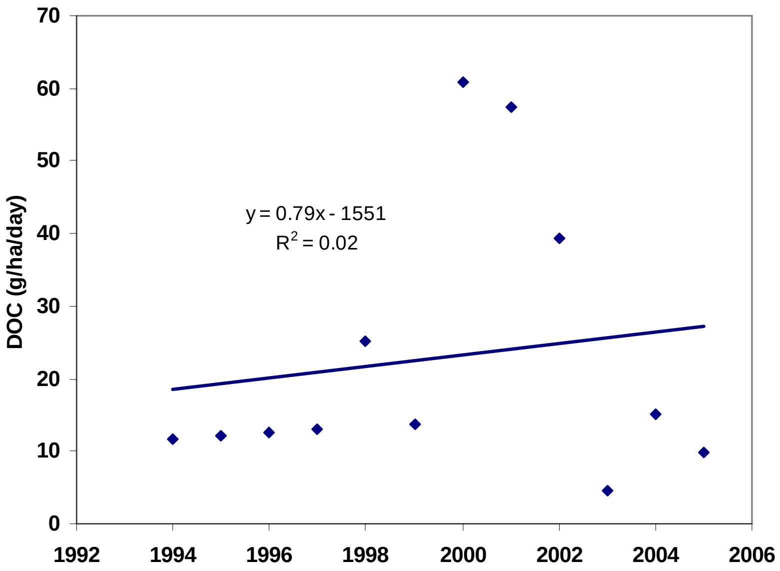


Figure 2.11 Temporal change in annual DOC flux from Sourhope ECN site



2.2.3.4 Deriving Carbon contents of Suspended Sediment

Particulate losses of C can only accurately be derived by determination of C contents of SS in addition to SS concentrations. However, data of C contents are substantially less available than for SS concentrations and previously studies have used a fixed value (e.g. 14% C, or 140 g kg^{-1}; Hope *et al.*, 1997). Table 2.5 shows sources of data for C contents of SS assessed in Scottish rivers. The changes in C contents of SS and in SS concentrations themselves with discharge can be complex and subject to considerable seasonality and storm hysteresis as shown by Figure 2.12 (and also Stutter *et al.,* 2007, submitted). Despite this considerable temporal variability, C contents in Table 2.5 show that mean values in the range 120-150 $g.kg^{-1}$ are appropriate for catchments with agricultural as well as moorland land use, but SS may have considerably greater C contents in smaller moorland catchments such as the ECN Glensaugh site.

Table 2.5 Carbon contents of Suspended Sediment (SS) from Scottish studies of rivers under different flow conditions

Site	Range in SS concentrations (mg l^{-1})	Mean (range) in Carbon contents (gC kg^{-1} dry mass SS)	Reference
Glensaugh ECN site:			Stutter *et al.*, submitted.
Regular sampling 2004-06	1.2 - 14	174 (51 - 392)	
Storm Aug 2005	1.6 - 11	65 (45 - 100)	
Storm Nov 2006	9.6 - 117	218 (145 - 346)	
River Dee catchment (13 sites)	0.1 - 57	196 (108 - 365)	Stutter *et al.*, 2007.
NE Scotland Rivers:			S. Hillier, pers. comm.
Bervie	1.6 - 42	97 (46 - 133)	
Dee	0.8 - 23	155 (112 - 170)	
Don	3.6 - 288	125 (94 - 161)	
North Esk	1.2 - 18	131 (95 - 180)	
South Esk	1.4 - 18	125 (59 - 167)	
Ugie	2.1 - 86	126 (102 - 164)	
Ythan	3.6 - 70	124 (88 - 154)	

Figure 2.12 **Carbon contents of Suspended Sediment (SS) as a function of SS concentrations in the water for the Cairn Burn catchment (adjacent to the ECN stream at Glensaugh and of similar size, soils and land use)**

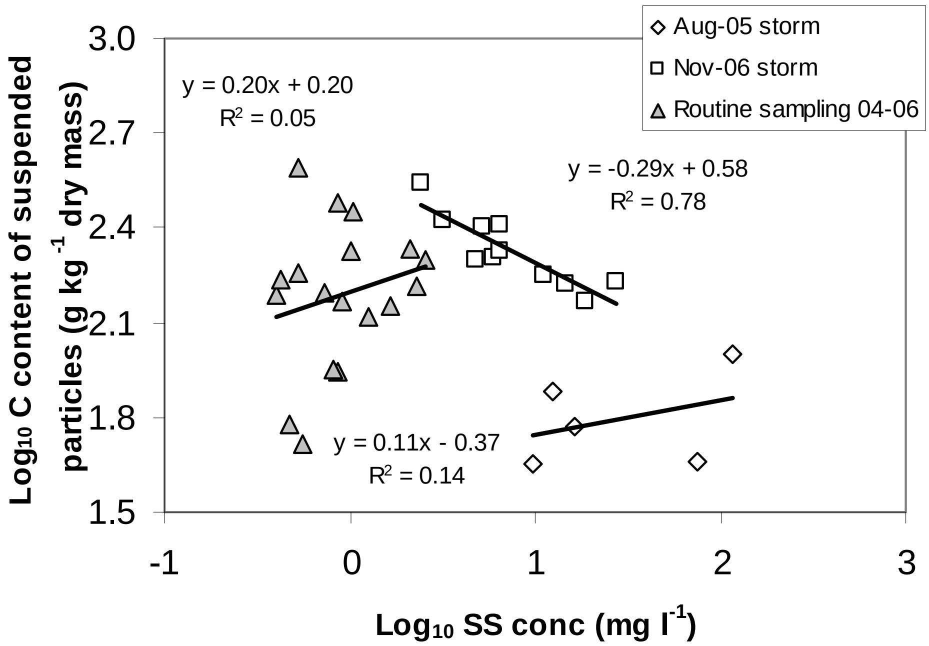
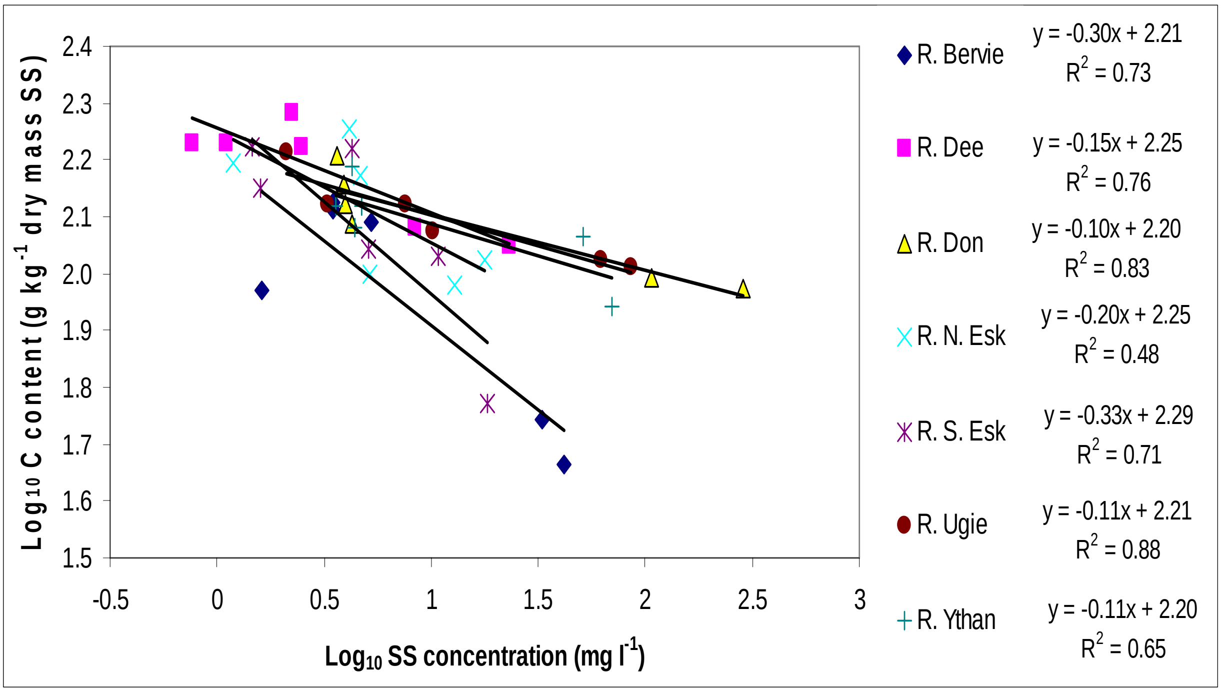


Figure 2.13 **Carbon contents of Suspended Sediment (SS) as a function of SS concentrations in the water for NE Scotland major river catchments used to calibrate POC concentrations of selected HMS sites**



C contents of SS have been determined for six dates (S. Hillier, pers. comm.) for four of the HMS river sites with >10% moorland + peatland land cover (Don, Dee, South and North Esk river sites). From these rather limited datasets, Log C content vs Log SS relationships (Figure 2.13) were constructed to calibrate the HMS time-series of SS concentrations for C content and water column POC (particulate organic C) concentrations. Additionally, POC concentrations were compared to a measure of decomposable organic C derived from the HMS biological oxygen demand (BOD) data. BOD is determined after a standard incubation at 20°C for 5 days. BOD (mg O_2 l^{-1}) was converted to decomposable C using the atomic mass ratio. The ratio of decomposable C to POC gives a measure of the metabolic quality of the POC. A greater ratio indicates C that is more readily assimilated by microbes and suggests increased sources of labile C which are likely to be from anthropogenic sources (such as waste water treatment works or industrial effluent) rather than more recalcitrant C from eroding soils.

Table 2.6 summarises the regression models predicting LogPOC concentrations and decomposable C / POC ratios. The model was month + runoff + date and was constructed to separate the effects of month, flow and residual date trend (for example the parameter of date is evaluated once the effects of month and flow have been removed; the same analyses carried out for Table 2.3). For the four HMS sites in NE Scotland only the Rivers Don and Dee showed that date was a significant factor and hence that there was a change over the time period of the observations once the effects of month and flow had been removed. The River Don showed a decreasing trend in POC during 1976-2005 and the River Dee (with greater moorland + peatland land cover than the Don) showed an increasing trend during 1980-2005. However, the increasing trend in POC over time was not replicated at the South and North Esk sites which have a similar catchment area cover of organic soils to the River Dee. It should be noted that this analysis makes the assumption that the C contents of SS do not vary over time. This assumption may not be valid, especially as changes in SS concentrations over time for the Don and Dee sites probably indicate changes in the type as well as magnitude of SS sources.

Table 2.6 Regression models of Log POC and BOD test C/POC time series for HMS sites

				POC data				DecomposableC / POC				% Land use
HMS ID	Site	Period	n	Runoff		Date		Runoff		Date		peat land +moorland
16	Don	1983-2004	322	0.597	***	-18.3	***	-1.58	***	-134	***	18
17	Dee	1976-2005	274	0.239	***	21.4	***	-0.65	***	-61.6	***	45
22	South Esk	1983-2005	226	0.271	***			-0.88	***	-112	**	33
23	North Esk	1983-2006	219	0.35	***			-0.91	***	-116	**	45

*, **, *** denote significance at $p<0.05$, <0.01, <0.001 levels, respectively.

Significant declining trends in decomposable C / POC ratios for all sites suggest that labile C inputs were declining for all sites. This possibly represents declines in industrial effluents for the River Don (paper mill factories) and the effects of improvements in waste water treatment works (WWTW) at all sites and the increasing trend observed for total POC may therefore underestimate the rise in POC derived from humic soil sources which are of low metabolic quality. It would also be overly simplistic to try to derive a concentration of a fraction of POC that was not decomposed during the BOD test and use this to suggest a concentration of POC which related only to soil-derived C. The reasons for this are that:

(i) an unknown fraction of soil-derived C may be respired by the BOD test,

(ii) the BOD test includes some respired C which would be operationally-defined by the filtration process as dissolved and this accounts for the occurrence of decomposable C / POC ratios >1 in the dataset.

2.2.4 Analysis of long term changes in soil carbon losses from two catchments in Northern Ireland

2.2.4.1 Methods

In Northern Ireland two river catchments were selected for study, the Main and the Moyola (Figure 2.14). These are both large catchments with 30% or more of their area covered by moorland or peat.

Organic matter percentages were determined for suspended sediments collected on 1.2µm filters by loss on ignition at 500°C. Values are given as organic matter concentrations (mg l^{-1}) in river waters but these can be converted to an approximate value of particulate organic C by dividing by two.

The continuous discharge record (daily mean flows) and sample concentration data for 1994-1999 (weekly samples) were used to calculate seasonal and annual river loads using the interpolation method ‘flux method 5’ (Walling and Webb, 1985):

$$Total\ load = K \frac{\sum_{i=1}^{n} C_i Q_i}{\sum_{i=1}^{n} Q_i} \overline{Q}$$

where K is a conversion factor to account for the period of measurement, $\overline{Q}$ is the mean annual discharge, C_i and Q_i are instantaneous organic matter concentrations and discharge respectively (mean daily value) and n is the number of samples. Flow weighted mean concentrations ($\overline{C_Q}$) were then calculated according to:

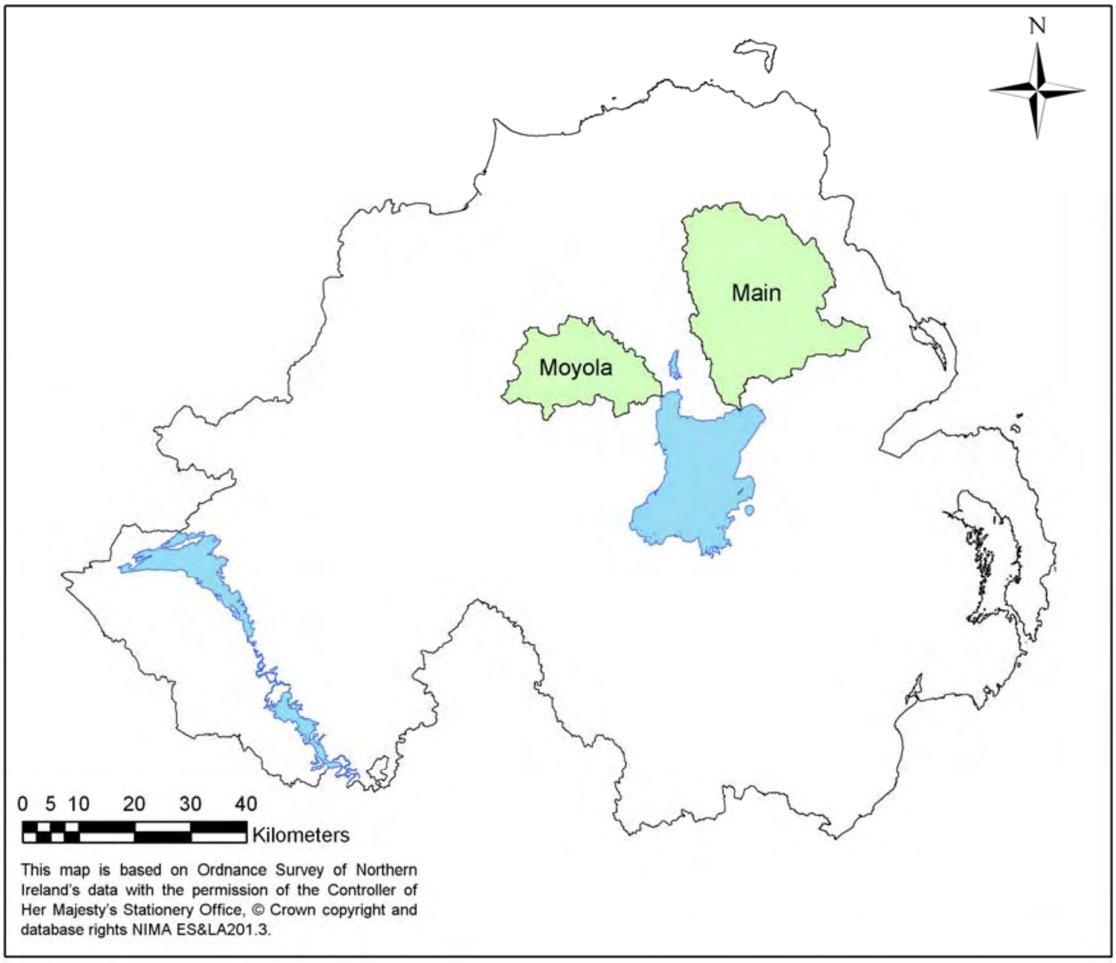
$$\overline{C_Q} = \frac{1}{n} \sum_{i=1}^{n} Ci \cdot Qi* \qquad [2.1]$$

where:

$$Qi* = \frac{Qi}{\overline{Q}} \qquad [2.2]$$

A simple multiple regression model (as used previously for the analysis of Scottish HMS river data) was used to separate the $\log_{10}$ organic matter concentration record into components of seasonal (months), flow-related ($\log_{10}$ flow in $m^3\ s^{-1}$) and residual time trend (days).

Figure 2.14 Location of the Main and Moyola river catchments within Northern Ireland



2.2.4.2 Results

These catchments provide an opportunity to assess short-term change over time in organic matter (OM) contents of suspended sediments (SS). They are large catchments both with 30% of moorland and peat areas (Table 2.7a), but are subject to the same restrictions as for HMS catchments in Scotland in that there are likely to be considerable anthropogenic inputs of sediment and in-stream processing downstream of headwater sites of eroding organic soils. However the data of OM contents is better than for other sites where only the change in time of the total mass of the SS is recorded and a fixed organic matter content is applied to calibrate the SS to particulate organic C or organic matter concentrations. The data for the Rivers Main and Moyola (Table 2.7b) show that use of a fixed constant OM content is not valid for these systems and this may also be the case for the other rivers analysed as part of the HMS dataset. The annual variability in OM% (loss on ignition mass of collected SS) was large for the Rivers Main and Moyola but was not correlated significantly with log flow. However, there were increases in %OM content of SS over 1994-99 at both sites which was nearly significant for the River Main ($p=0.08$; slope 0.66% increase per year). Therefore should erosion of upland soils be increasing, then %OM contents as well as the SS concentrations/fluxes may well increase simultaneously, leading to underestimation of increased particulate C losses should fixed C or OM contents be applied.

There was an apparently large and significant linear increase in organic matter loads for the River Main over the short period 1994-99 (Table 2.7c; Figure 2.15a). The length of the data record and the frequency of sampling, however make this result unreliable as a true long-term trend. This is due to natural climatic variability over short periods and the bias toward low flows associated with sampling at fixed time resolutions (although examples of studies of weekly hydrochemical data as in this case are rare). The runoff (Table 2.7b) for the period for which the loads were calculated shows an increase. Hence it is difficult to separate the rising OM load trend from differences in the flows experienced between years, or in the representation of sampling of the range of flows between years (especially for the higher runoff years 1998, 1999). There were no apparent relationships between flow-weighted mean concentrations and years (Figure 2.15b). However, the multiple regression modelling used previously for the HMS sites showed significant increases in OM concentrations during the period for both sites (greater and more significant for the River Main than the Moyola) once the effects of seasonality (not significant) and changing flow (highly significant) had been factored out (Table 2.7c). This evidence points to an increase in OM concentrations given the data provided.

Figure 2.15. Changes in (a) annual mean fluxes and (b) flow-weighted mean concentrations for Rivers Main and Moyola during 1994-99

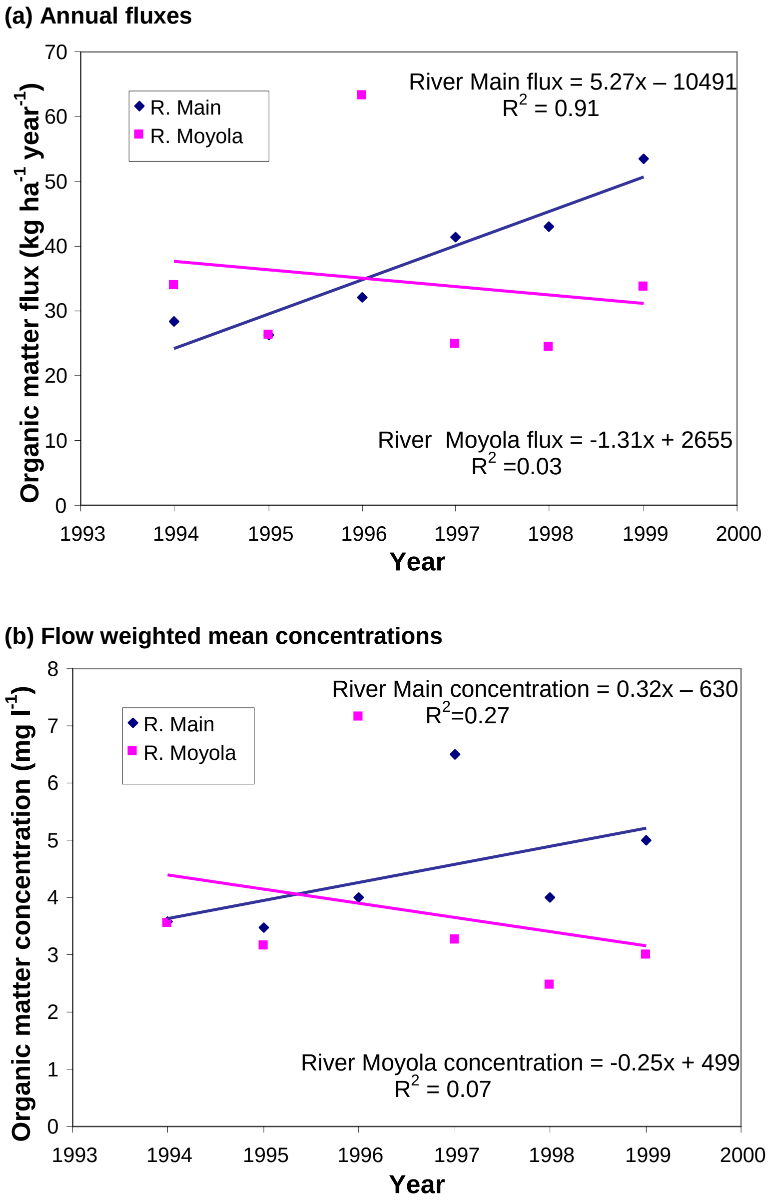


Table 2.7 Analyses of data for Rivers Main and Moyola. (a) Catchment attributes, (b) annual summaries of runoff and %OM compositions of suspended sediments and (c) trend analyses of change in OM loads and concentrations over 1994-1999

	River Main		River Moyola	
Area (km^2)	715		313	
(a) Whole catchment land Use (%)				
Arable	3		7	
Improved Grassland	52		37	
Rough Grassland	11		21	
Heather Moorland	16		16	
Peatland	14		14	
Montane	0		0	
Urban	3		2	
Forest	2		2	
Water	0		0	
(b) River Data	Runoff (mm)	Mean (range) sediment %OM	Runoff (mm)	Mean (range) sediment %OM
1994 (Apr-Dec only)	792	46 (24 - 76)	960	44 (17 - 87)
1995	755	46 (13 - 98)	828	38 (1 - 89)
1996	802	48 (32 - 84)	884	56 (20 - 90)
1997	637	49 (22 - 96)	758	51 (11 - 100)
1998	1076	51 (27 - 100)	991	51 (10 - 98)
1999	1069	48 (11 - 92)	1117	47 (7 - 88)
(c) Trends				
Linear trend in annual load (kg ha^{-1} year^{-1})	5.3***		-1.3^{ns}	
Linear trend in conc. (mg l^{-1} year^{-1})	0.32^{ns}		-0.25^{ns}	
Multiple regression predicting LogOM conc.				
Slope for factors:				
Season	0.009^{ns}		0.002^{ns}	
Flow	0.193***		0.463***	
Residual date trend	77x10^{-6}**		60x10^{-6}*	

Significance levels: ns, not significant; *p<0.05, **p<0.01, ***p<0.001

2.3 Future trends impinging on soil erosion

Policies such as the GAEC requirements, the Forests and Water Guidelines and the Water Framework Directive are explicitly directed towards minimising soil erosion and should reinforce recent trends in reducing erosion of agriculture and forest soils. However, future trends in soil erosion linked to extreme weather conditions are more difficult to predict. Climate models suggest an increase in rainfall for Scotland (Barnett *et al.*, 2006a, 2006b), and major flood events have attracted considerable media attention in the last few years. A recent analysis predicts that for the UK as a whole, event magnitudes at a given return period will increase by 10% for short-duration (1-2 day) events and by up to 30% for longer frequency (5-10 day) events (Ekstrom *et al.*, 2004). Analysis of extreme rainfall data for the period 1961 to 2000 indicates that event magnitudes have significantly increased, particularly for Scotland. For example the 10-day, 50 year rainfall event in Scotland has become an 8 year event for Eastern Scotland, an 11 year event for Southern Scotland and a 42 year event for Northern Ireland during the analysis period (Fowler and Kilsby, 2003).

Crawford and Favis-Mortlock (2006) make further predictions of extreme events becoming more common in Northern Ireland in the future. For example, by the 2060s, the HAD GCM predicts that parts of the upland Sperrins (north-west of Northern Ireland) will receive the same mean daily precipitation in July that is currently experienced by their lower slopes bordering Lough Neagh, while the European Center for medium-range weather Forecasts Global Circulation Model (ECHAM GCM) predicts that the greater Belfast area will have the same mean daily precipitation in January that is currently experienced by the lower slopes of the Mourne Mountains.

Such predicted increases in the frequency of extreme rainfall events suggest that soil erosion incidence linked to extreme weather conditions may increase in the next few decades. It is therefore expected that landslides such as occurred in the autumn of 2004 (Glen Dochart, north of Lochearnhead, Scotland) and bog bursts like those seen on Shetland in 2003 and other significant erosion of peat may increase in frequency in the future. However, climate models generally predict average conditions and the errors on the predictions are substantial. Models are incapable of predicting localised summer storms. It is therefore difficult to suggest policy changes by which the effects of such events may be avoided. Agricultural and forestry policies aimed at reducing the erodibility of soils and runoff from soils will undoubtedly limit the impact of extreme events. Predicting and mapping the areas most susceptible to such events will also enable better targeting of protective measures for infrastructure such as roads.

Other pressures on organic and organo-mineral soils in the uplands include those associated with developments such as wind-farms. These often involves disturbance such as access road construction, borrow pits for extraction of rock and the not-insignificant areas associated with pylon construction. Unpublished measurements indicate that the fluxes of dissolved organic carbon can be markedly greater in streams draining affected catchments when compared to control catchments with no disturbance. As with forestry operations, the maximum adverse impacts are likely to be seen during the construction phase.

2.4 Conclusions: key drivers of erosion of organic soils

(i) The evidence from a wide range of studies suggests that erosion of surface organic horizons has had a significant impact on peats and peaty soils in Scotland and Northern Ireland. At the national scale, erosion has impacted on around 14% of blanket bog in Northern Ireland and some 35% of blanket bog in Scotland.

(ii) It is difficult to quantify the major drivers of erosion. The complexity lies in the fact that some drivers of erosion act to damage surface (vegetation) cover and increase the susceptibility of surface organic horizons of soils to erosion while others control the occurrence and rates of erosion from sites with such surface damage.

(iii) The evidence reviewed here suggests that overgrazing is probably the major anthropogenic driver leading to vegetation damage and greater susceptibility of organic surface soil horizons to erosion. The evidence shows that sheep numbers have decreased in recent years but, in Scotland, there is still concern over the numbers of wild deer.

(iv) Extreme climatic events are the most important triggers for specific erosion incidences. The occurrence of these is difficult to predict but most climate change scenarios suggest that the magnitude and/or frequency of extreme precipitation events are likely to increase and therefore that the frequency of erosion events may also increase.

(v) There is some evidence that degradation has been taking place for many centuries and that key climatic perturbations over this period may have triggered the development of gully systems that we see today. Any change in climate that increases desiccation of the ground surface is likely to make that surface more vulnerable to other agents such as trampling animals, rainfall or wind; current climate change scenarios suggest that this could happen.

(vi) It is also important to note that human trampling and wildfires associated with recreational pressures can also cause significant damage to vegetation and therefore trigger erosion; trampling appears to act at a much more localised scale than other factors. It is probable that recreational-induced trampling will increase in the next few decades and also that higher temperatures and droughts may increase the potential for wildfires.

(vii) It is unlikely that drainage, controlled burning or air pollution act as drivers of soil erosion on any significant scale in Scotland or Northern Ireland.

(viii) The widespread adoption of the Forests and Water Guidelines has effectively reduced erosion caused by forestry activities such as road construction, drainage and harvesting to very low levels.

(ix) Potential new drivers of erosion in upland peaty soils must also be taken into account in modelling. The large number of proposed wind farm developments in upland areas with peaty soils at one sample.

(x) It is unlikely that the increased losses of carbon from peaty soils which are reflected in the increased flux of dissolved organic carbon measured in streams draining upland catchments are driven by changing climate alone. Much of the increased DOC flux represents an adjustment to reduced levels of sulphate deposition following reduced SO_2 emissions over the last 2 decades.

CHAPTER 3

Erosion models

Objective 3

To identify currently available models that can be applied in Scotland and Northern Ireland and (1) assess the robustness and sensitivity of erosion driver and factor responses to changes; and (2) evaluate the ability of selected erosion model(s) to inform on potential risk and its regional variability in Scotland and Northern Ireland for both loss of soil and evidence of soil loss such as DOC or habitat changes.

3 EROSION MODELS

There are three main components to Objective 3: (i) a review of existing soil erosion risk models: (ii) the testing of models appropriate to Scottish and Irish conditions to assess their ability to model likely land use and climate changes; and (iii) an assessment of the ability of the models to represent regional variation in climate and land use.

The review encompasses a wide range of process-based, conceptual and empirical models but any model that is subsequently used has to be available to the project team, be parameterised with available data, be applicable to national scale modelling (Scotland and Northern Ireland), be conceptually robust and allow land use and climate input data to be modified. This will inevitably limit the number of suitable models. Unless the model is currently supported it would be very difficult to commission the model within the short space of time available to the project team.

The ability of the chosen model(s) to predict absolute sediment losses or dissolution of organic carbon is less important than its ability to identify regional differences and to respond to key drivers such as climate or land use/management changes. Thus model sensitivity is a key attribute. This approach has the additional benefit in that suitable sediment yield validation data are not readily available in either Scotland or Northern Ireland.

In order to be able to identify regional differences, the model needs to be implemented within a GIS and be able to utilise soil, land use and topographic data common to both Scotland and Northern Ireland. The model output will be validated against existing data and other modelled output.

Current rule-based models from both Scotland and Northern Ireland are described briefly in Appendix 1 for information.

3.1 Methods to assess erosion models

By a process of expert knowledge, literature review and Internet searching, 50 soil erosion risk models were identified and reviewed. The outcomes of the model assessment are summarised in Appendix 2 which provide the characteristics of each model.

Each model was assessed on a range of attributes relevant to this project (Table 3.1). The type of the model is important; for example, empirical models such as the USLE do not transfer readily to Scotland as the model is based on experimental data from Mid-West USA. The model needs to be able to be applied at a regional/national scale and therefore the input data requirements need to be available and manageable at that scale. If the model is very data hungry, we will not be able to parameterise it for all Scotland and Northern Ireland.

The main source of literature was a review paper by Merrit *et al.* (2003) who extensively reviewed a wide arrange of soil erosion risk models. This was supplemented by personal knowledge and a web search.

Table 3.1 Attributes used to assess each soil erosion model

Type	Type of model ie conceptual, physical or empirical.
Spatial scale	Spatial scale that the model is appropriate for.
Temporal scale	Temporal scale of output e.g. daily, weekly, annual.
Input data	The data requirements of the model. High implies that the model requires a large amount of detailed input data.
Output data	An indication of what the model predicts.
Climate variation	An indication if the model can deal with changes in the climate input data.
Land use variation	An indication if the model can deal with changes in the land use input data.
Availability/ support	Is the model currently supported by the developers?
Suitability for organic soils	Can the model predict erosion in organic soils?
Rainfall/ runoff	Can the model simulate runoff from rainfall?
Land surface sediment	Can the model simulate production, transport and deposition of sediment in the terrestrial environment?
In-stream sediment	Can the model simulate production, transport and deposition of sediment in streams?
Sediment-associated water quality	Does the model predict water quality parameters (i.e. nutrients, organic carbon) associated with sediment in the terrestrial and stream environment?

3.2 Results of erosion model assessment

A total of 50 models were reviewed (see Appendix 2). Of these, 8 are empirical, 22 are conceptually-based, 18 are physical and 2 can be described as both conceptual and empirical.

3.2.1 Empirical models

There were 8 empirical models reviewed but 5 required high levels of input data and, although 7 models are currently supported, most are from the Universal Soil Loss Equation (USLE) suite of models and therefore have limited application in Scotland and Northern Ireland. Empirical models rely on regression relationships being developed but these relationships do not always hold outside of the biogeographical area where they were derived. The USLE is widely used but it places all soils with organic matter contents greater than 4% in one class. The majority of mineral soils in both Scotland and Northern Ireland will exceed this concentration. Only one empirical model was able to predict erosion losses in organic or organo-mineral soils.

3.2.2 Conceptual models

Of the 22 conceptual models, 13 require a large amount of input data that are either not available for all Scottish and Irish soils or mean that running the models at a national scale would be very difficult. The remainder can function with low to moderate levels of input data. Only 10 of these models are currently supported (5 of these require high levels of input data). Almost all of these models can deal with variations in climate and land use input data, so that sensitivity to these key drivers could be assessed, but only three will model erosion of organic soil horizons. Only one, INCA-C, can model losses of dissolved organic carbon.

3.2.3 Physical models

Physically–based models are generally the most scientifically robust and flexible in both input and output. These models are based on an understanding of the physical processes that cause erosion and are therefore often applicable to a wide range of soils, climatic and land use conditions. However, this also means that they are often difficult to parameterise (14 of the 18 reviewed had high data requirements). Only six of these models are currently supported and only one (PESERA) was capable of modelling at the national or regional scale.

3.3 Discussion of erosion model assessment

In order to meet the objectives of the project and to assess regional variability in losses of particulate and dissolved organic carbon due to land use and climate changes, we require models that are scientifically robust, supported, relatively easy to parameterise with existing data (or through the use of pedotransfer functions). Of the 50 models reviewed, only two met these criteria: INCA-C (Integrated Catchments Model for Carbon) and PESERA (Pan-European Soil Erosion Risk Assessment, http://eusoils.jrc.it/ESDB_Archive/pesera/pesera_cd/index.htm). Members of the project team had also some experience with these models and considered that, of the currently available models, these were the most appropriate for use in the project.

PESERA was developed initially to predict soil erosion risk over all of Europe at a 1km grid cell resolution. Application of the model for Scottish conditions was tested under the EU-funded ENVASSO project where locally derived climate data (precipitation, evapotranspiration, temperature and storminess) were utilised along with data from the Scottish Soils Knowledge and Information Base (SSKIB), allied with rule-based pedotransfer functions. Land use statistics were derived from the agricultural and horticultural census data and spatially distributed using the Land Cover Scotland dataset (LCS88). A 50m digital elevation model was used to derive relief inputs.

There were, however, some drawbacks to using the models selected. For example, the ability of PESERA to accurately predict absolute losses of particulate carbon is limited but the important output for comparative purposes is the relative changes in particulate loss due to changes in climate and/or land use rather than the absolute losses.

The INCA-C model is catchment based but its application could provide insight into organic carbon and sediment dynamics on a national scale. INCA-C was developed to predict carbon fluxes in within catchments. The model simulates the production and transport of dissolved organic (DOC) and inorganic (DIC) carbon in soils and surface waters. It is also capable of simulating in-stream sediment transport. It operates on a daily time-step and is able to simulate the effects of land-use and climate change on in-stream carbon and sediment fluxes. The model has been applied to forested sites in Finland, Norway, Sweden and Canada. A preliminary application has been made to the Lochnagar catchment in Scotland. As part of this project, INCA-C is used to simulate long-term particulate and dissolved organic carbon dynamics at the Glensaugh Environmental Change Network catchment.

3.4 National scale modelling

Based on a consideration of available soil erosion risk models that were supported, were applicable at the national scale and could have key drivers such as land use and climate altered, the PESERA model (Pan-European Soil Erosion Risk Assessment) was selected as being the most appropriate for this work.

In order to achieve some degree of compatibility with existing national datasets, the baseline input data (that is, current climatic and land use conditions) for the PESERA model were, wherever possible, similar to those datasets used in the diffuse pollution screening tool – WFD19 (Anthony *et al.,* 2006) as these data were derived in a compatible form for both Scotland and Northern Ireland.

3.4.1 The PESARA model

The Pan-European Soil Erosion Risk Assessment model (PESERA) is designed to predict hillslope erosion and the transport of sediment downslope and can be applied at a range of scales from small catchments to national and international scales (Kirkby *et al.*, 2004). The model is physically-based in which land-use, soil, topography and climate data are used to estimate the amount and frequency of saturated overland flow in a grid cell by the application of a simple soil moisture storage model. The model uses a frequency distribution of rainfall events to estimate the long-term averages for each month, summed to give annual totals. How easily soil particles can be transported is predicted from soil texture and combined with the runoff calculated from the storage model, the gradient of the slope and the slope length to estimate sediment losses. The model output is monthly sediment yields per grid cell (tonnes/ha) and its application within a Geographic Information System means that the model is spatially distributed.

The datasets required by the PESERA model include climate data (monthly average rainfall, potential evapotranspiration and temperatures), soil data (texture and available water capacities), land cover including crop type where appropriate, and topography. All input data (apart from temperature data) were at a 1 km^2 grid cell resolution (1x1 km), while temperature data were available at 25km^2 grid cell resolution (5x5km). The model runs within ArcGIS and requires over 100 spatial coverages.

3.4.1.1 Climate input data

The climate data used in PESERA for both Scotland and Northern Ireland were derived from previous projects, in particular, the development of the NIRAMS model (Dunn *et al.*, 2004) and the Diffuse Pollution Screening Tool (Anthony *et al.*, 2006). The climate input data for PESERA, which is required for each month, are shown in Table 3.2.

Table 3.2 Climate input data required by PESERA

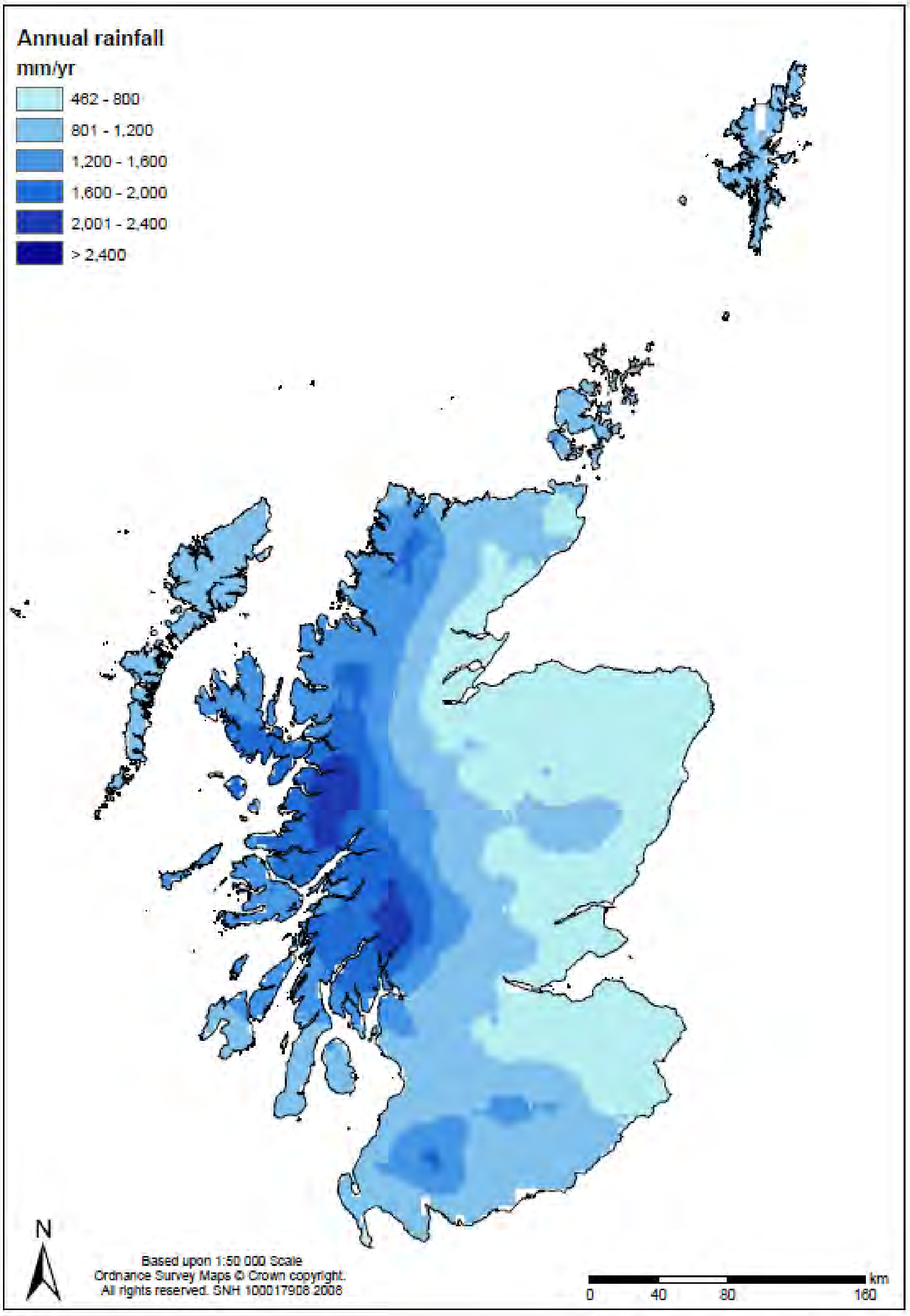
Mean monthly rainfall
Mean monthly rainfall per rain day
Coefficient of variation of monthly rainfall per rain day
Mean monthly temperature
Monthly temperature range (max-min)
Mean monthly potential evapotranspiration

The mean monthly rainfall and mean monthly potential evapotranspiration were taken from the NIRAMS dataset (which was subsequently extended to encompass Northern Ireland as input to the Diffuse Pollution Screening Tool). These data were extrapolated from the NERC British Atmospheric Data Centre (BADC) daily rain gauge and synoptic station archive for the period 1989-1998 and were processed to derive, amongst others, mean monthly precipitation for each 1km^2 grid cell (Figure 3.1a and 3.1b). The 1989-98 period appears to have been drier than the long-term average rainfall for both Scotland and Northern Ireland. The temperature data and number of rain days were derived from the Diffuse Pollution Screening Tool and covered the period 1971-2000. The coefficient of variation of rainfall was taken from the PESERA Europe-wide dataset except for the Shetland Islands which were missing from this dataset. The coefficient for Shetland was generated from 30 years of rainfall data from Lerwick synoptic station. The temperature data were only available at a 5x5 km grid resolution (25 km^2).

The spatial pattern of the PET data (Figure 3.2a and 3.2b) is due to extrapolation from a limited number of synoptic stations where all the attributes required to calculate potential evapotranspiration are systematically measured.

Figure 3.1 Predicted average annual rainfall (1989-98) per 1km grid cell, extrapolated from NERC BADC daily rain gauge archive.

a) Scotland



b) Northern Ireland

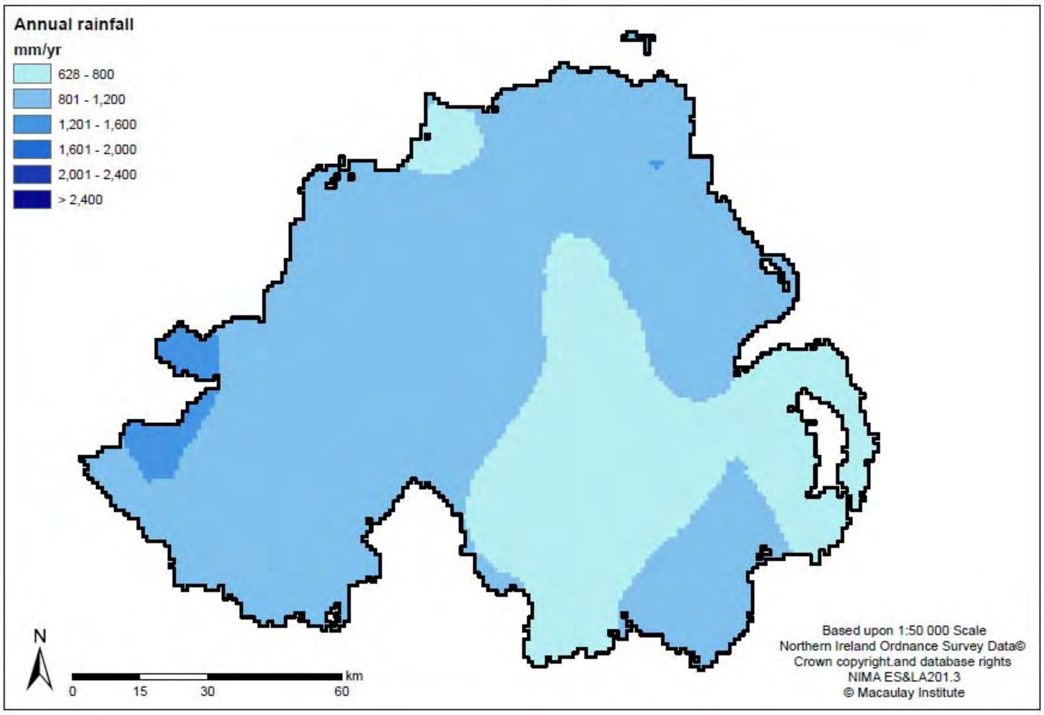
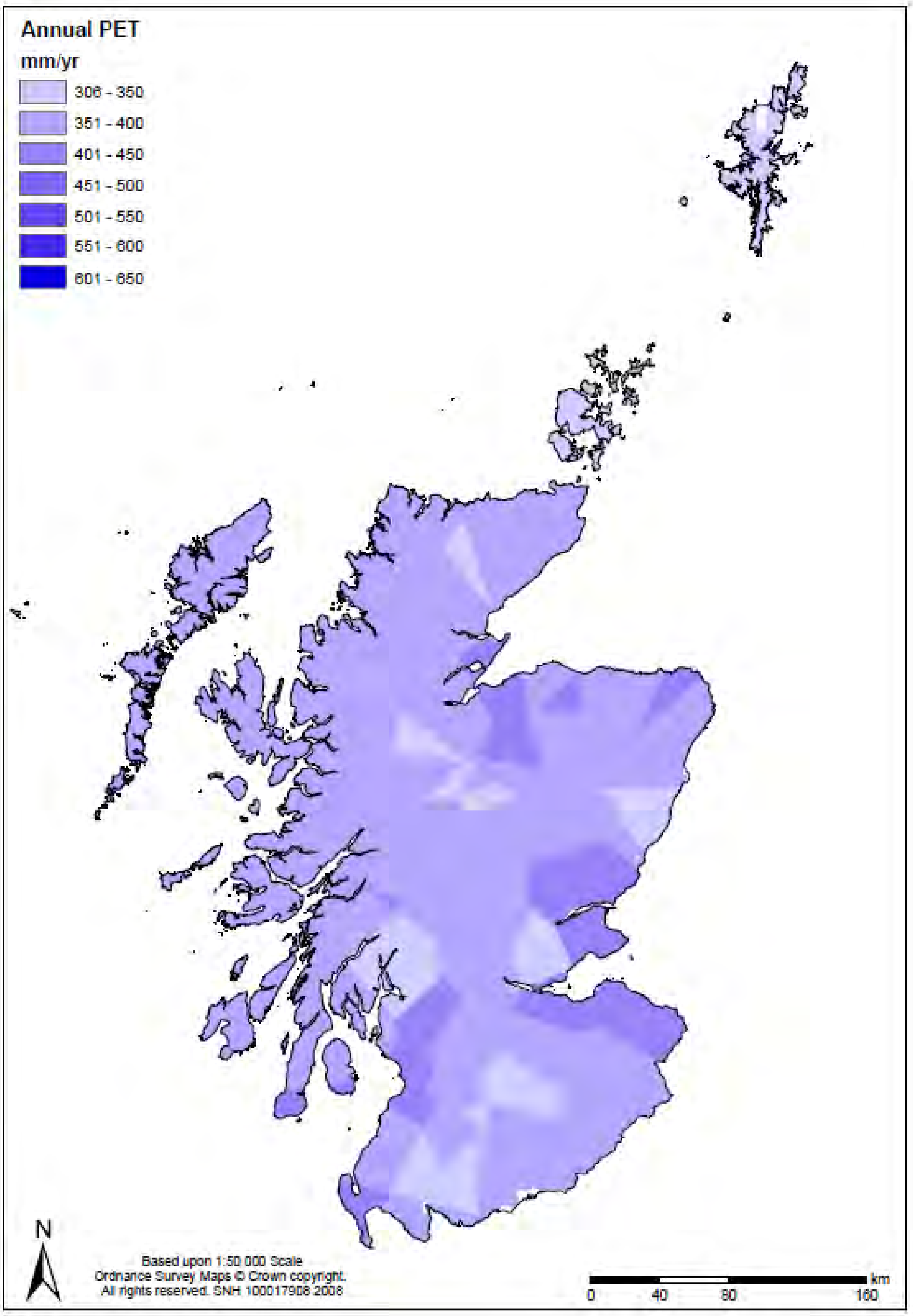
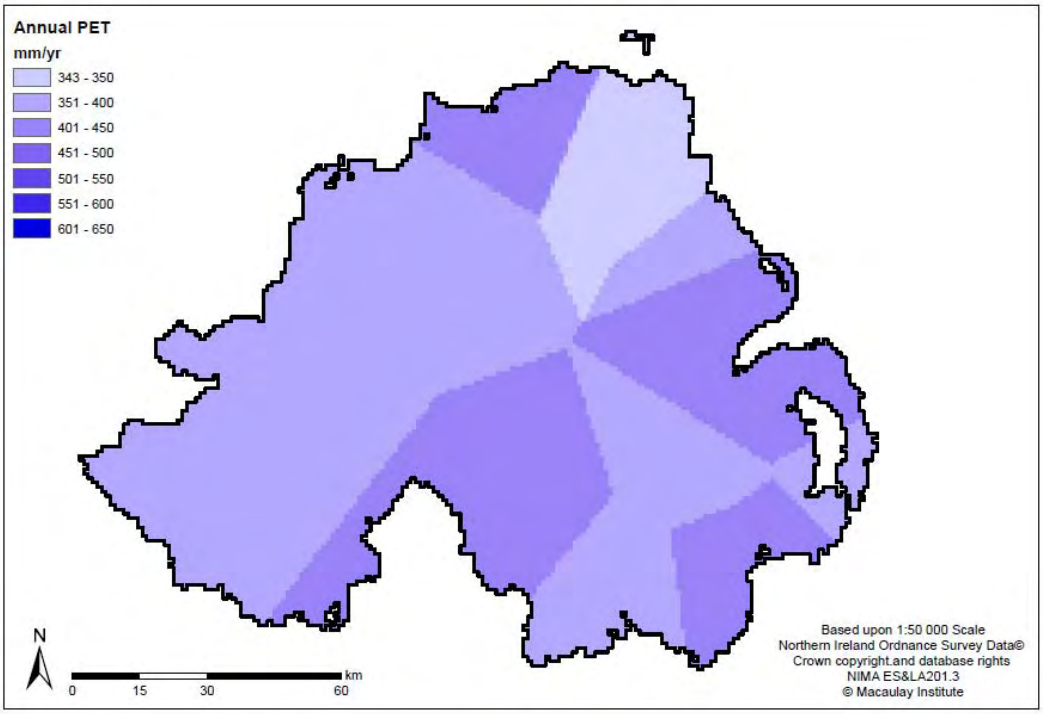


Figure 3.2 Predicted average annual potential evapotranspiration (1989-98) per 1km grid cell extrapolated from NERC BADC data.

a) Scotland



b) Northern Ireland



3.4.1.2 Soil input data
Scotland

The dominant soil series in each 1km^2 grid cell was derived from the 1:250 000 scale soil map (Soil Survey of Scotland Staff, 1981) using a GIS to calculate the proportion of soil map units in each cell and multiply this value by the proportion of the different soils (as described in Boorman *et al.*, 1995) within each map unit. The results were then ranked by areal extent and the most extensive soil selected to represent that grid cell.

An existing attributes dataset (SSKIB), which is linked to the soil spatial dataset, was used to derive the required soil input data (Lilly *et al.*, 2004). SSKIB (Scottish Soils Knowledge and Information Base) holds statistical summary data for all Scottish soils delineated on the 1:250 000 soil map of Scotland, including median particle size classes for sand, silt and clay contents (FAO/USDA size classes), organic matter content and horizon designation and thicknesses. These median values were used to derive available water storage capacities for each soil using established pedotransfer rules (Dunn *et al.*, 2004). The European soil texture classes (Figure 3.3) were also derived from these particle size data and subsequently used within the PESERA model to derive crusting, erodibility and scale depth parameters (Irvine and Cosmas, 2003). The erodibility values were subsequently modified after discussions with Brian Irvine, Leeds University. Figure 3.4 shows the spatial distribution of European soil texture classes in Scotland.

<u>Northern Ireland</u>

A GIS was used to extract the underlying dominant soil series in each 1km^2 grid cell from the 1:50,000 scale soil map of Northern Ireland (AFBI, 2006). The Northern Ireland “5km Attribute Dataset” was linked to the derived 1km^2 dominant soil series map. These data were determined on samples taken, by horizon, from soil pits on a near-regular 5 km grid. The data included average values for sand, silt and clay contents (based on Soil Survey of England and Wales size classes), pH, organic matter content, horizon designations and thicknesses. These values were used to derive available water storage capacities for each soil using established pedotransfer rules (Dunn *et al.*, 2004) and to determine the European soil texture classes required as input to PESERA (Figure 3.5).

Figure 3.3 European soil texture classes in relation to particle size distribution.

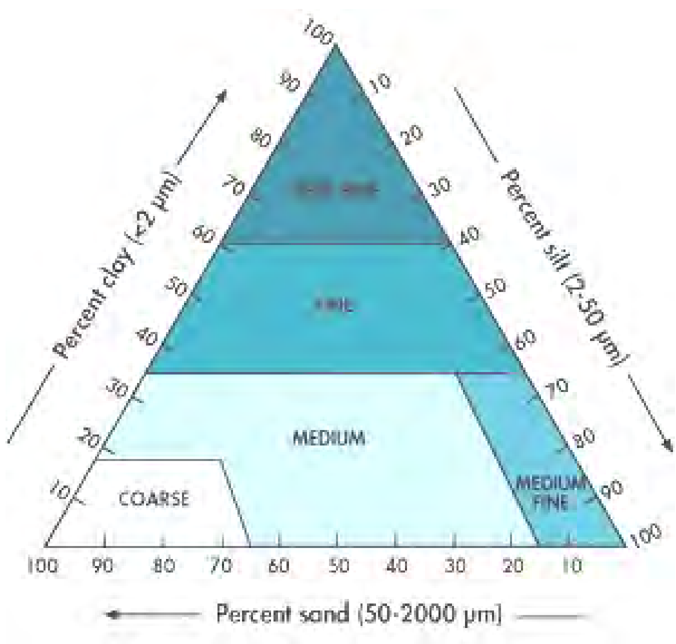


Figure 3.4 Distribution of European soil texture classes in Scotland

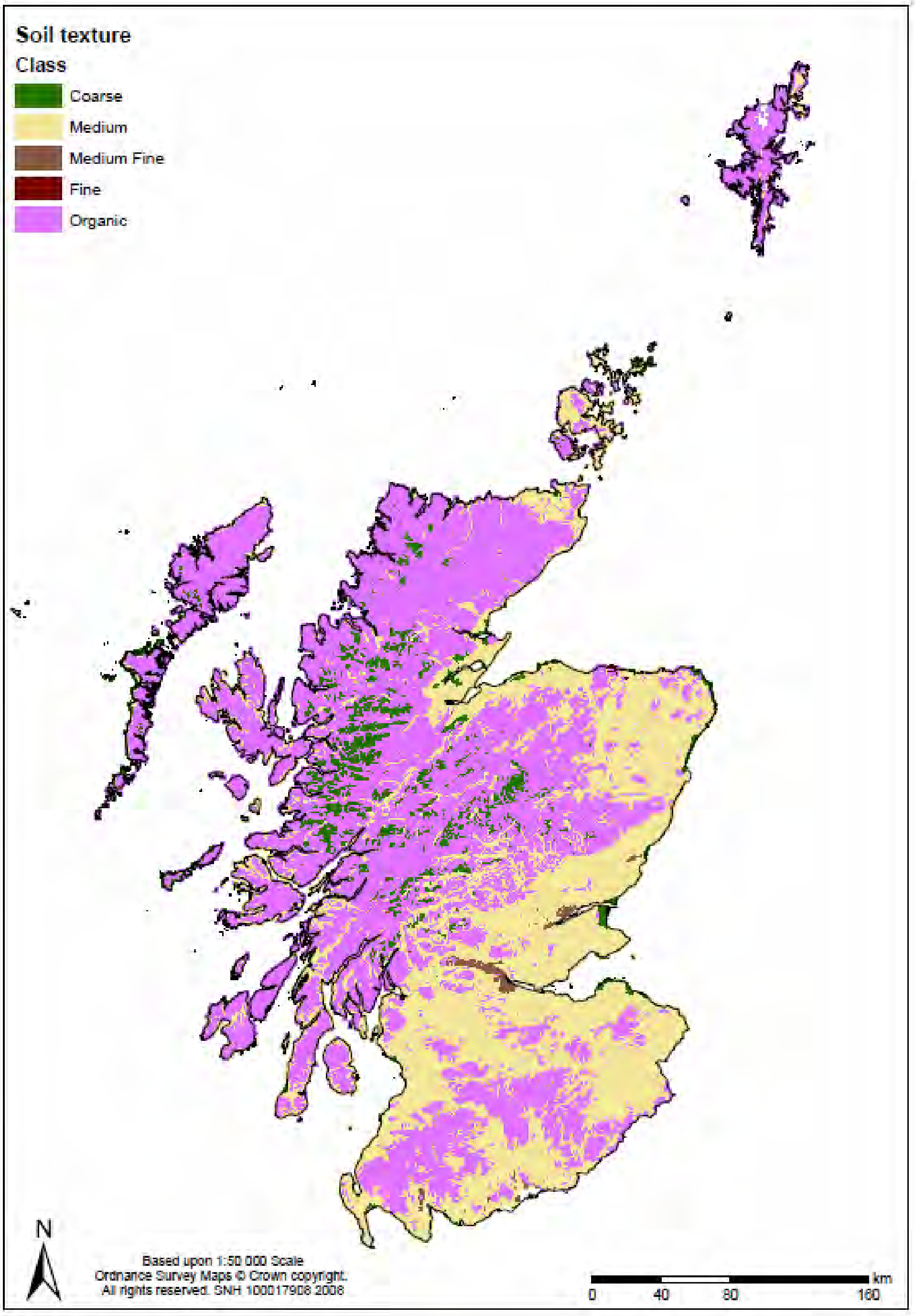
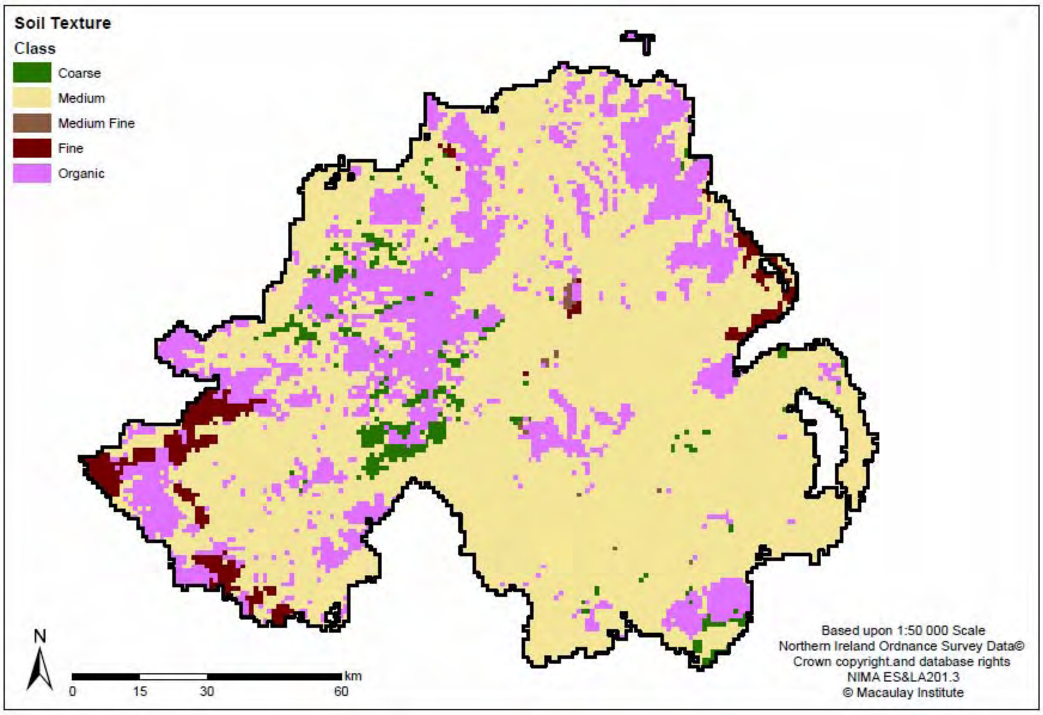


Figure 3.5 Distribution of European soil texture classes in Northern Ireland



3.4.1.3 Land cover input data

The land cover data were modified from the Land Cover Map 2000 (Fuller *et al.*, 2002) that was used within the Diffuse Pollution Screening Tool. This dataset was derived from remotely sensed imagery and the land cover types were converted to the CORINE classes that are used within the PESERA model (Table 3.3, Figure 3.6 and 3.7).

There is a more limited number of land cover class in PESERA than in LCM2000, and some land use classes were merged.

The arable land was subdivided into dominant crop types through the use of the Agricultural and Horticultural Census data that are collected by the Scottish Government on an annual basis and from the 26 District Council areas in Northern Ireland (Anthony *et al.*, 2006). The dominant crop type was identified for each 1km^2 grid cell and the percentage of crop cover throughout the growing season was modified to suit local conditions in Scotland and Northern Ireland.

The most obvious PESERA land cover class for the dwarf shrub dominated peatlands of Scotland and Northern Ireland would be ‘scrub’. However, this PESERA category was ascribed a fixed percentage of vegetation cover (30%) by Irvine and Cosmas (2003). Kirkby et al. (2004) used the forestry category within PESERA as a surrogate for the dwarf shrub heath of the Scottish uplands. The proportion of vegetation cover of this land cover category could be varied from 0 to 100%, allowing the testing of the effects on sediment yield of reduced vegetation cover. In order to test if using forestry as a surrogate for dwarf shrub cover had any unusual effects, the model was also run with the land cover set as permanent pasture for the dwarf shrub dominated areas. The output in terms of sediment yield from both was the same, indicating that the percentage cover was more important than the land cover type. Therefore, the PESERA ‘forestry’ land use was allocated to those vegetation communities identified as scrub (designated as scrub /forest in Table 3.3), though a distinction between afforested areas and these scrub communities was retained within the spatial data used to run the model. An eroded peat category was added to take account of the presence of eroded peat. That is, data from Land Cover of Scotland 1988 dataset (Macaulay Institute, 1993) were overlain with the soil texture map layer to delineate areas of eroded peat land cover class coincident with organic soils at 1km2 resolution. Similar data were available for Northern Ireland from a Peatland Survey (Cruickshank and Tomlinson, 1988). The proportion of bare soil in these areas was set at 40% of the 1km2 grid cell.

Table 3.3 PESERA land cover classes derived from LCM2000

LCM2000 land classes	PESERA land cover
Sea and Estuary	sea and estuary
Water (Inland)	water (Inland)
Littoral Rock	rock
Littoral Sediment	water surfaces and wetland
Saltmarsh	water surfaces and wetland
Supra-Littoral Rock	rock
Supra-Littoral Sediment	water surfaces and wetland
Bog (Deep Peat)	scrub /forest
Dense Dwarf Shrub Heath	scrub /forest
Open Dwarf Shrub Heath	scrub /forest
Montane Habitats	scrub /forest
Broadleaved and Mixed Woodland	forest
Coniferous Woodland	forest
Improved Grassland	pastures and grassland
Neutral Grass	scrub /forest
Setaside Grass	pastures and grassland
Bracken	scrub /forest
Calcareous Grass	scrub /forest
Acid Grassland	scrub /forest
Fen, Marsh and Swamp	scrub /forest
Arable Cereals	arable
Arable Horticulture	arable
Arable Non-Rotational	heterogeneous agricultural land
Suburban and Rural Development	artificial land
Continuous Urban	artificial land
Inland Bare Ground	bare land
Unclassified	artificial land

Figure 3.6 Distribution of PESERA Land cover classes in Scotland

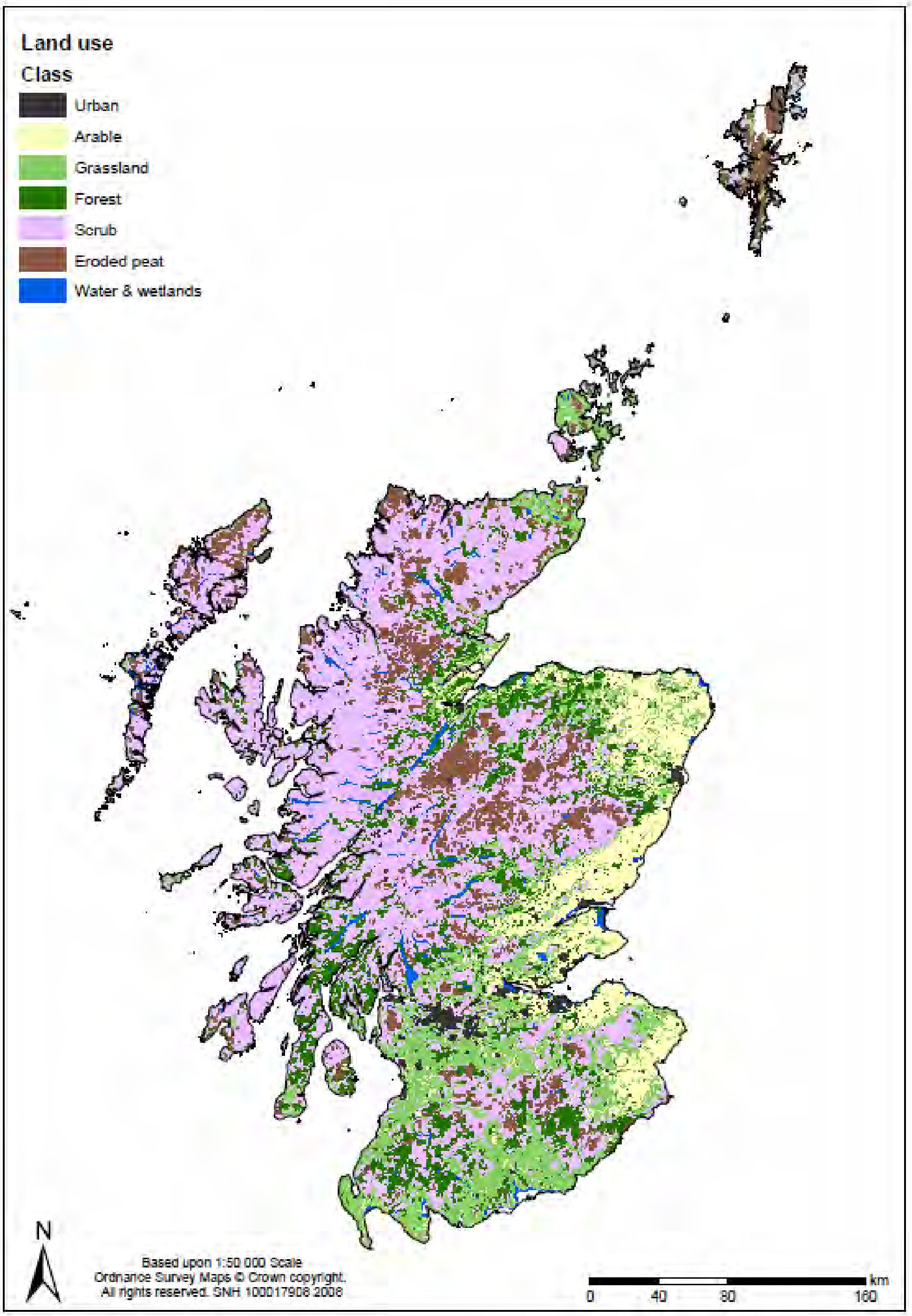
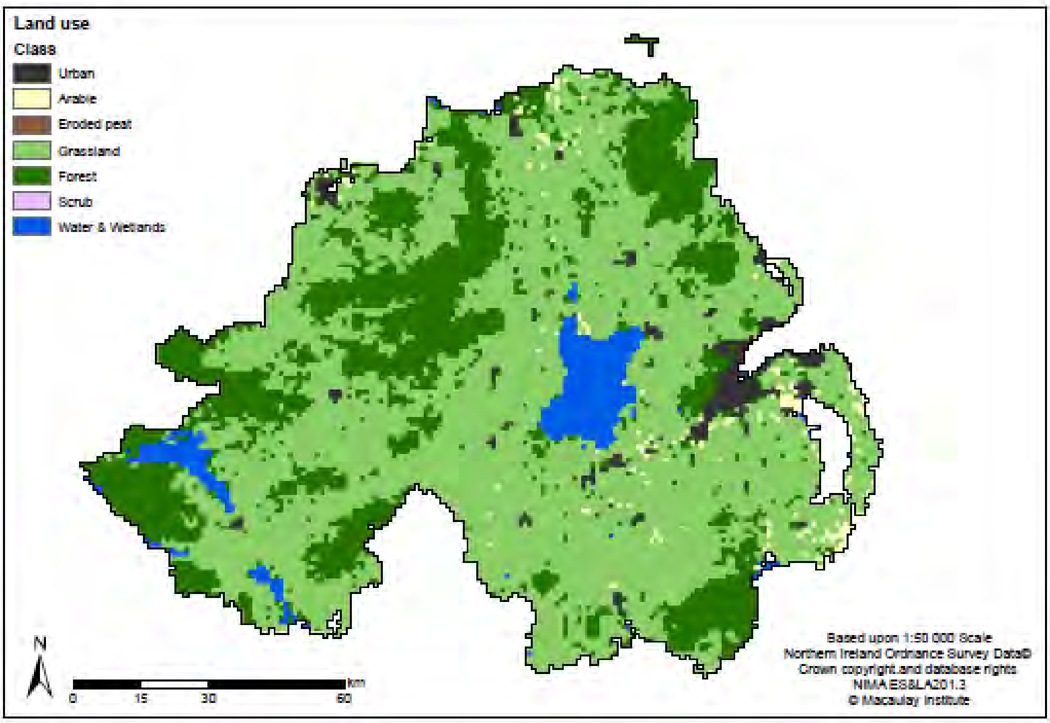


Figure 3.7 Distribution of PESERA Land cover classes in Northern Ireland



3.4.1.4 Topographic input data

The topographic information used in this project was that provided with the model. This is standard deviations of elevation calculated from 1km resolution, satellite-derived, digital elevation data. (http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html).

The alternative for Scotland would have been to use the 10m Ordnance Survey (OS) Landform PROFILE ® data derived from high resolution digital photogrammetry and LiDAR (Light Detection and Ranging) data and recalculate the standard deviation of elevation. Extensive testing with these data failed to accurately reproduce the 1km dataset used by Kirkby *et al.* (2004). This may have been due to the inherent differences between the base resolution of the underlying topographic data or differences in the method used to derive the standard deviation, or both. A decision was taken to utilise the same 1km grid of standard deviations as used by Kirkby *et al.* (2004) to derive an erosion risk map for Europe. Using this data set prevents the introduction of additional uncertainty into the prediction of total sediment yield.

While the OS terrain data gave similar spatial patterns in the topographic input data to that used by Kirkby *et al.* (2004), there is likely to be little change in predicted sediment yield throughout much of Scotland except in the areas of high relief such as the mountainous areas of the west Scotland where mass movement is more of an issue than erosion by overland flow. Further research is needed to fully determine the sensitivity of the PESERA model to high resolution digital terrain data and the effects that this may have on deriving erosion risk assessments for smaller spatial extents.

3.4.1.5 Base line output

Scotland or Northern Ireland-specific data were used throughout the model runs wherever possible. The only datasets that accompanied the PESERA model that were used were the coefficient of variation of rainfall (except for Shetland) and the digital terrain model input. The remaining datasets and input grids were derived from Scottish or Irish data or from a modified land cover dataset used within the Diffuse Pollution Screening Tool (Anthony *et al.*, 2006). This baseline land cover dataset included areas of eroded peat as these were considered to be more vulnerable to further erosion than vegetated peats. The proportion of bare soil in these areas was set at 40% of the $1km^2$ grid cell, based on expert judgement.

The baseline results predict an annual total sediment loss from Scotland of 216,290 $t.yr^{-1}$ and 5,219 $t.yr^{-1}$ from Northern Ireland, but the lack of validation data means that those figures cannot be verified. However, by running the model with both different climate and land cover values, we can determine the changes in sediment yield relative to this baseline value. As there were no 2050 climate projections available for Northern Ireland, only the land cover could be manipulated.

3.4.1.6 Sensitivity analysis

Some of the required outputs of the project are to explore the sensitivity of Scottish and Irish soils to changes in drivers of erosion such as climate and land use and to characterise the potential erosion risk in Scotland and Northern Ireland and its regional variability. This can be done by changing the input parameters of the PESERA soil erosion risk model. In order to determine the potential changes in sediment yield under different land uses and climates, the model was run a number of times with different land use and climate scenarios and the results compared to the baseline output in order to gauge relative changes.

The land use scenarios comprised changing the percentage cover of dwarf scrub categories in line with the vegetation changes due to burning or intensive grazing suggested in Chapter 5. The cover was altered successively from 100% to 80% in 5% increments for Scotland (Table 3.4) which is a greater range than shown in Chapter 5 (minimum cover 85%) but was designed to test the sensitivity of the model to extreme losses in vegetation cover due to grazing.

Table 3.4 Effect on sediment yield due to decreased dwarf shrub cover in Scotland

	Percentage cover of dwarf shrub				
	100	95	90	85	80
Sediment totals ($t.yr^{-1}$)	216,290	267,578	333,365	400,144	468,941
Increase from baseline (%)		23.7	54.1	85	116.8

The modelling results show that a 5% decrease in land cover results in a substantially increase in sediment totals. Since only the land cover of dwarf shrub moorland was altered in the model, these results indicate the predicted increase in erosion due to loss of vegetation cover by over grazing or burning. Severe cover loss of 20% resulted in over double the annual sediment loss. The relative proportion of the loss is greater as all other land uses were kept constant, so this increase can be attributed to changes in the dwarf shrub cover on semi-natural organo-mineral soils.

As there was less upland scrub vegetation in Northern Ireland and muirburn is not a common practice (A. Higgins, *pers comm*), the land cover change scenarios were restricted to 90% and 80% cover of dwarf shrub moorland (Table 3.5). These results show an increase in sediment total from a base line of 5,219 $t.yr^{-1}$ to 6,139 $t.yr^{-1}$ at 90% cover and 7,194 at 80% cover. These percentage increases (18 and 38%) are less than those observed for Scotland.

Table 3.5 Effect on sediment yield due to decreased dwarf shrub cover in Northern Ireland

	Percentage cover of dwarf shrub		
	100	90	80
Sediment totals ($t.y^{-1}$)	5,219	6,139	7,194
Increase from baseline (%)		18	38

Two future UKCIP02 2050 climate scenarios were investigated for Scotland; low Greenhouse Gas (GHG) emissions and high GHG emissions (Dunn *et al.*, 2008). The rainfall and potential evapotranspiration input data for PESERA were modified by applying a correction factor to the baseline data to derive new rainfall and potential evapotranspiration (PET) coverages (Figures 3.8 and 3.9). Changes in both rainfall and PET were made in combination as the PESERA model determines sediment erosion and transport from the amount of predicted overland flow generated by saturation excess. This is determined by a simple bucket model of soil storage capacity allied with rainfall input and evaporative losses. Therefore, it is important to change both rainfall and PET parameters simultaneously rather than focussing on rainfall alone. As these correction factors were derived from work done on only Scottish data (Dunn *et al.*, 2008), it was not possible to simulate the effect on sediment yield of climatic scenarios for Northern Ireland. These climate scenarios were also applied to the land cover changes scenarios.

Dunn *et al.* (2008) predict a decrease in mean annual runoff in the west of Scotland for both UKCIP02 2050 low and high emission scenarios. This is where the majority of organic and organo-mineral soils occur, which would suggest a decrease in erosion in these areas. There is a seasonal pattern to the overall decrease in runoff but as there is a limited seasonal change in vegetation cover on these soils, then there is likely to be limited seasonal variation in erosion.

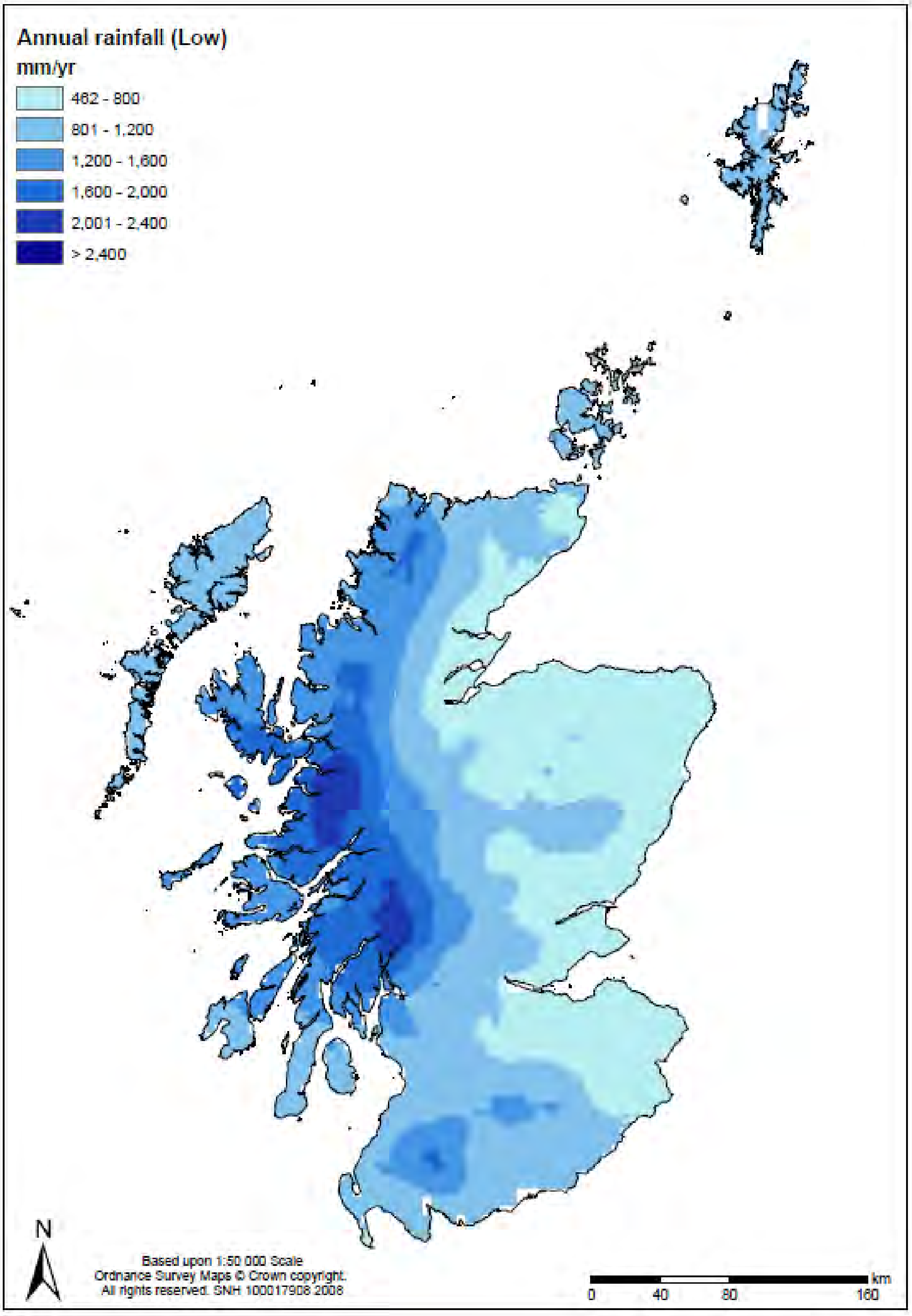
Table 3.6 Effect on total sediment yield ($t.yr^{-1}$) under UKCIP02 2050 climate scenarios

	Percentage cover of dwarf shrub moorland				
Climate	100	95	90	85	80
Baseline (1989-89)	216,290	267,578	333,365	400,144	468,941
High Emissions 2050	145,250	172,285	207,458	244,418	280,473
Low Emissions 2050	145,055	171,234	204,811	239,844	274,900

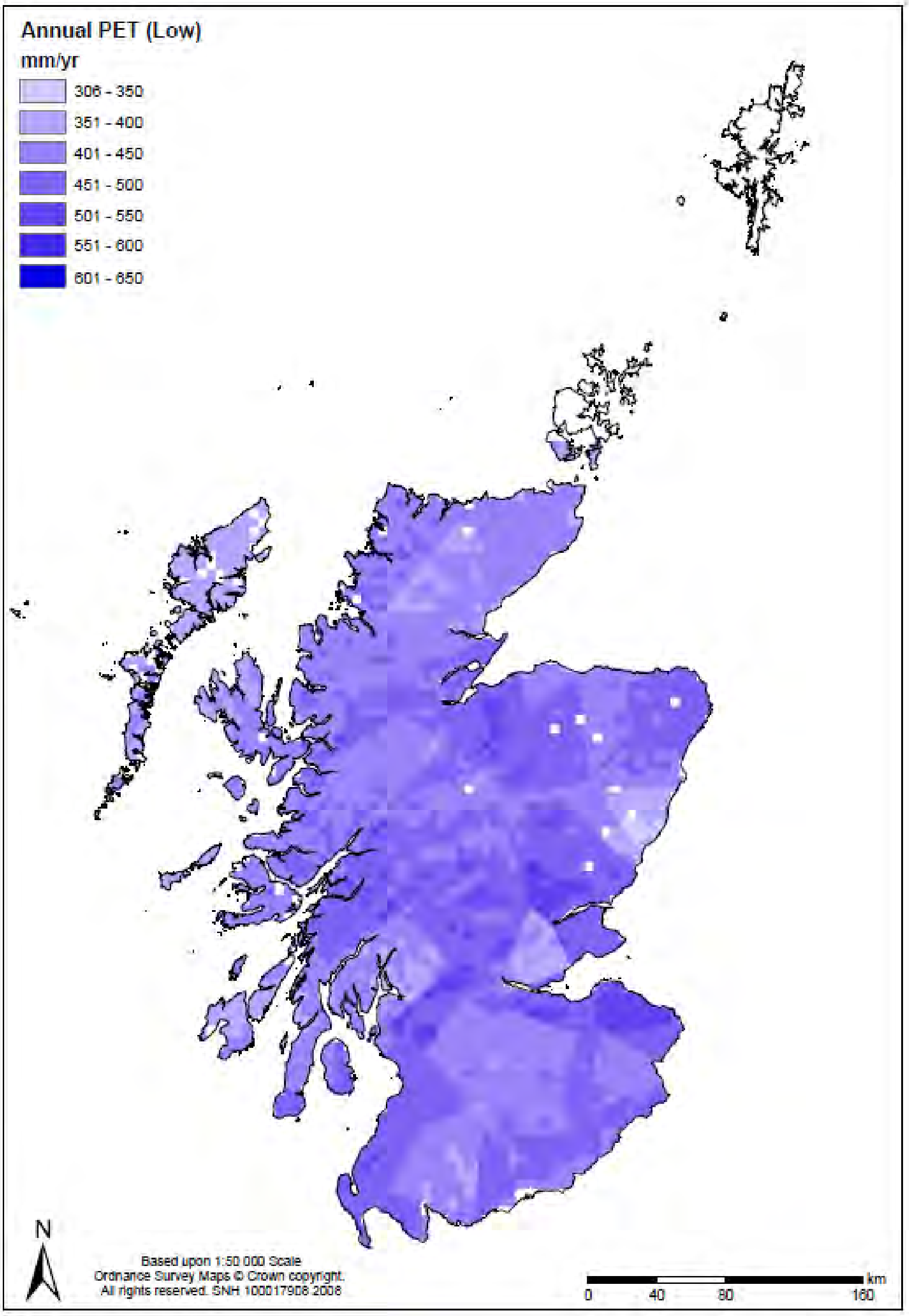
The model indicates a potential 30% reduction in annual erosion in Scotland under both the UKCIP02 emission climate scenarios (Table 3.6), primarily as there is a predicted decrease in runoff (rainfall-potential evapotranspiration). As there was a lack of storminess indices (coefficient of variation of monthly rainfall per rain day) associated with the Dunn *et al.* (2008) dataset, changes in rainfall patterns and intensity could not be fully taken into account. Similarly, changes in vegetation due to climate change were not examined due to the complexity of assessing likely changes in land use/land cover due to climate change. However, the model did allow some assessment of erosion rates given predicted climate change over the next 40 years, demonstrating that the model is

Figure 3.8 Rainfall (a) and potential evapotranspiration (b) predictions for 2050 - low emission scenario.

a)



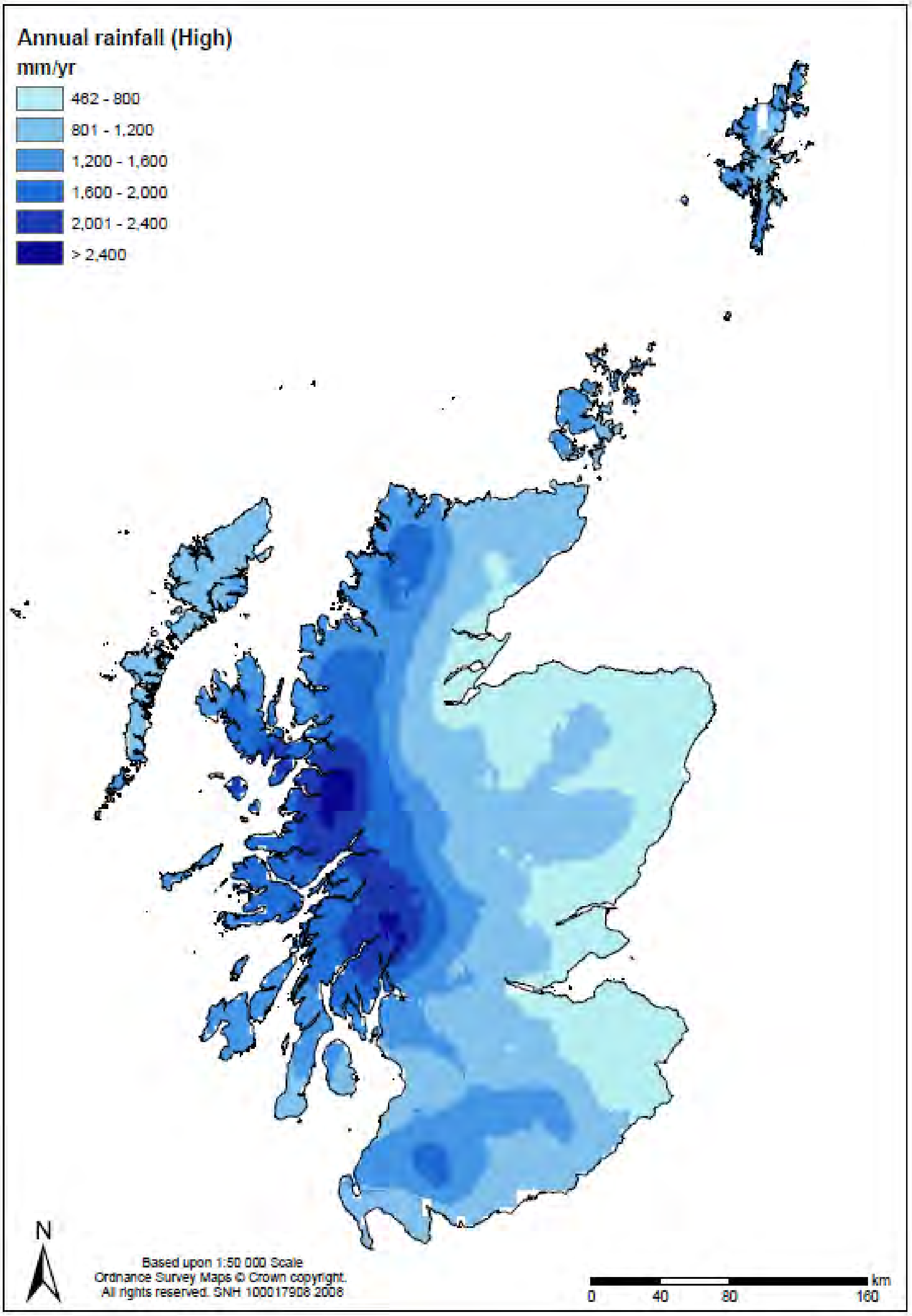
b)



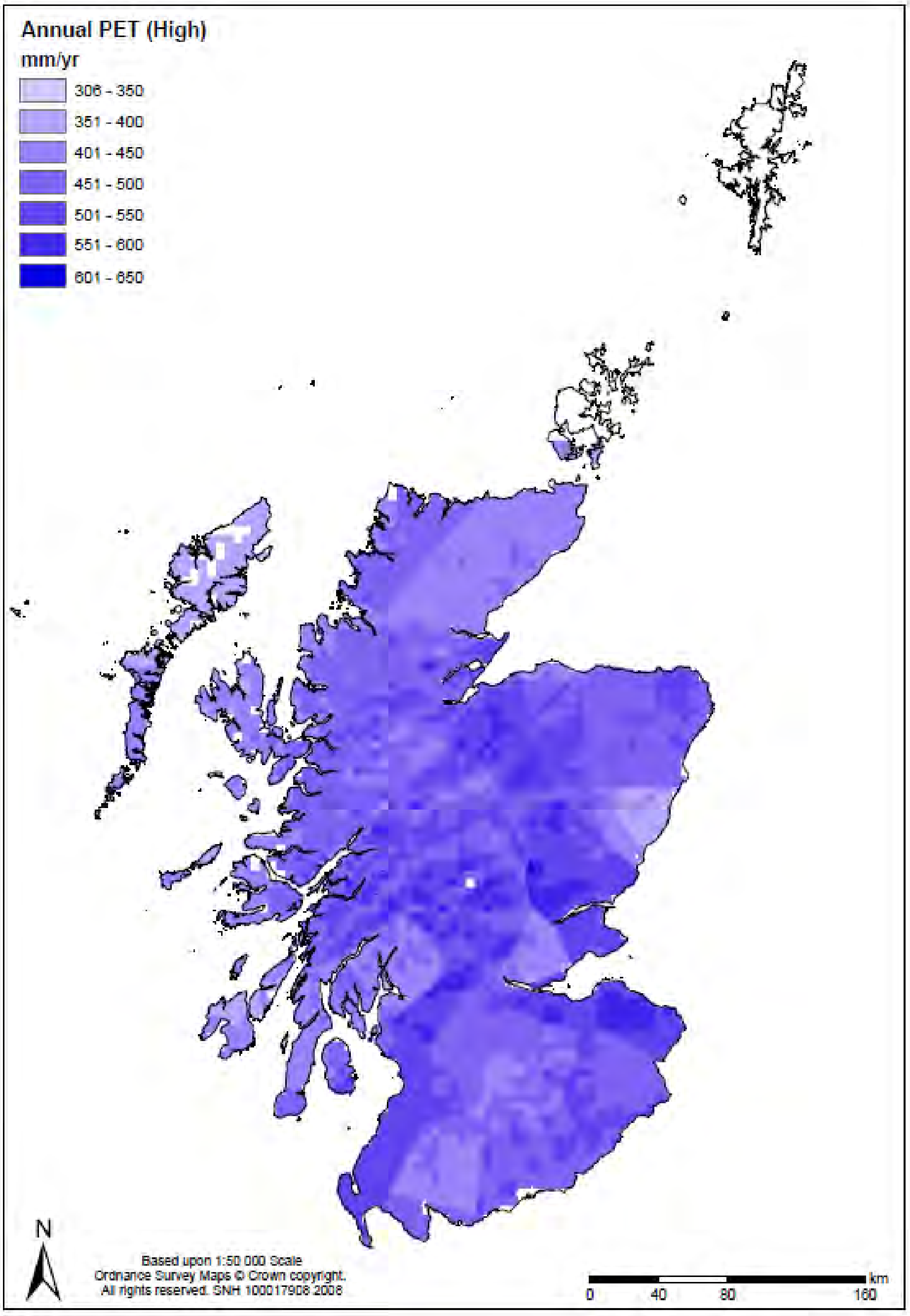
Note: there were no PET predictions available for Orkney or Shetland

Figure 3.9 Rainfall (a) and potential evapotranspiration (b) predictions for 2050 - high emission scenario.

a)



b)



Annual PET (High)
mm/yr
306 - 350
351 - 400
401 - 450
451 - 500
501 - 550
551 - 600
601 - 650
N
Based upon 1:50 000 Scale
Ordnance Survey Maps © Crown copyright.
All rights reserved. SNH 100017908 2008
0
40
80
160
km

capable of assessing future regional changes in soil erosion risk. A similar level of reduction (30-40%) from the baseline is also maintained over all the land cover scenarios.

These results clearly show that the PESERA model is sensitive to both land cover and climate changes. The land cover changes were selected as representative of land use changes that may influence upland organo-mineral soils (i.e. changes in vegetation cover through burning and changes in grazing pressure). Other gross changes such as cultivation of semi-natural vegetation and resulting long-term changes to soil type could also be accommodated. It has been demonstrated that the model has the ability to inform on potential risk.

3.4.1.7 Spatial variability

A key outcome of Objective 3 is to assess the ability of the selected model (PESERA) to assess regional variability in erosion risk. PESERA is a spatially distributed model and is therefore capable of showing regional changes in erosion output. Changes in vegetation cover of the dwarf shrub heather category from 100% to 80% (an extreme value) in Scotland showed an increase in erosion in Lochaber, the Northern and Western Highlands the Cairngorms and the Southern Uplands (Figures 3.10a, 3.10b and 3.10c). In Northern Ireland the key changes were increased erosion in the Mourne Mountains and the Antrim Plateau and with some small increases in the Sperrins (Figures 3.11a ,3.11b and 3.11c). Figures 3.10 and 3.11 need to be considered with caution. Large areas shown as having no change are mainly land with vegetation other than dwarf shrub,, whilst the land with dwarf shrub vegetation shows slight to large increases in erosion risk when the vegetation cover is reduced. The extent of the predicted increased erosion rates is considerably less in Northern Ireland than in Scotland which probably reflects the influence of the topography in the Northern and Western Highlands of Scotland which is dominated by over-steepened, glaciated valley sides.

There was a reduction in annual sediment yield of around 30% when the baseline climate input data were replaced with the UKCIP02 2050 predicted climate for Scotland simulation. The model showed regional changes (Figures 3.12a, 3.12b and 3.12c) which reflected the new climate patterns, with large decreases in sediment yield in Mull and Skye, Lochaber, the Northern and Western Highlands and the Angus Glens. Areas of increased erosion included the western central lowlands and eastern Scotland, though

Figure 3.10 Variation in the distribution of annual sediment losses with reduction of dwarf shrub heath cover in Scotland: (a) 100% cover; (b) 80% cover; (c) difference between (a) and (b).

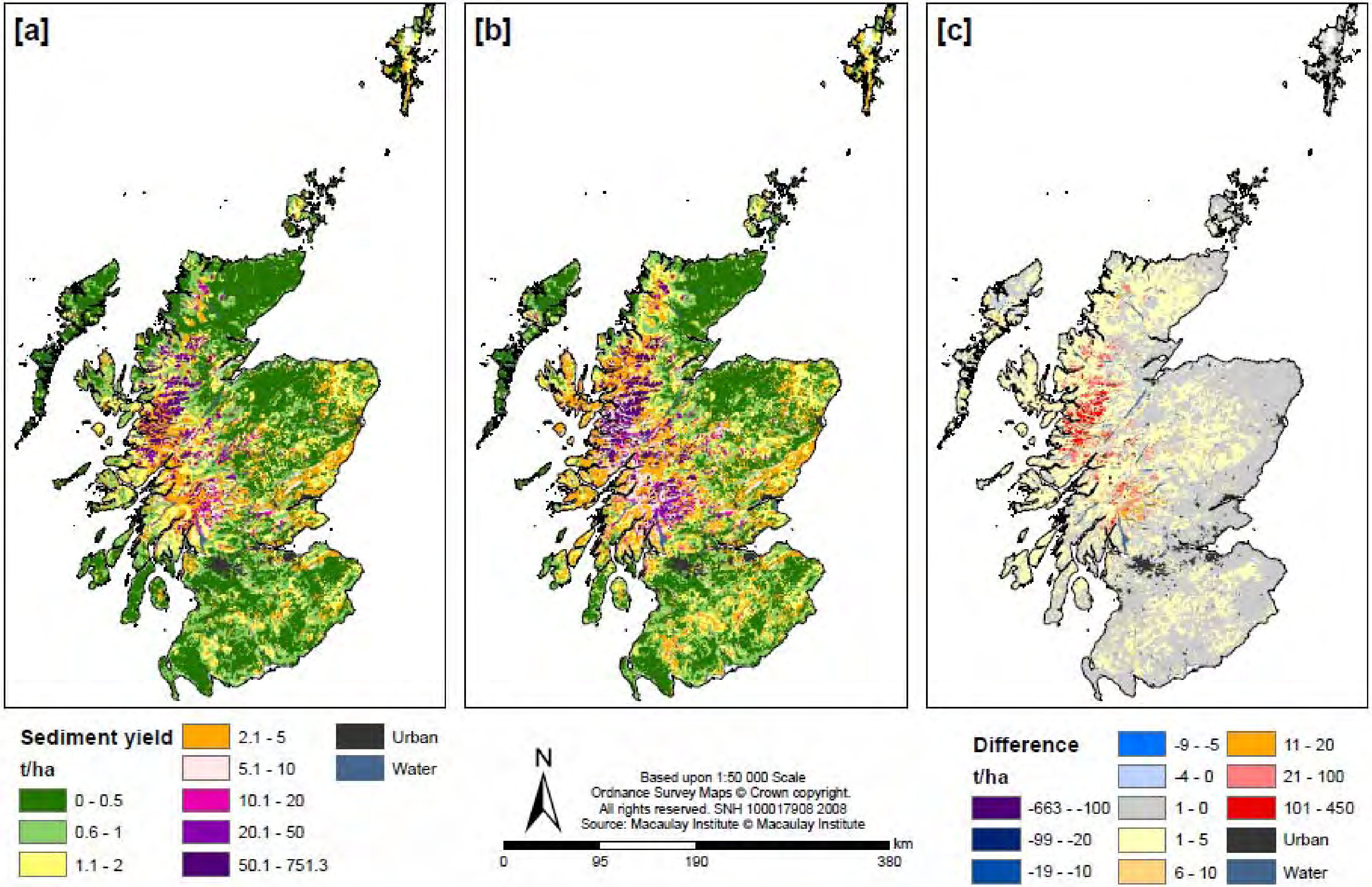


Figure 3.11 Variation in the distribution of annual sediment losses with reduction of dwarf shrub heath cover in Northern Ireland: (a) 100% cover; (b) 80% cover; (c) difference between (a) and (b).

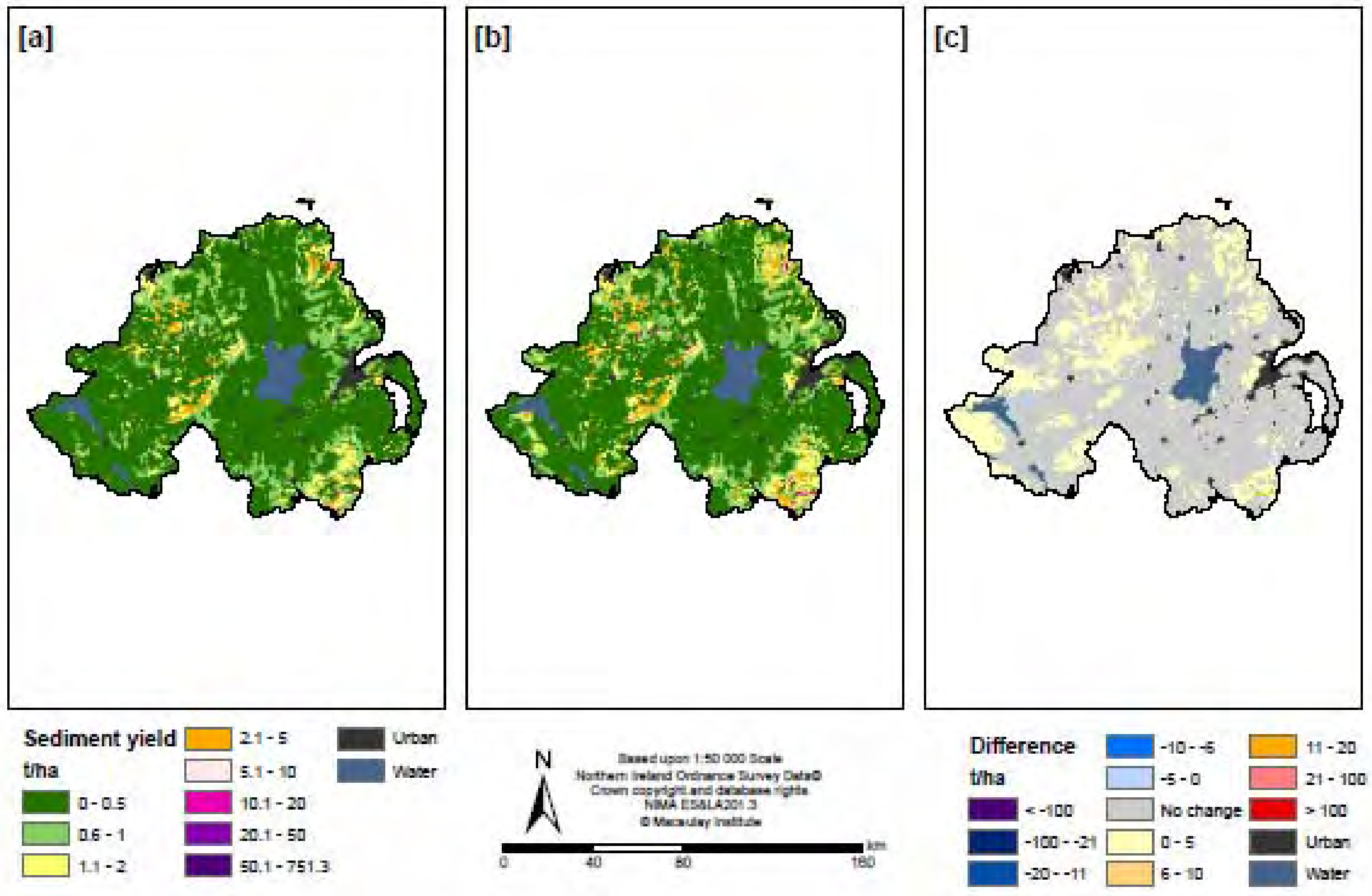
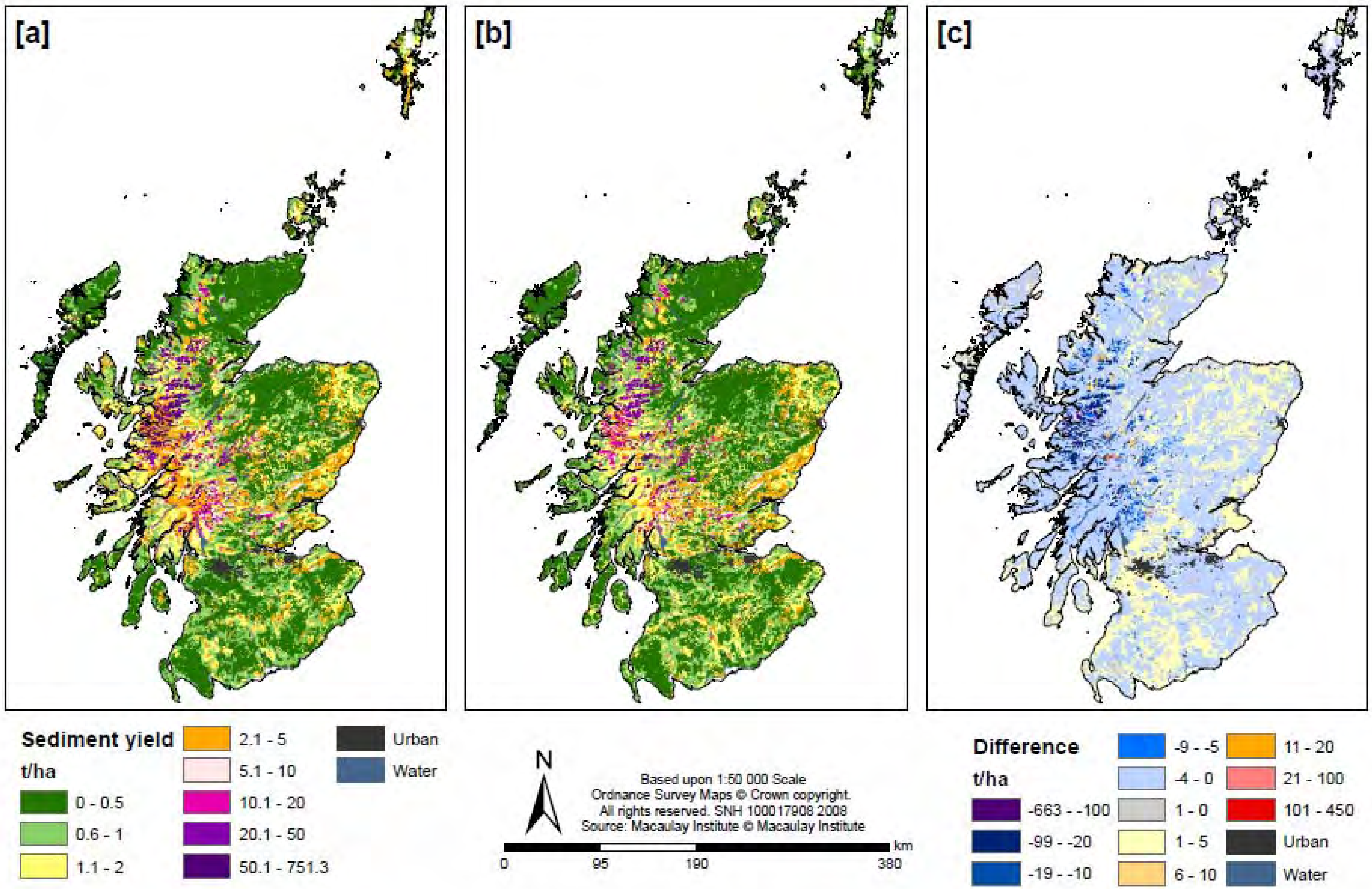


Figure 3.12 Distribution of sediment yield under (a) 1989-98 climate; (b) UKCIP02 2050 climate; (c) change in sediment yield.



the model predicts only slight increases in these areas. However, the climate input data used in the future climate scenarios did not include a measure of increased (or decreased) storminess and may not be an accurate representation of future erosion risk.

Overall, the PESERA model is capable of showing (and quantifying) regional variability in erosion losses in both Scotland and Northern Ireland through changes in land use or climate, though further work would be required to fully assess the likely changes.

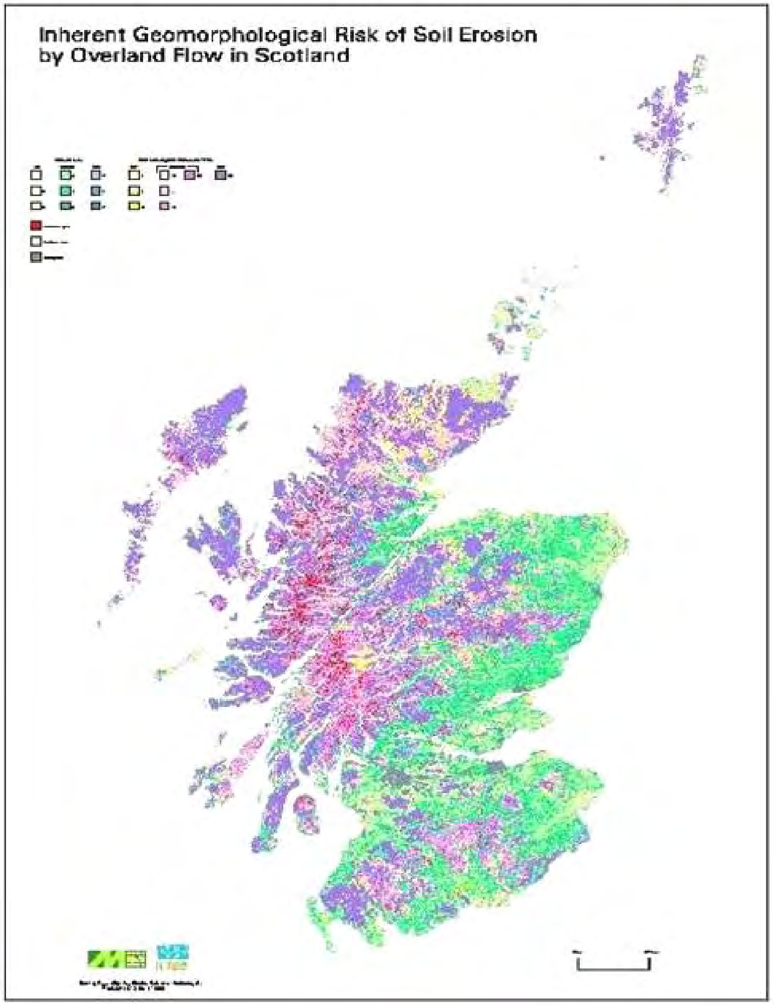
3.4.2 Comparison with existing national scale erosion risk assessments

To date there have been two major soil erosion risk assessments for Scotland; the inherent geomorphological risk assessment (Lilly *et al.*, 2002) and the prediction of diffuse sediment losses to water bodies as part of the Water Framework characterisation (Anthony *et al.*, 2006). The former assessment by Lilly *et al.* (2002) was a rule-based assessment of the inherent risk of soil erosion and assumed no vegetation cover (Figure 3.13a). There is a degree of similarity with the PESERA output which probably reflects the underlying soil and topographic data. One key difference is that Lilly *et al.* assumed that all peat soils were inherently at a high risk of erosion, whereas PESERA predicts low sediment yields from these areas, for example, on Lewis and the Flow Country. However, the PESERA model was run with complete or partial vegetation cover.

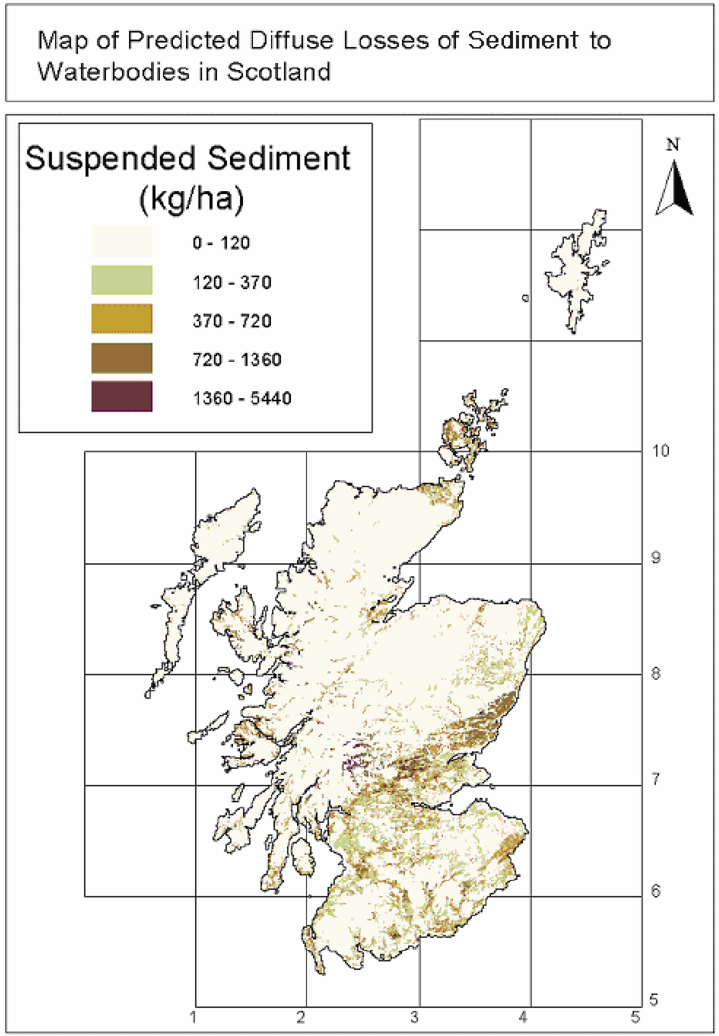
The second national scale soil erosion assessment by Anthony *et al.* (2006) was developed to predict the amount of mobilised sediment at the plot scale (1 to $10m^2$). Losses at the landscape scale ($1km^2$) were calculated by multiplying the loss by an index of landscape connectivity to take account of retention within the landscape (Figure 3.13b and 3.13d). PESERA determines the sediment yield from gully erosion for each grid cell and assumes no connectivity in the landscape. Therefore PESERA may have a tendency to over-predict sediment loss. However, even with this in mind there are stark differences between the two in the distribution of sediment yield; indeed the authors remark on the low sediment yields predicted for the Scottish Highlands. The underpinning PSYCHIC model calculates the amount of soil detached by rainfall impact (kinetic energy) and the shear effect of overland flow. The model uses a statistical distribution of probable daily rainfall intensities to produce a kinetic energy (KE) value but the rainfall impact is mitigated by the presence of vegetation cover. The soil erodibility component is also driven by soil texture and assumes that the finer fraction of the soil is

Figure 3.13 Existing national scale soil erosion risk assessments: a) Inherent geomorphological risk for Scotland; b) Diffuse pollution screening tool for Scotland; c) rule based risk assessment for Northern Ireland; d) Diffuse pollution screening tool for Northern Ireland.

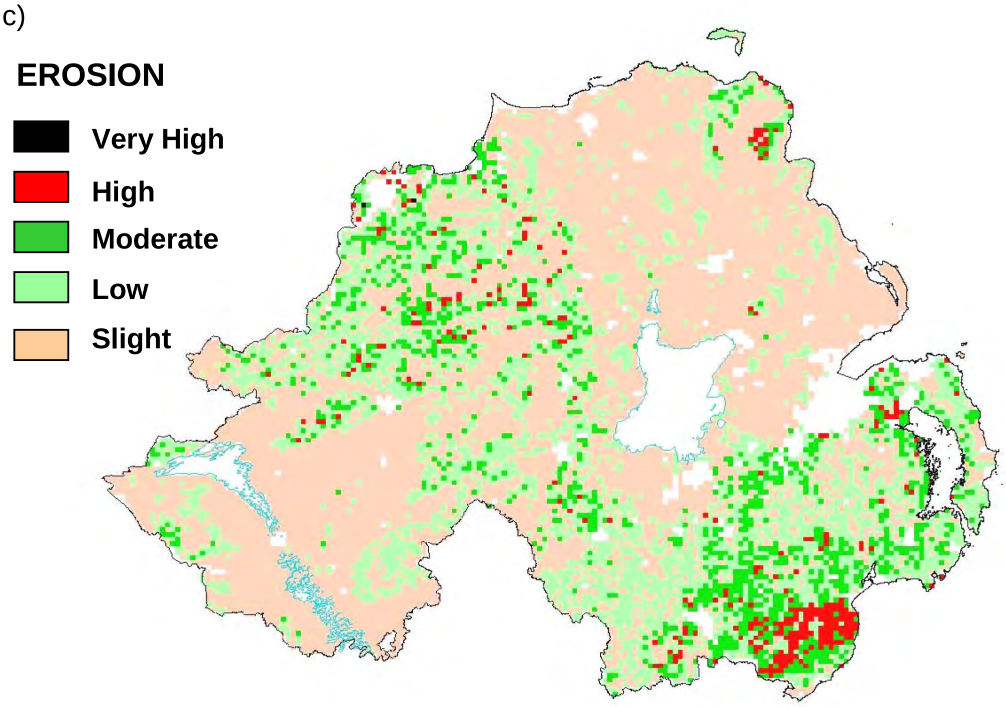
a)



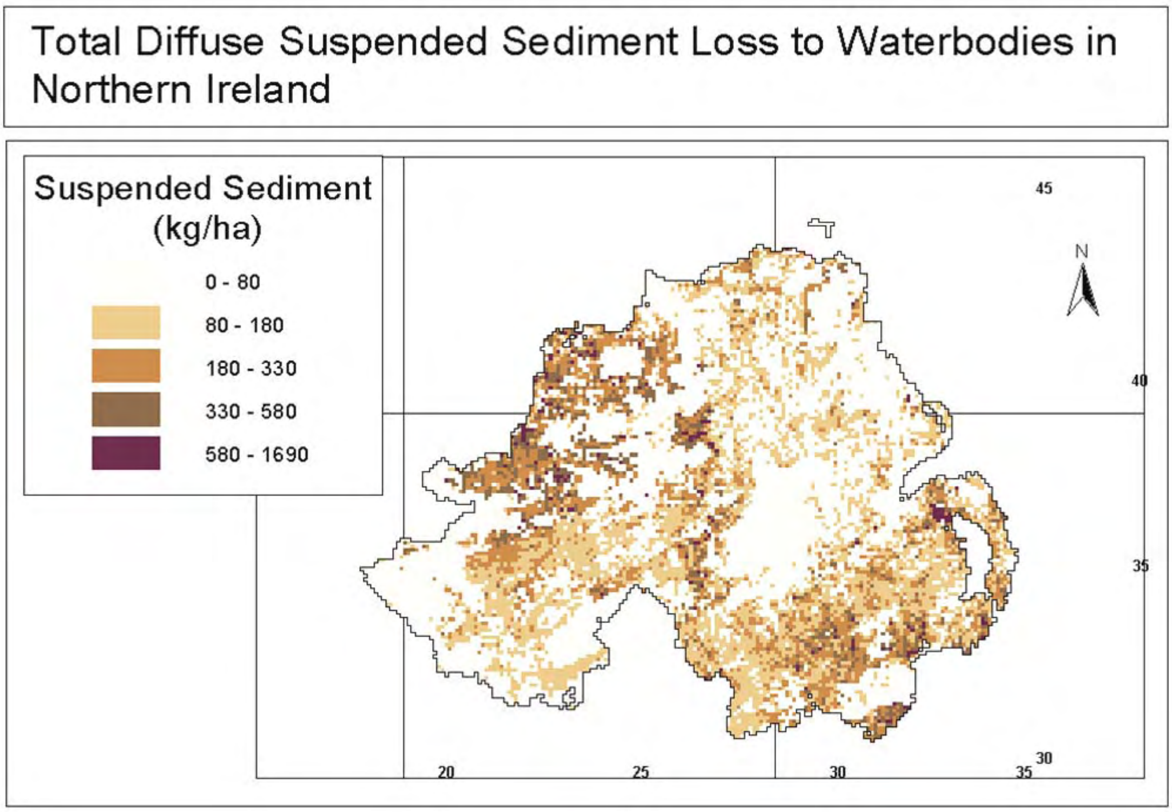
b)



c)


EROSION
Very High
High
Moderate
Low
Slight

d)


Total Diffuse Suspended Sediment Loss to Waterbodies in Northern Ireland
Suspended Sediment (kg/ha)
0 - 80
80 - 180
180 - 330
330 - 580
580 - 1690
N
45
40
35
30
20
25
30
35

preferentially transported, that is, the clay fraction and a proportion of the silt. The model was initially developed to predict phosphorous losses from lowland catchments. Since most of the uplands of Scotland and Northern Ireland have a more dissected topography and soils with organic surface layers, a model developed for lowland mineral soils may not be the most appropriate for these areas. Figure 3.13b shows output from the PSYCHIC model and a lack of sediment delivery to Scottish water bodies in upland areas.

The rule-based soil erosion risk map produced by Jordan *et al.* (pers. comm.) for Northern Ireland is perhaps more similar to that produced by Anthony *et al.* (2006), though the high-risk areas of the Mourne Mountains identified by Jordan *et al.* are predicted as having a low sediment yield in the Anthony *et al.* model output (Figures 3.13c and 3.13d).

3.4.3 Conclusion of national scale modelling

The PESERA model is relatively easy to parameterise using standard soil, climate, land cover and topographic data making it suitable for national scale risk assessment. The lack of data to validate the model means that it should be used to determine relative risk of erosion between regions, land uses and climate scenarios. It is able to predict changes in sediment yield given changes in land cover and climate and is sufficiently flexible that both land cover and climate change can be assessed simultaneously if required.

The land cover changes made during this assessment of the model were based on likely changes in land cover given changes in grazing pressure and grazers as a consequence of drivers of land use change and were taken from work done under Objective 5. Currently, these changes were applied across one dominant land cover type but could be regionalised (if more detailed information was available of predicted land use changes) by simple modifications to the input data for a group of grid cells.

The changes in the predicted climate for 2050 do show that the model can deal effectively with regional variation in climate change and the risk of increased erosion predicted for specific parts of the country. The lack of climate change data for Northern Ireland means that this aspect of the model could not be tested for the Province.

3.5 Catchment scale modelling

INCA, the Integrated Catchments model is a generic, catchment-scale biogeochemical modelling framework. INCA is semi-distributed and operates on a daily time step. Versions of the INCA model have been developed to simulate nitrogen dynamics (Whitehead *et al.,* 1998; Wade *et al.* 2002a), phosphorus (Wade *et al.,* 2002b), organic carbon (Futter *et al.,* 2007) and suspended sediments (Jarritt and Lawrence, 2005, 2007).

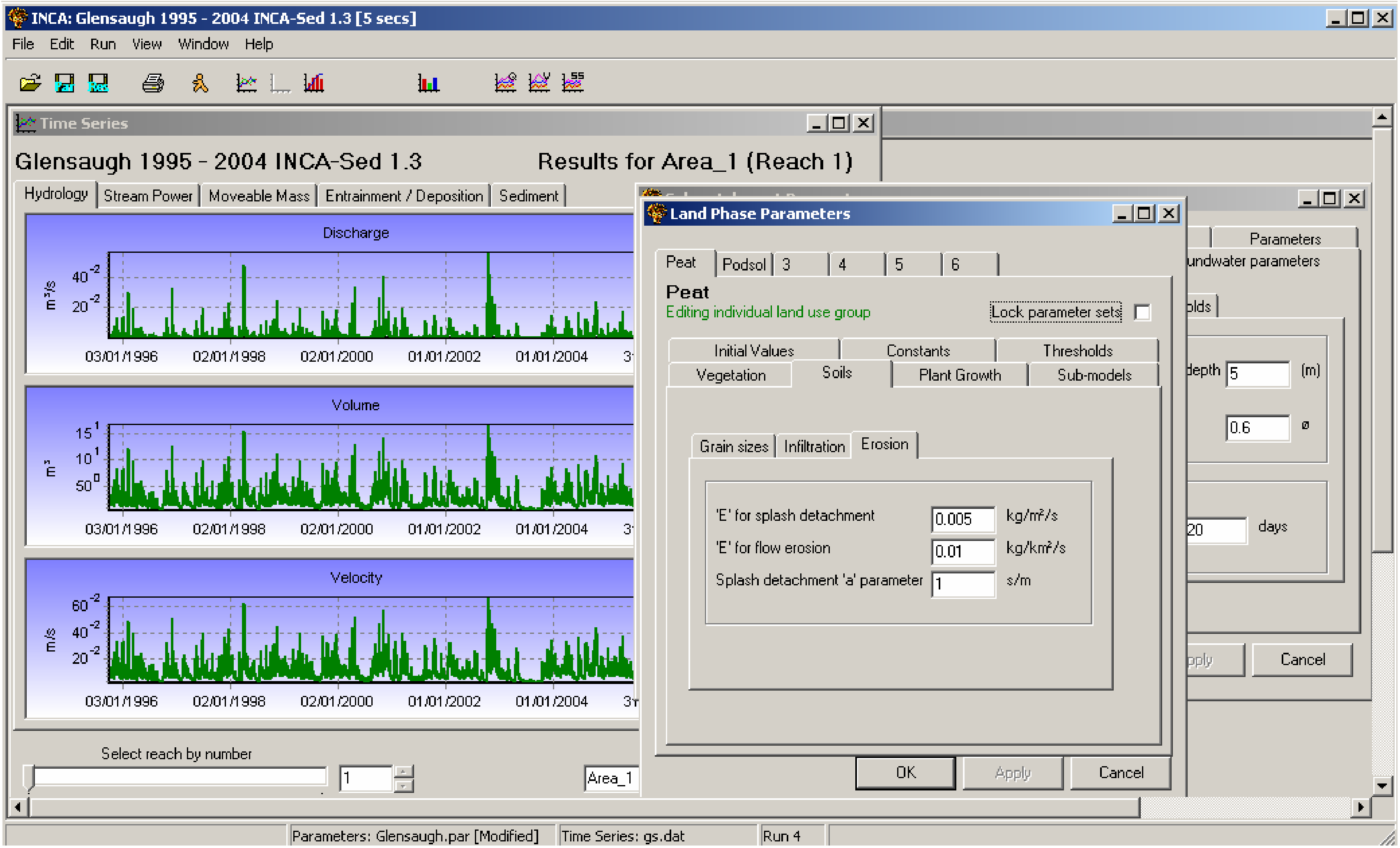
3.5.1 Modelling Dissolved and Particulate Organic matter fluxes using INCA

Here we evaluate the suitability of INCA-C and INCA-Sed for simulating fluxes of dissolved (INCA-C) and suspended solid (INCA-Sed) organic matter from catchments dominated by organo-mineral soils in Scotland. INCA-C has been used to simulate dissolved organic matter dynamics in forested catchments in Canada (Futter *et al.,* 2007) and Finland (Futter *et al.,* 2008). Published applications of INCA-Sed have only been made for lowland UK catchments (Jarrit and Lawrence, 2005, 2007). There have been unpublished applications to peat-dominated sites in Finland and the model is being applied to a number of other upland and lowland sites in the UK. This is the first application of INCA-C and INCA-Sed to an upland organo-mineral soil dominated catchment in Scotland.

The INCA modelling system runs under the MS-Windows computing environment on PC compatible computers. The modelling system consists of a user-friendly graphical interface (Figure 3.14), a data management system and a fourth-order Runge Kutta differential equation solver. All environmental processes in INCA are represented as a set of linked first order differential equations. The INCA model operates on a daily time step. There are plans to build a version of INCA in the future that will operate on arbitrary time steps.

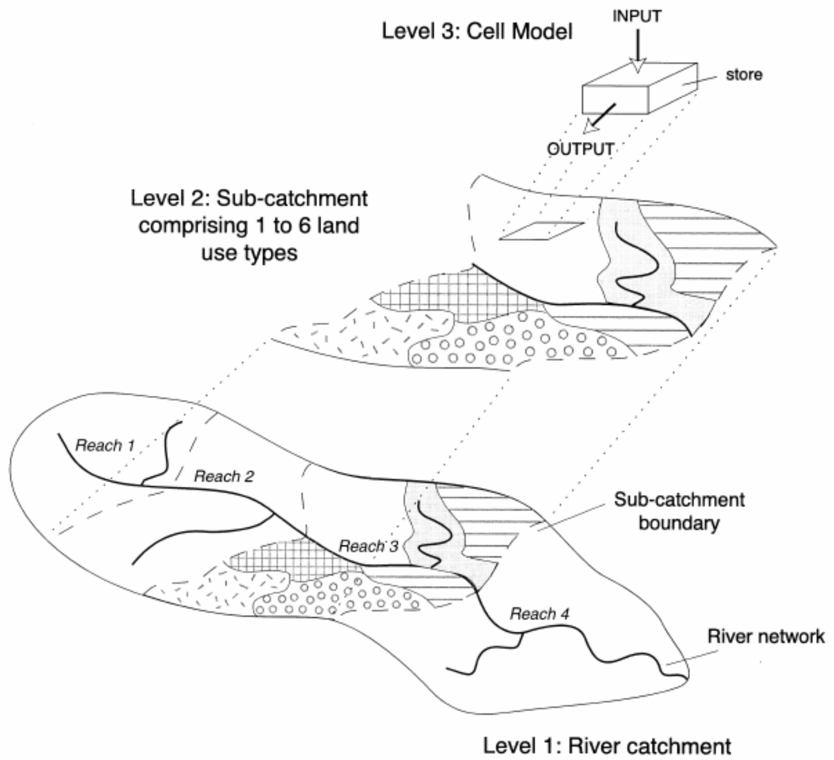
There are three levels to the landscape representation in INCA (Figure 3.15): the river catchment, the sub-catchment and a generic cell in which terrestrial biogeochemical and sediment processing occurs.

Figure 3.14 Screen-shot of the INCA user interface



INCA has limited data requirements. Estimates of catchment area, land cover, soil size classes and mean stream slope are requires to run the model. Information on vegetation cover and length of growing season will help to constrain model predictions. The model requires daily time series of temperature and precipitation. Time series of stream flow and solute concentrations (e.g. DOC, suspended sediments) are used in model calibration.

Figure 3.15 The INCA landscape model



Hydrologically effective rainfall (HER) and soil moisture deficits (SMD) are simulated using an external rainfall-runoff model. HBV (Bergström, 1995; Sælthun, 1996) is typically used for this purpose. In the UK, data on HER and SMD can be obtained from the MORECS system (http://www.metoffice.gov.uk/water/morecs.html).

Estimates of HER and SMD must be obtained from an external rainfall-runoff model. HBV (Sælthun, 1996) was used for this purpose. HBV is a conceptual rainfall-runoff model that has been extensively used in Finland and Scandinavia. In HBV, time series of precipitation and temperature and a description of the catchment are used to simulate daily flows, HER and SMD. The model is calibrated by adjusting parameters so as to minimize the difference between modelled and observed flow. The estimate of HER generated by HBV is the depth of water that may enter the soil on any given day. For the purposes of this application, HER is defined as the sum of precipitation and snowmelt minus losses to evaporation and evapotranspiration. SMD is the difference between the amount of water in the soil and its water holding capacity, expressed as a depth of water. Stream flows estimated in HBV are only used for model calibration. They are not used in DOC simulations as INCA is able to route HER through the catchment and provide estimates of stream flow.

3.5.2 INCA Land Phase Hydrological Model

Within INCA, direct runoff (overland flow) can be generated by two processes, which occur under very different soil moisture states: saturation from above ('Hortonian' or infiltration excess overland flow) and saturation from below (saturation excess overland flow). In the original INCA hydrological model, the input to the direct runoff zone (q_{dr}) is a proportion of the total soil zone flow (q_{sw}) when the soil zone flow exceeds a user-defined threshold soil zone flow above which direct runoff is generated (q_{sat}). Change in direct runoff flow is defined as follows in when q_{sw} exceeds q_{sat}.

$$\frac{dq_{dr}}{dt} = \frac{c_1 q_{sw} - q_{dr}}{T_1} \qquad [3.1]$$

where c_1 is the proportion of the soil zone flow that becomes direct runoff and T_1 is the residence time of water in the direct runoff (surface) zone.

The generation of saturation direct runoff ($q_{dr(Sat)}$) in INCA-Sed is changed such that the input to the direct runoff zone is equal to the soil zone flow *in excess* of the saturation threshold:

$$\frac{dq_{dr(Sat)}}{dt} = \frac{(q_{sw} - q_{sat}) - q_{dr}}{T_1} \qquad [3.2]$$

The input to the direct runoff zone includes only flow in excess of the saturation threshold, and the remaining soil zone flow does not exceed the saturation threshold. The proportion of the soil zone flow excess above the threshold that does not form direct runoff input is assumed to be lost to the filling of surface depressions and the subsequent evaporation of this water. The value of the soil zone saturation flow is related to the soil type. Appropriate values may be determined from the literature or through calibration.

Direct runoff can also be generated when the rate at which rain falls onto the ground surface exceeds the rate at which that water can be infiltrated into the soil. This is the Hortonian method of runoff generation. If such conditions exist, the rainfall in excess of the infiltration rate provides infiltration excess input ($q_{dr(Inf)}$) to the direct runoff:

$$\frac{dq_{dr(Inf)}}{dt} = \frac{c_2(p-i)-q_{dr}}{T_1} \qquad [3.3]$$

where p is the rainfall rate, i is the variable infiltration rate and c_2 is the proportion of the rainfall excess that becomes direct runoff. From the infiltration models above, the key relationships that determine the infiltration rate can be identified. The infiltration rate is directly proportional to the hydraulic conductivity of the soil and inversely proportional to the water content of the soil. On a daily time-step, the best available proxy for the water content at the soil surface is the sum of rainfall and snow melt on that day. The more rain or snow melt there has been, the wetter the soil surface will be and the lower the infiltration rate.

$$\frac{dq_{dr}}{dt} = \frac{(q_{sw}-q_{sat})+c_2(p-i)-q_{dr}}{T_1} \qquad [3.4]$$

In the event that q_{sw} is less or than or equal to $q_{sat,}$ change in direct runoff is equal to:

$$\frac{dq_{dr}}{dt} = \frac{c_2(p-i)-q_{dr}}{T_1} \qquad [3.5]$$

The time-varying infiltration rate (i) is expressed as follows:

$$i = \frac{I}{86.4}\left(1-e^{-\frac{86.4\cdot p}{I}}\right) \qquad [3.6]$$

where I is maximum infiltration rate for a given soil type. This parameter is allowed to vary in each sub-catchment.

The change in diffuse flow from the upper soil box is equal to the hydrologically effective rainfall (U_4) minus upper soil box diffuse and saturation excess flows divided by the organic layer water storage time constant:

$$\frac{dq_O}{dt} = \frac{U_4 - q_D - q_O}{T_O} \quad [3.7]$$

Change in diffuse flow from the lower soil box compartment (q_m) is equal to the rate of inflow from the upper soil box (βx_2) minus the volume of water diffusing from the lower soil box to the open water (x_3) divided by the mineral layer water storage time constant (T_m).

$$\frac{dq_M}{dt} = \frac{\beta \cdot q_O - q_M}{T_M} \quad [3.8]$$

3.5.3 Sediment Delivery Model - Land Phase

The land phase of the sediment delivery model entails four processes:

1) generation of sediment through splash detachment of soil;

2) transport capacity of direct runoff;

3) erosion capacity of direct runoff; and,

4) a mass balance accounting of the sediment store on the sub-catchment slopes.

3.5.3.1 Splash detachment

Fully processed-based equations for splash detachment of soil particles use the energy or momentum of the rainfall in their calculation. In order to effectively include this in a model it is necessary to include equations to describe the interception of rainfall by vegetation, the cover of vegetation on the ground surface, and also have rainfall intensity, rather than total rainfall data available as a model input. This complexity, however, would impose excessive data demands. Within INCA-Sed the splash detachment (S_{SP}) is modelled as a function of precipitation (p), a scaling parameter, (c_{x1}), a soil erodibility parameter linked to soil type, (E_{SP}) and an effective vegetation cover index linked to growing season and land use (V'):

$$S_{SP} = c_{x1} p E_{SP}^{\,V'} \cdot 8.64 \cdot 10^{10} \quad [3.9]$$

The effective vegetation cover (V') is determined from the vegetation cover index (V) and the day of year. The rainfall input in the INCA-Sed model is the total rainfall for each day. This is converted for use in the equations from a depth total (mm) to a flow rate per square meter (m^3. s^{-1}. m^{-2}). Therefore, although the rainfall input to the splash detachment equation is expressed as a rainfall intensity, it is wholly derived from daily rainfall rather than representing the true intensity of rainfall during storm events. The rainfall intensity is moderated by interception by canopy and litter covers, and these factors are accounted for by the vegetation cover index, *V*. The soil erodibility parameter, *E,* can be based either on experimental measurements for a given soil, or it can be estimated from soil texture using published methods.

3.5.3.2 Flow erosion

Flow erosion (S_{FL}) is modelled as a function of the potential of a soil to be mobilised through flow erosion (E_{FL}), mass of sediment mobilised through splash detachment (S_{SP}) and the sediment transport capacity (S_{TC})

$$S_{FL} = \frac{K}{\left(1+\frac{K}{S_{TC}}\right)}\left(1-\frac{S_{SP}}{S_{TC}}\right) \quad [3.10]$$

where K is equal to the following:

$K = a_1 E_{FL}\left(\frac{Aq_{DR}}{L} - a_2\right)^{a_3}$, where a_1 and a_2 are catchment calibration parameter, L is the reach length, A is the catchment area and qDR catchment direct runoff discharge.

3.5.3.3 Direct runoff transport capacity

The transport capacity of surface runoff is of critical importance in the modelling of sediment delivery. Within INCA-Sed, the sole pathway for sediment delivery from the catchment slopes to the river channel is direct runoff. The transport capacity of this runoff is the maximum rate at which sediment can be delivered to the channel, independent of any other process operating on the catchment slopes.

In all of the published equations for overland flow sediment transport, the transport capacity is related to a flow quantity (e.g. stream power or boundary shear stress) *in* *excess* of some critical value of that quantity. In developing a transport capacity equation for INCA-Sed, the data available to drive the equation again constrain its form. The hydrological model calculates the direct runoff discharge. In order to calculate any other flow quantity to use in a transport capacity equation such as stream power or shear stress, a further equation would be needed to relate this flow quantity to the discharge. Since INCA-Sed is not a fully distributed model, there is no topographical information available and no spatial information about the direct runoff flow, such as flow length or width. It is therefore not possible to derive other flow information from the direct runoff discharge using physical characteristics. An equation to achieve this would therefore be empirical and include a number of parameters for which there would be no reliable method of calibration. The key relationship that needs to be incorporated is the link between direct runoff discharge and transport capacity (S_{TC}). The discharge, as moderated by the sub-catchment geometry, is therefore being used as an available proxy for flow quantities more directly related to transport, such as stream power or shear stress:

$$S_{TC} = a_4 \left(\frac{Aq_{dr}}{L} - a_5 \right)^{a_6} \quad [3.11]$$

where a4, a5 and a6 are calibration parameters. The direct runoff discharge qdr is multiplied by the sub-catchment area divided by the reach length. In two sub-catchments with the same physical properties under the same input data the direct runoff discharge per square meter of sub-catchment will be identical. If the overall shape of the sub-catchment differs, however, the transport capacity of the direct runoff for each sub-catchment will be different.

3.6 INCA Carbon Model

INCA-C, the Integrated Catchments model for Carbon, is a dynamic, daily time-step, semi-distributed catchment scale process-based model of the effects of climate on DOC in surface waters (Futter *et al.,* 2007). It is based on INCA-N (Wade *et al.,* 2002a), which was developed to simulate nitrogen fluxes in European rivers. Because INCA-C is semi-distributed, multiple sub-catchments can be modelled. When sufficient data are available on catchment land cover and soil properties, or if DOC and flow data are available at multiple points within the catchment, the overall catchment can be split and modelled as a series of sub-catchments (Figure 3.15). Up to six different user-specified land-cover classes can be simulated in INCA-C. Within each land cover class, the soil is represented as a litter layer and two vertically stacked soil boxes. Water is routed directly from each land-cover class to surface water. There is no exchange of water or carbon between land-cover classes within a sub-catchment.

INCA-C simulates mass and flux of solid organic (SOC), dissolved organic (DOC) and dissolved inorganic carbon (DIC) in soils and surface waters. Breakdown of litter and root material contribute SOC and DOC to the upper soil box. Sorption and desorption processes transform organic carbon between DOC and SOC. Mineralization transforms SOC and DOC to DIC. DIC is lost to the atmosphere through degassing. DOC and DIC are transported advectively by water movement from the upper to lower soil boxes and from the soil to surface waters

INCA-C models carbon transformations in soils and surface waters as a series of first-order processes. All in-soil rate coefficients are dependent on soil temperature and moisture status. The effect of soil temperature on the rate coefficients in INCA-C is simulated using a Q_{10} type model and the rate coefficient for the effect of soil moisture is a linear function of soil moisture content. The processes operate at a maximum rate when the simulated SMD is equal to zero. Processes cease when the SMD is greater than SMD_{Max}, a calibrated threshold representing the maximum soil moisture deficit at which carbon processing may occur. The following shows the effects of soil temperature (T_{Soil}) and SMD on the change in mass of DOC in a soil box caused by sorption and desorption. The effect of soil temperature on the rate of carbon processing is simulated using a calibrated Q and modelled soil temperature (T_{Soil}). The effects of soil moisture are simulated using daily values of SMD and a calibrated SMD_{Max}. The base rates of desorption (k_D) and sorption (k_S) are estimated during the calibration process.

$$\frac{dDOC}{dt} = Q^{(T_{Soil}-20)}\left(\frac{SMD_{Max} - \min(SMD, SMD_{Max})}{SMD_{Max}}\right)(k_D SOC - k_s DOC) \qquad [3.12]$$

DOC is lost from the open water through a combination of microbial and photo-mineralization. In open water, the DOC photo-mineralization rate is simulated as a function of incident solar radiation (R) and surface water [DOC]. The photo-mineralization rate is a linear function of solar radiation. As high surface water [DOC] can lower rates of photo-mineralization, actual rates of photo-mineralization are calculated by multiplying the potential rate by 'a' the [DOC]-dependent self-shading factor, *a/(a+[DOC])*. The following shows the rate at which [DOC] changes in surface waters as a function of microbial (k_B) and photolytic (k_M) decay coefficients.

$$\frac{d[DOC]}{dt} = -\left(k_B + k_P R\left(\frac{a}{a+[DOC]}\right)\right)[DOC] \qquad [3.13]$$

3.7 Catchment scale modelling results

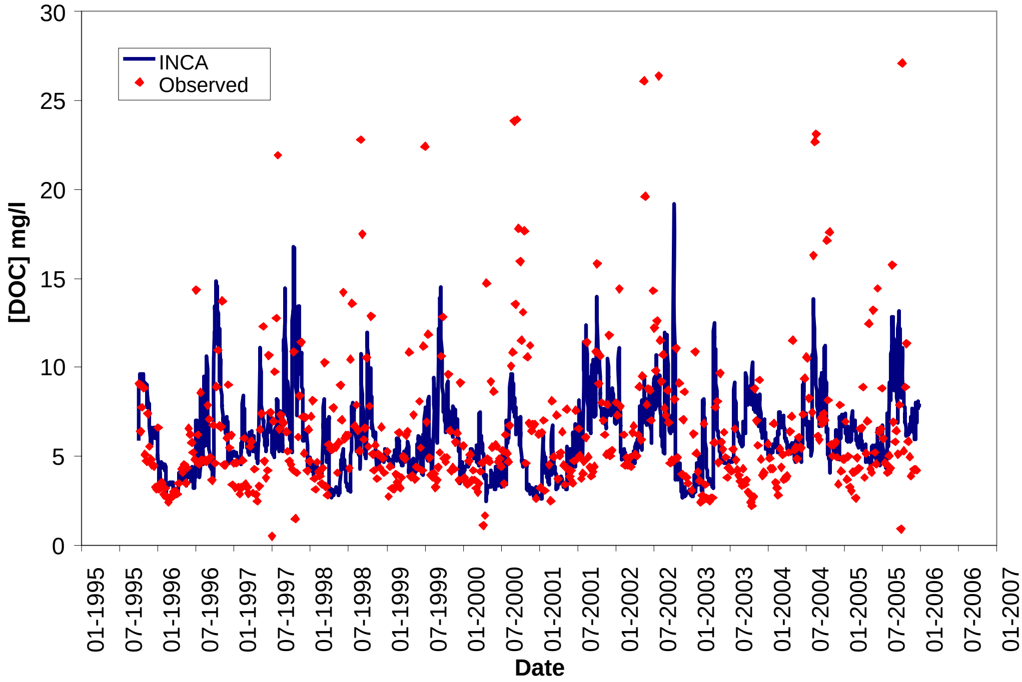
3.7.1 INCA-C simulations

The INCA-C and INCA-Sed models were run to simulate present day DOC (Figure 3.16) and suspended sediment (Figure 3.17) concentrations in the stream at Glensaugh.

The INCA-C model was able to provide a reasonable fit to the observed data (r^2=0.4, median absolute deviation=1.5 mg C/l, root mean square error=2.4 mg C/l). The model provided a better fit to the periods when DOC concentrations were low. It consistently under-predicted high DOC concentrations observed during the late summer and early autumn. This may be an artefact of the calibration strategy. As each observation is weighted equally and there are many more observations at low DOC concentrations, the model calibration strategy would tend to have poorer fits to the relatively fewer high DOC values. It is also possible that the high DOC values in the late summer and early autumn are being driven by processes occurring in the riparian zone. As INCA-C is a catchment scale model, it may not adequately represent these processes.

A sensitivity analysis of the INCA-C calibration suggested that model predictions were sensitive to soil moisture conditions. Less DOC was produced under drier conditions than when soils were wet. The effects of soil temperature on DOC production were less apparent. This may be due to the relatively small variability in seasonal soil temperatures between years when compared to the variability in soil moisture.

Figure 3.16 Observed and INCA-C simulated dissolved organic carbon concentrations at Glensaugh



The UKCIP02 2050 high emissions scenarios project an average annual temperature increase in Scotland of between 1.5 and 2.0^{0} C (http://www.ukcip.org.uk/images/stories/Scenarios/seasons/temp_annual.gif). Annual average precipitation is projected to decline by approximately 10% in the eastern part of the country and remain within the bounds of natural variability in the west (http://www.ukcip.org.uk/images/stories/Scenarios/seasons/prec_annual.gif).

Five climate-change scenarios based on the UKCIP 2050 high emissions scenarios were explored (Tables 3.7 and 3.8). In each case, the scenario was based on the delta-shift method, where temperature or precipitation data from an observed climate time series were modified. This was done as time did not permit a full climate down-scaling exercise at Glensaugh and because the aim of this exercise was to show sensitivities to potential climate change scenarios. The five scenarios evaluated were warmer (+2 ^{0}C, no change in precipitation), wetter (no change in temperature, precipitation increased by 20%), drier (no change in temperature, precipitation decreased by 20%), warmer and wetter (+2 ^{0}C, precipitation increased by 20%) and warmer and drier (+2 ^{0}C, precipitation increased by 20%).

Model predictions were more sensitive to changing precipitation scenarios than to temperature (Figures 3.19 and 3.20). Drier conditions resulted in higher winter [DOC] early in the year and lower concentrations in late summer and autumn. The reverse pattern was observed for wetter projected conditions, where lower concentrations were simulated in the early months of the year and higher concentration in the later months. Organic carbon fluxes (not shown) are projected to be higher under the wetter scenarios as a result of higher flows. The lower [DOC] simulated in the early part of the year under the increased precipitation scenario are the result of increased flushing. The higher autumn concentrations are a result of increased production in the soil. It should be noted that in the warmer temperature, no change in precipitation scenario, concentrations of dissolved organic carbon were projected to decline in all months except October and November.

Table 3.7 Average monthly [DOC in mg l^{-1}] under warmer (+2 ^{0}C), wetter (20%) and drier (-20%) conditions. Changing moisture regime has a more pronounced effect on [DOC] than does temperature.

Month	Base	Dry	Warm	Warm Dry	Warm Wet	Wet
January	6.11	6.28	6.04	6.22	5.88	5.96
February	6.06	6.34	5.95	6.25	5.69	5.81
March	6.31	6.65	6.18	6.53	5.85	5.98
April	5.39	5.69	5.19	5.48	4.90	5.11
May	5.61	5.88	5.35	5.61	5.09	5.34
June	5.74	5.84	5.45	5.54	5.35	5.62
July	6.70	6.48	6.50	6.25	6.78	6.94
August	8.74	7.82	8.65	7.66	9.67	9.70
September	9.70	8.93	9.67	8.88	10.44	10.44
October	10.49	9.87	10.64	10.01	11.40	11.22
November	8.04	7.86	8.09	7.92	8.39	8.33
December	6.92	7.00	6.90	7.00	6.85	6.88

Table 3.8 **Deviations (DOC in mg l^{-1}) from monthly average modelled values under changing temperature and precipitation regimes. Regimes tested included warmer (+2 ^{0}C), wetter (+20%), drier (-20%) and combinations of changed temperature and moisture.**

Month	Base	Dry	Warm	Warm Dry	Warm Wet	Wet
January	0	0.17	-0.07	0.12	-0.23	-0.14
February	0	0.28	-0.11	0.18	-0.38	-0.25
March	0	0.34	-0.13	0.22	-0.46	-0.33
April	0	0.30	-0.20	0.09	-0.49	-0.28
May	0	0.27	-0.26	0.00	-0.52	-0.27
June	0	0.11	-0.29	-0.19	-0.39	-0.12
July	0	-0.22	-0.20	-0.45	0.08	0.25
August	0	-0.92	-0.09	-1.08	0.94	0.96
September	0	-0.76	-0.03	-0.82	0.74	0.74
October	0	-0.62	0.16	-0.48	0.91	0.73
November	0	-0.18	0.05	-0.12	0.35	0.29
December	0	0.08	-0.02	0.08	-0.07	-0.04

3.7.2 INCA-Sed simulations

By contrast with INCA-C, the INCA-Sed simulation results are driven largely by precipitation regime only. The model can be driven either by observed precipitation or hydrologically effective rainfall (Figure 3.17). All INCA-Sed simulations presented here were driven by observed precipitation.

As INCA-Sed is relatively insensitive to temperature, temperature scenarios were not explored. The model is sensitive to changing land use, land cover and precipitation. The baseline simulation is shown in figure 3.18.

Three scenarios were evaluated: (i) increased susceptibility to erosion, (ii) increased precipitation and (iii) drought. In the first scenario, the parameter representing effective vegetation cover, *V'*, was changed from 10 (representing complete cover) to 0 (representing bare soil). In the increased precipitation scenario, observed precipitation values were multiplied by 1.2. In the drought scenario, observed precipitation values were multiplied by 0.8.

Figure 3.17 Daily precipitation (black, thin line) and hydrologically effective rainfall (HER) (grey, thick line) at Glensaugh for the period of simulation.
HER is defined as the rainfall (or snow melt) that contributes to stream flow. The INCA-Sed simulation presented here have been driven by actual precipitation

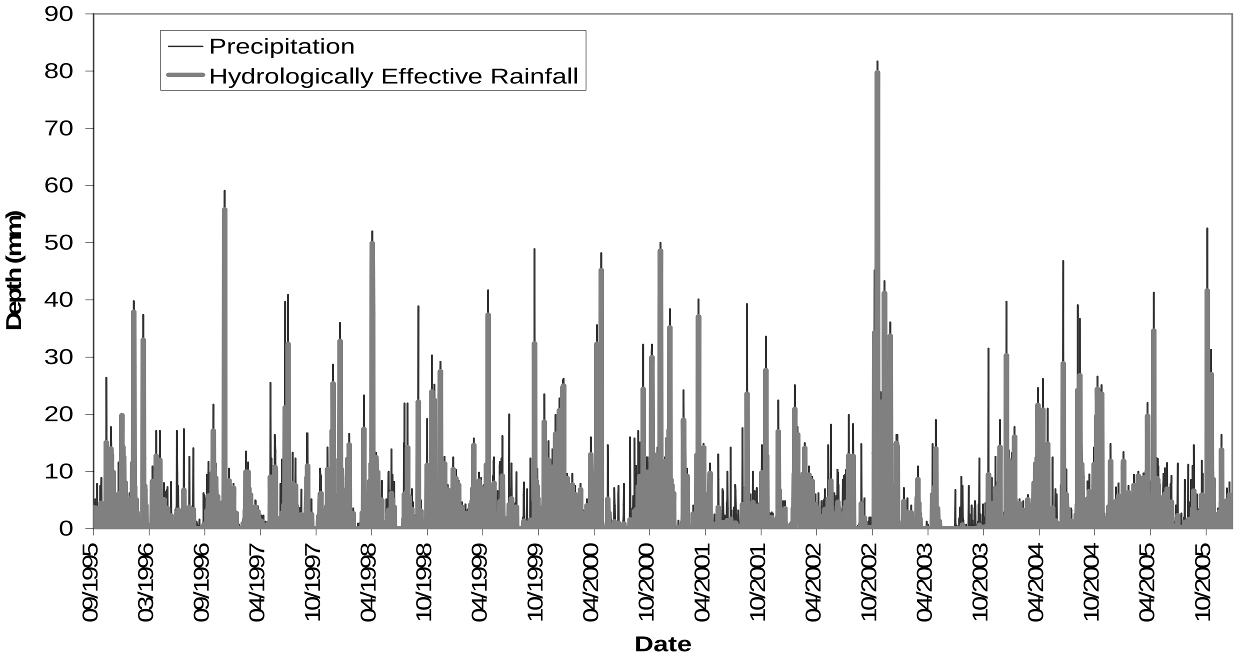
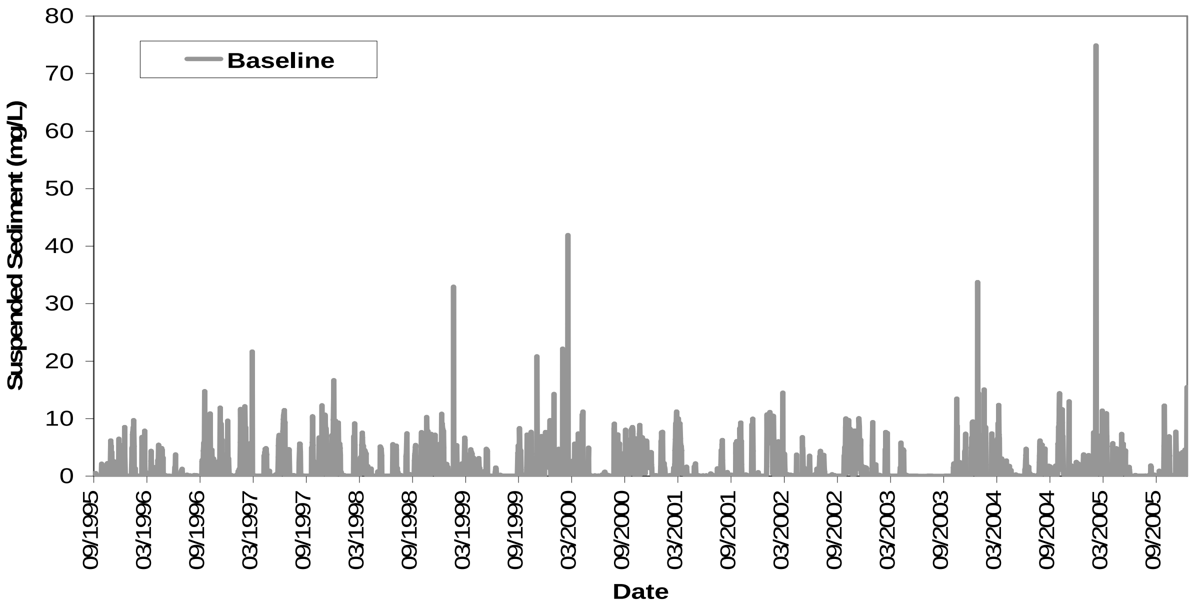


Figure 3.18 Baseline simulations of in-stream suspended sediment concentrations at Glensaugh



When compared to the baseline scenario (Figure 3.18), increasing susceptibility to flow erosion in the catchment, as a result of increased stocking density or human traffic, leads to greater sediment export at low flows and higher peaks in suspended sediment concentrations.

<u>Scenario 1</u>	=	increased susceptibility to flow erosion (Figure 3.19)
<u>Scenario 2</u>	=	increased precipitation - increased flows lead to higher peak concentrations but little change in low flows (Figure 3.20)
<u>Scenario 3</u>	=	decreased precipitation - under the reduced precipitation scenario both peak and base flow suspended sediment concentrations decline (Figure 3.21)

Figure 3.19. Plot showing the effects of increased erosion susceptibility and baseline simulated conditions. Increased susceptibility to erosion was simulated by removing vegetation cover in the model. Overall, this lead to a 60% increase in suspended sediment concentrations and a 47% increase in flux.

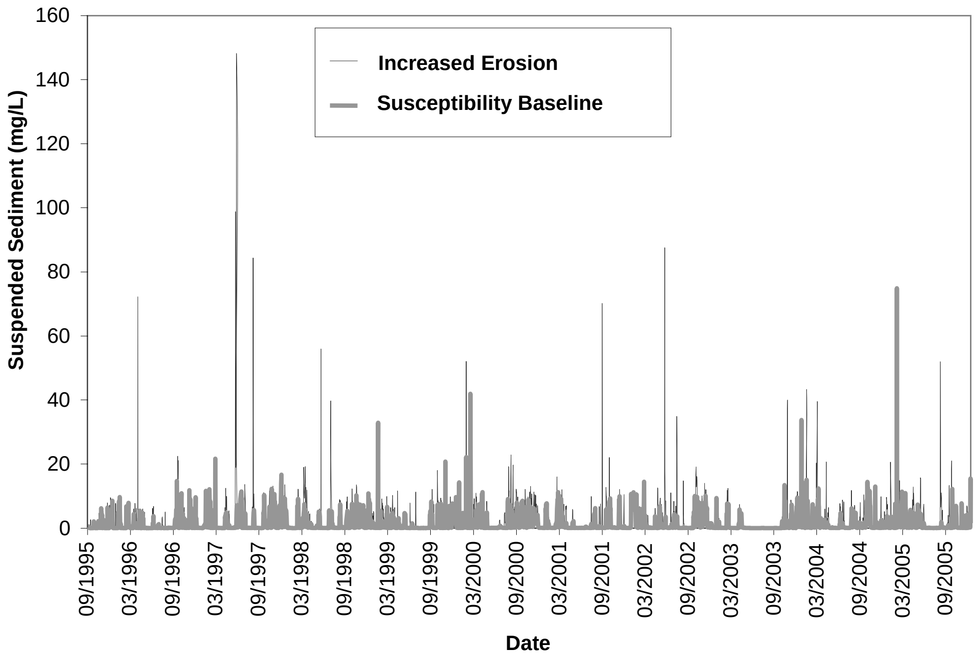


Figure 3.20 Simulation showing the effects of wetter conditions (20% increase in precipitation) versus baseline simulated conditions. On average, wetter conditions lead to a 90% increase in suspended sediment concentrations and a 225% increase in flux.

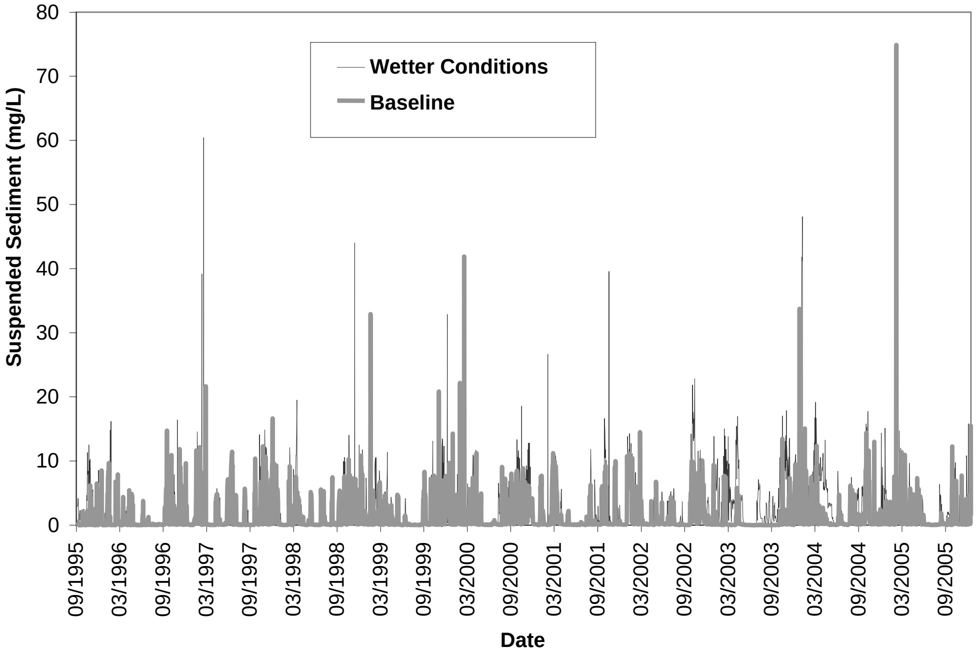
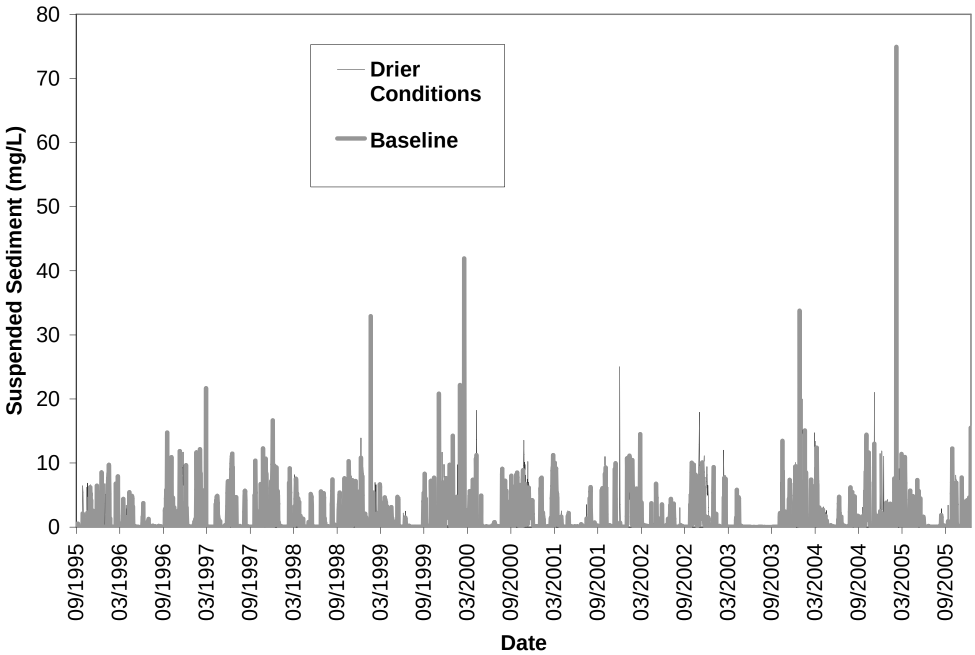


Figure 3.21 Simulation showing the effects of drier conditions (20% decrease in precipitation) versus baseline simulated conditions. On average, drier conditions lead to 25% decreases in both simulated suspended sediment concentrations and fluxes.



3.8 Conclusions to catchment scale modelling

The preliminary applications of the INCA-C and INCA-Sed models presented here show some promise for understanding the patterns of export of organic matter from organo-mineral soils in Scotland. INCA-C is able to reproduce some of the observed dynamics of dissolved organic carbon fluxes from catchments dominated by organo-mineral soils. The INCA-Sed model is able to simulate sediment transport, but model interpretation is has been hampered by a lack of observed sediment data.

The climate change scenarios presented here suggest that changing climate will alter the flux of both dissolved and particulate organic carbon from catchments dominated by organo-mineral soils. Increasing temperature may have little direct effect on particulate or dissolved organic carbon export, but changes in precipitation may have large effects. Fluxes of both particulate and dissolved organic carbon are correlated with precipitation. Increased precipitation will result in increased fluxes. Declining precipitation will lead to less export of both particulate and dissolved organic carbon from catchments dominated by organo-mineral soils.

CHAPTER 4

Estimating rate of change of carbon content at national-scale

Objective 4

Identify means of assessing and quantifying the response of peat and organo-mineral soils to the effects of climate change scenarios (e.g. land use change and change in climatic factors; temperature, precipitation and storm frequency).

4 ESTIMATING RATE OF CHANGE OF CARBON CONTENT AT NATIONAL - SCALE

4.1 Introduction

Currently there is contrasting evidence of changes in organic carbon status of soils in the UK (Bellamy et al., 2005; Black et al., in prep.). Bellamy et al. (2005) found a significant negative linear correlation between the rate of change in organic carbon and the original measurements of carbon (Co, g kg-1) in soils sampled as part of the National Soils Inventory England & Wales. However, analysis of data generated during the re-sampling of the UK Countryside Survey would suggest that these losses have been over-estimated (Black *et al.*, in prep.).

4.2 Methods

The equation published by Bellamy *et al.* (2005) has been applied to the surface horizon carbon value in the National Soils Inventory and spatial data in both Scotland and Northern Ireland (Equation 4.1). It should be noted that the equations developed in Black *et al.* were unavailable for this study as this publication was still under review at the time of writing.

$$\frac{\delta C}{\delta t} = 0.6 - 0.0187 C_o \qquad (4.1)$$

Where δC represents change in concentration of carbon (g kg^{-1}), δt represents change in time (yr^{-1}).

Equation 4.1 was applied to the National Soils Inventory data (Figure 4.1) which are collected from sites distributed on a regular 10km grid across Scotland. Estimates of rate of change of carbon (g kg^{-1} yr^{-1}) are presented in Figure 4.2.

Equation 4.1 was also applied to spatial data in the form of soil map units. Figure 4.3 represents the mean carbon content of the dominant soil series in each of the 1: 250 000 soil map units. In some map units, using the mean value is highly representative of the entire area, whereas in many of the more heterogeneous landscapes, it can be as low as 35%. Nevertheless there is a good correspondence between the pattern displayed by the NSI point data (which represent hard data) and that from the soil maps (which represent summary data). The same equation has been applied to these values to produce the predicted carbon loss maps and again there is a good correspondence with the NSI plots (Figure 4.4). The same exercise was repeated for the Northern Ireland data (Figures 4.5 to 4.8).

It must be stressed that the original Bellamy *et al.* paper did not identify the driver nor the mechanism (e.g. decomposition or erosive processes) for these losses and therefore care must be taken not to ascribe these predictions to erosive processes. The maps simply represent the extrapolation of the findings in England and Wales to Scotland and Northern Ireland where highly organic soils occupy a larger proportion of the land surface than in England. If soil carbon loss does manifest itself in this way, the depletion in terrestrial carbon in the UK would be serious.

Other studies have questioned the findings of the Bellamy *et al.* paper. Smith *et al.* (2007) used modelling which indicated that climate change cannot be responsible for that level of soil carbon loss and further suggested that sampling technique, analytical method and bulk density might contribute to the uncertainties associated with estimates of, and changes to soil carbon stocks. Potts *et al.* (in press) discuss some of the statistical analyses in addition to soil analytical uncertainties.

The highest predicted losses, say in a soil with an original C content of 500 g kg^{-1} (50%), is of the order of 9.00 g kg^{-1} yr^{-1} whereas soils with a low original C content of 30.0 g kg^{-1} (3.0%) are predicted to gain carbon. It is important to highlight that all soils have been included in these analyses – i.e. mineral soils as well as organo-mineral and organic soils. Mineral soils were included by way of comparison, and it can be seen that predicted carbon losses are significantly greater in the organo-mineral and organic soils compared to the mineral soils. Further, it should be noted that the approach of Bellamy *et al.* (2005) assumes that the rate of change of carbon content (g kg^{-1} y^{-1}) is a constant. Thus the inference could be made that soil carbon should decline in a linear fashion and at a constant rate. This is unlikely to be the case, with the erosion of carbon being associated with climatic trends, likelihood of extreme weather events, and land management such as pressures from grazing.

Initial findings from the first phase of resampling of the National Soils Inventory of Scotland (NSIS) has not found such large decreases in the C content of organic soils. These results should be viewed as preliminary as more data analyses are required and they only pertain to that part of Scotland to the east of the Great Glen and to the north of the Firth of Tay.

These preliminary findings concur with those summarised by Carey *et al.* (2008). Between 1998 and 2007 there was a decrease in the average carbon concentration of the soil (0-15cm depth) across Great Britain. This followed an increase from 1978-1998. Overall, there was no significant change in carbon concentration in soil (0-15cm) between 1978 and 2007. With particular reference to ‘bog soils’, a small decrease was observed but very small compared to the losses reported by Bellamy *et al*. (2005). By way of contrast, in a recent comparison of topsoil carbon contents between 1995 and 2005 at the 5km locations in Northern Ireland a general increase of 12% across all soil types was found (the figure for organic soils was slightly higher, but based on a relatively small comparison number).

The ECOSSE project report (Scottish Executive 2007b) highlighted the current uncertainties of what the effects that the change from semi-natural, extensively grazed vegetation to forestry on organo-mineral soils might be. They summarised these as follows:

- There have been few directly relevant studies of the effects on soil organic carbon stocks of afforestation of organo-mineral soils, so all conclusions about the likely effects of land use change to forestry are inferential from related studies on UK peatlands and studies from abroad.
- It is not possible yet to identify likely effects on soil organic carbon stocks down to individual soil types or even broad categories of freely and non-freely drained soils.
- The overall conclusion (as assumed by UK carbon balance models) is that afforestation probably has little net effect on soil organic carbon stores in organo-mineral soils, but this is a very uncertain statement.

The main areas of uncertainty for organo-mineral soils are:

- What is the net effect on the soil organic carbon store of planting and disturbance versus subsequent carbon capture by trees and inputs to soil as litter?
- What effects does forest harvesting have on soil organic carbon stores?
- To what extent is the gain in soil organic carbon from litter deposited at the soil surface offset by any loss of pre-existing soil organic carbon from the subsoil?
- How much of the carbon captured by trees and deposited as litter finds its way into the “stable” soil organic carbon store?
- What are the effects of different species and forest management regimes (e.g. continuous cover forestry vs. conventional patch clearfell) on soil organic carbon storage?

The ECOSSE report also contains a review of the impacts of agricultural management on organic soils, the soil C losses that have occurred as a result and provides a summary of good management practices to help minimise C losses. Most of the more damaging activities such as ploughing, fertilising and liming rarely take place on Scottish and Northern Irish organic soils, with grazing and burning the more common land use practices. These activities, however, were part of standard forestry practice until about 1990, when less intrusive techniques were encouraged.

The ECOSSE model does not include a component to assess soil C losses due to physical detachment and subsequent transport (the subject of this report). Its components comprise modules that contain routines describing soil C and N turnover (initialisation, additions, microbial and physical processes), crop processes (growth, N demand and return of C and N in debris), and the soil water processes (drainage and evapotranspiration). It therefore seeks to model inputs and offtakes of soil C by other processes.

Soil carbon stocks under forestry are also part of a major review being carried out by the Forestry Commission (C. MacCulloch pers. comm.) and due to report in early 2009, indicative of the high level of interest in soil carbon stocks in relation to climate change mitigation strategies.

Figure 4.1 Topsoil organic carbon content (g kg^{-1}) at National Soils Inventory for Scotland sample locations

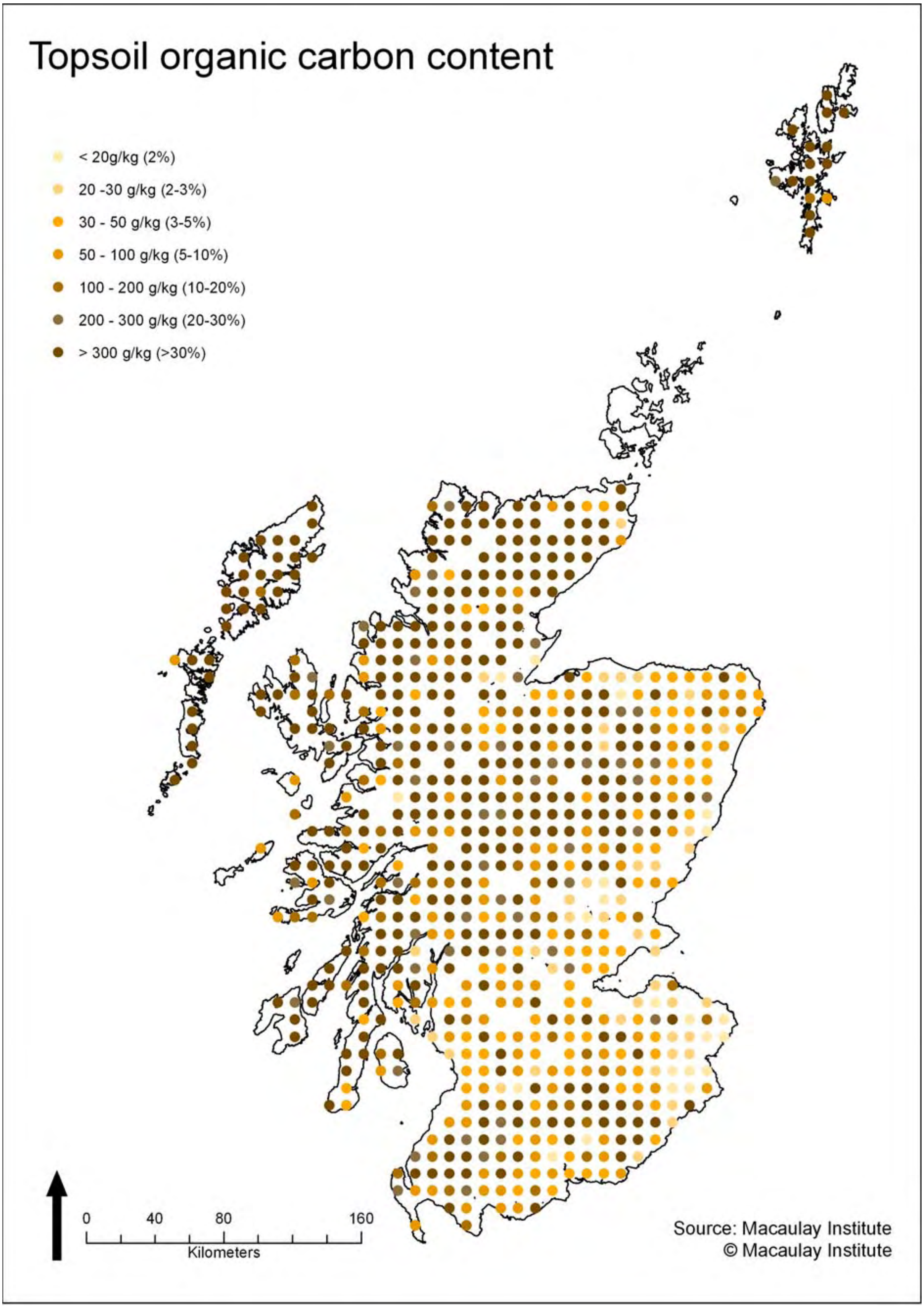


Figure 4.2 Estimated rate of change (g kg^{-1} yr^{-1}) of topsoil carbon derived from applying Equation 4.1 to the data presented in Figure 4.1

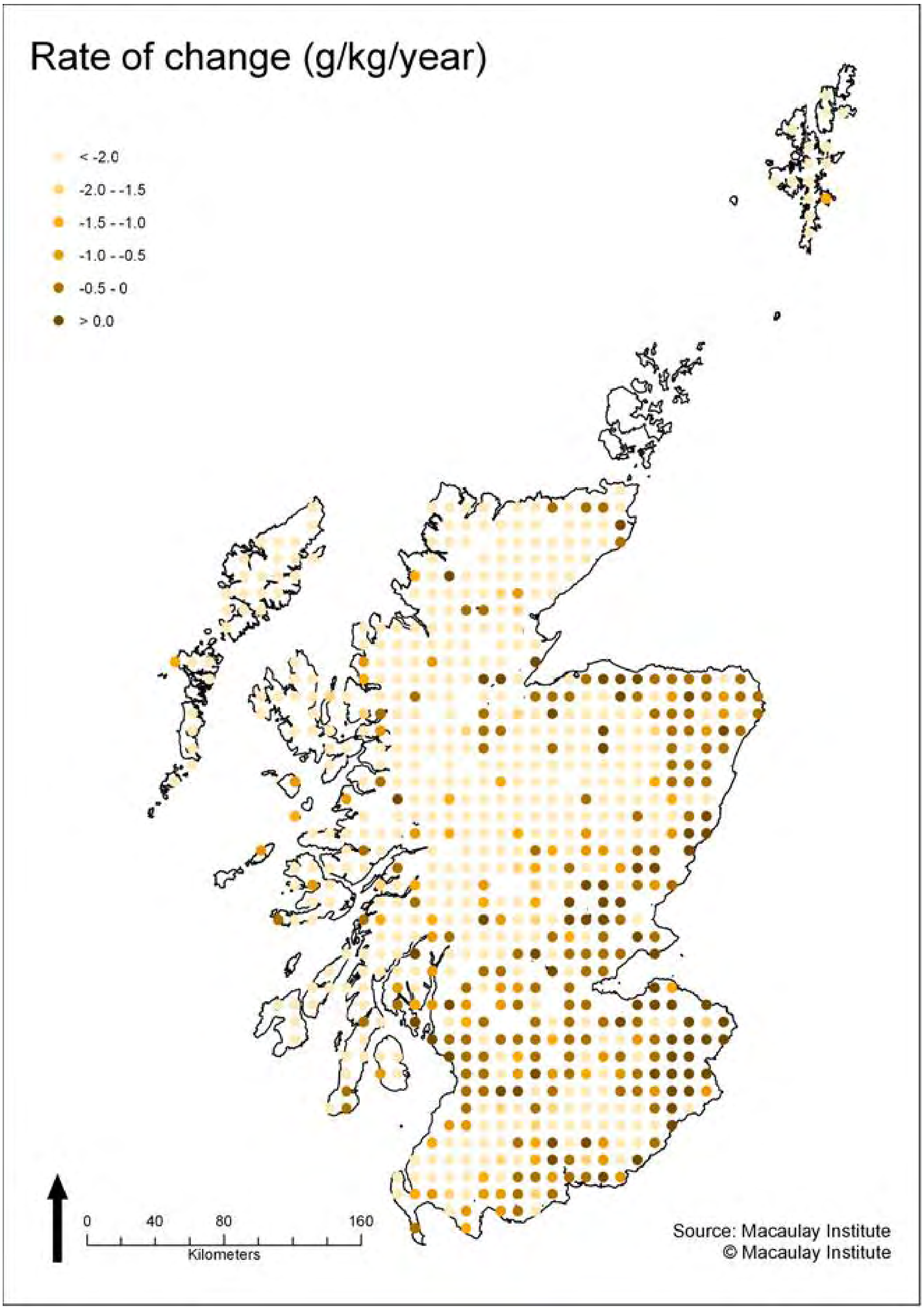


Figure 4.3 Mean carbon content (g kg^{-1}) of the dominant soil series in each of the 1: 250 000 soil map units

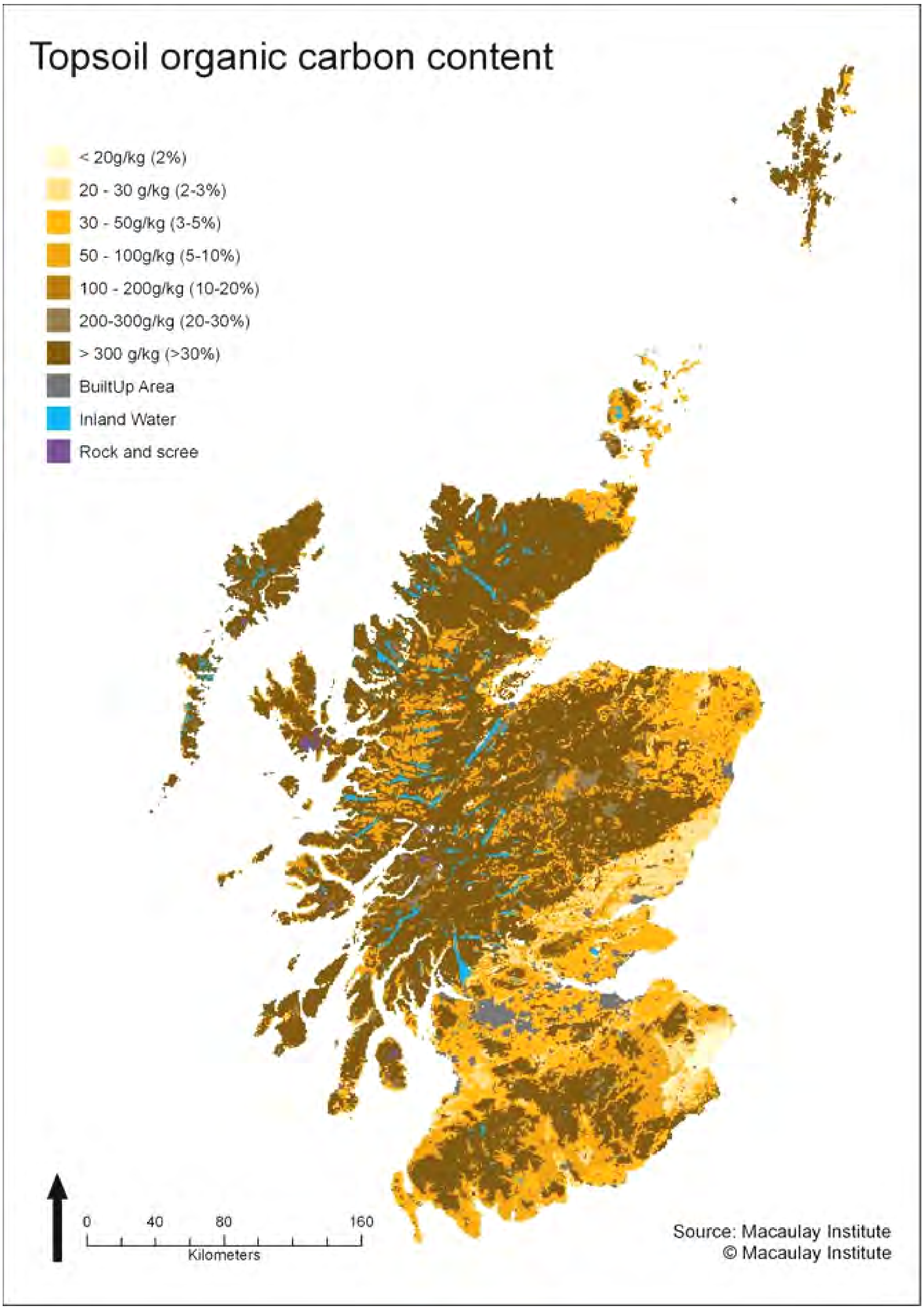


Figure 4.4 Estimated rate of change (g kg^{-1} yr^{-1}) of topsoil carbon derived from applying Equation 4.1 to the data presented in Figure 4.3

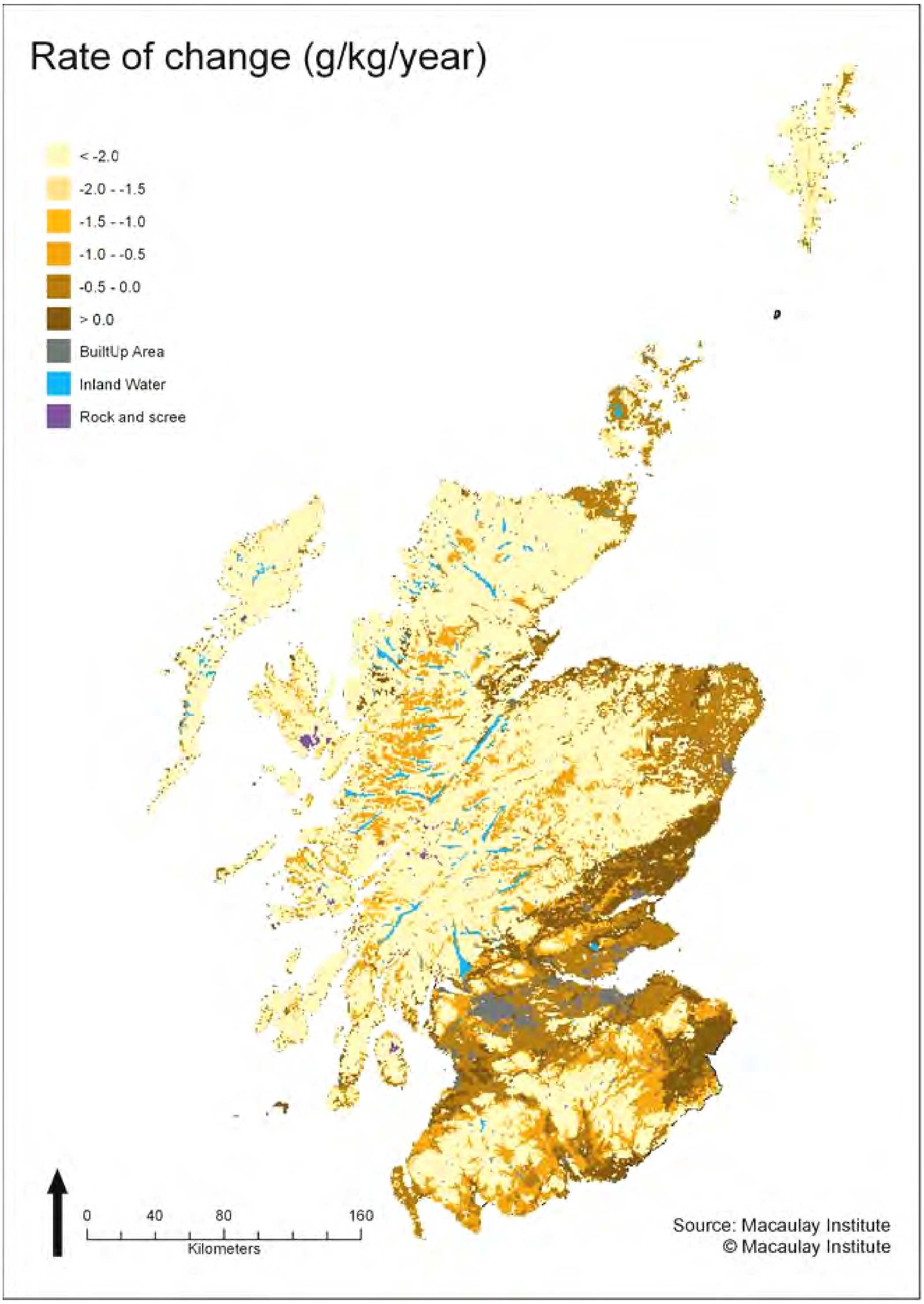


Figure 4.5 Topsoil organic carbon content (g kg^{-1}) as reported by the Northern Ireland Soil Inventory

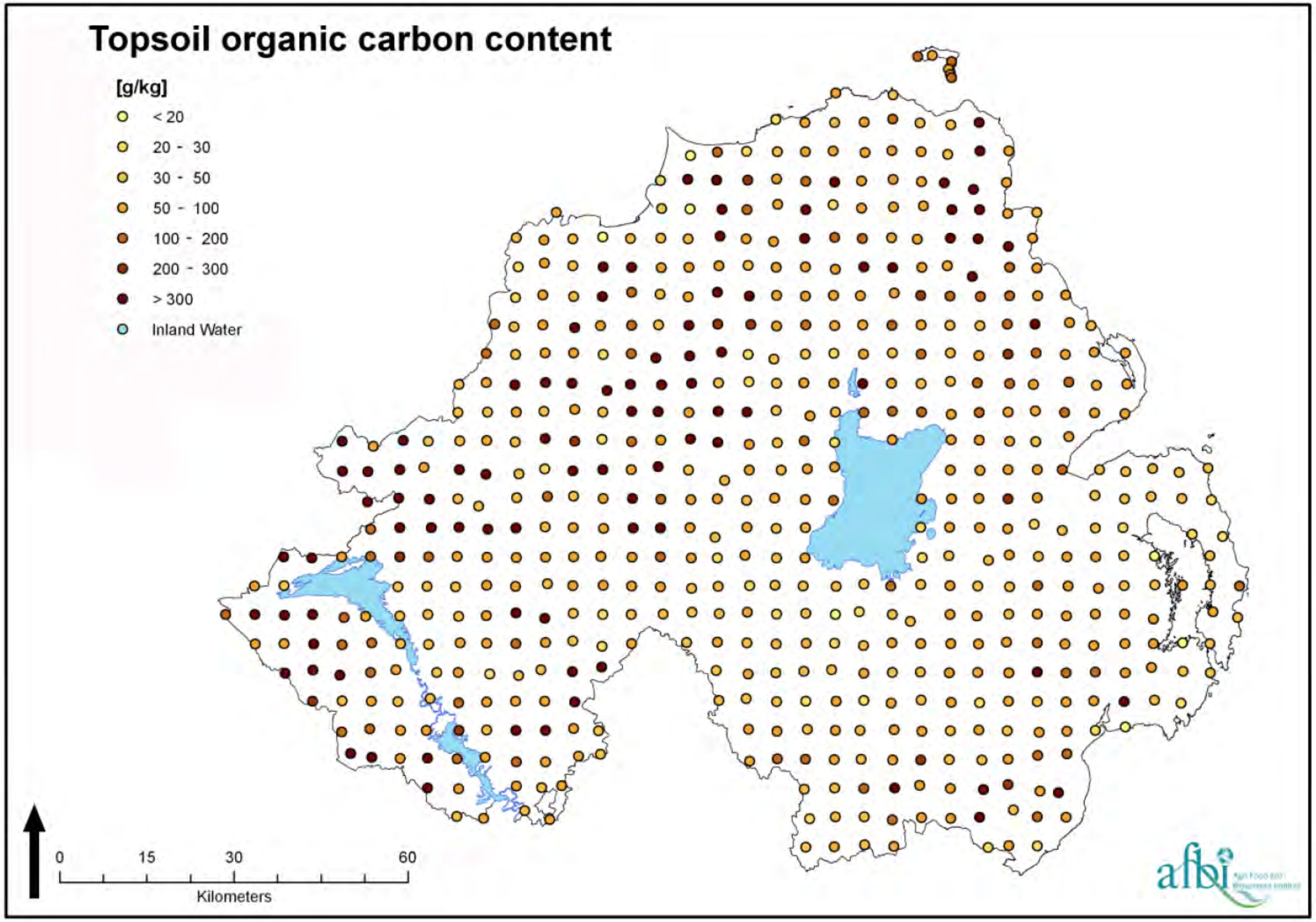


Figure 4.6 Estimated rate of change (g kg^{-1} yr^{-1}) of topsoil carbon derived from applying Equation 4.1 to the data presented in Figure 4.5

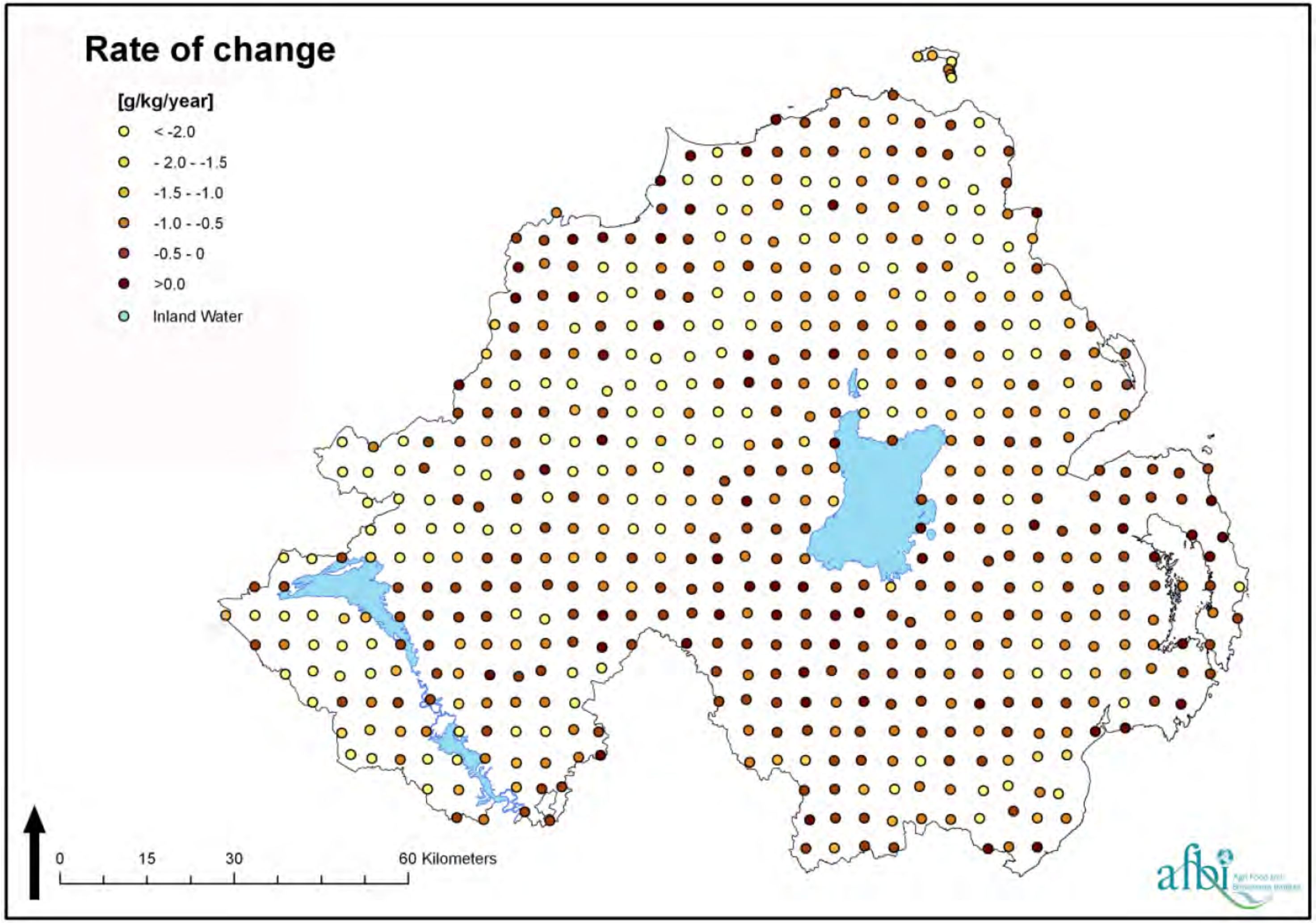


Figure 4.7 **Mean carbon content (g kg^{-1}) of the dominant soil series in each of the 1: 250 000 soil map units**

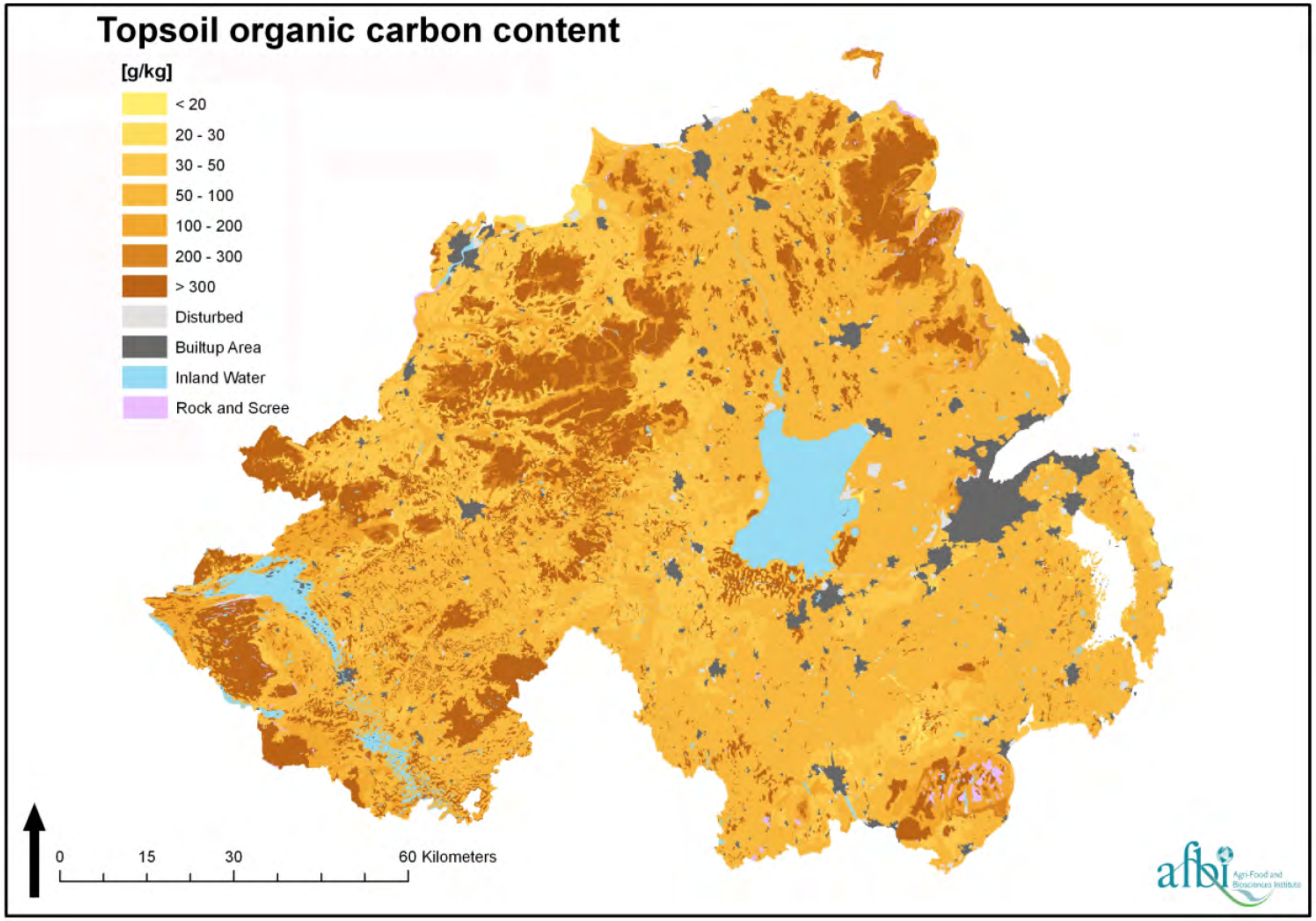
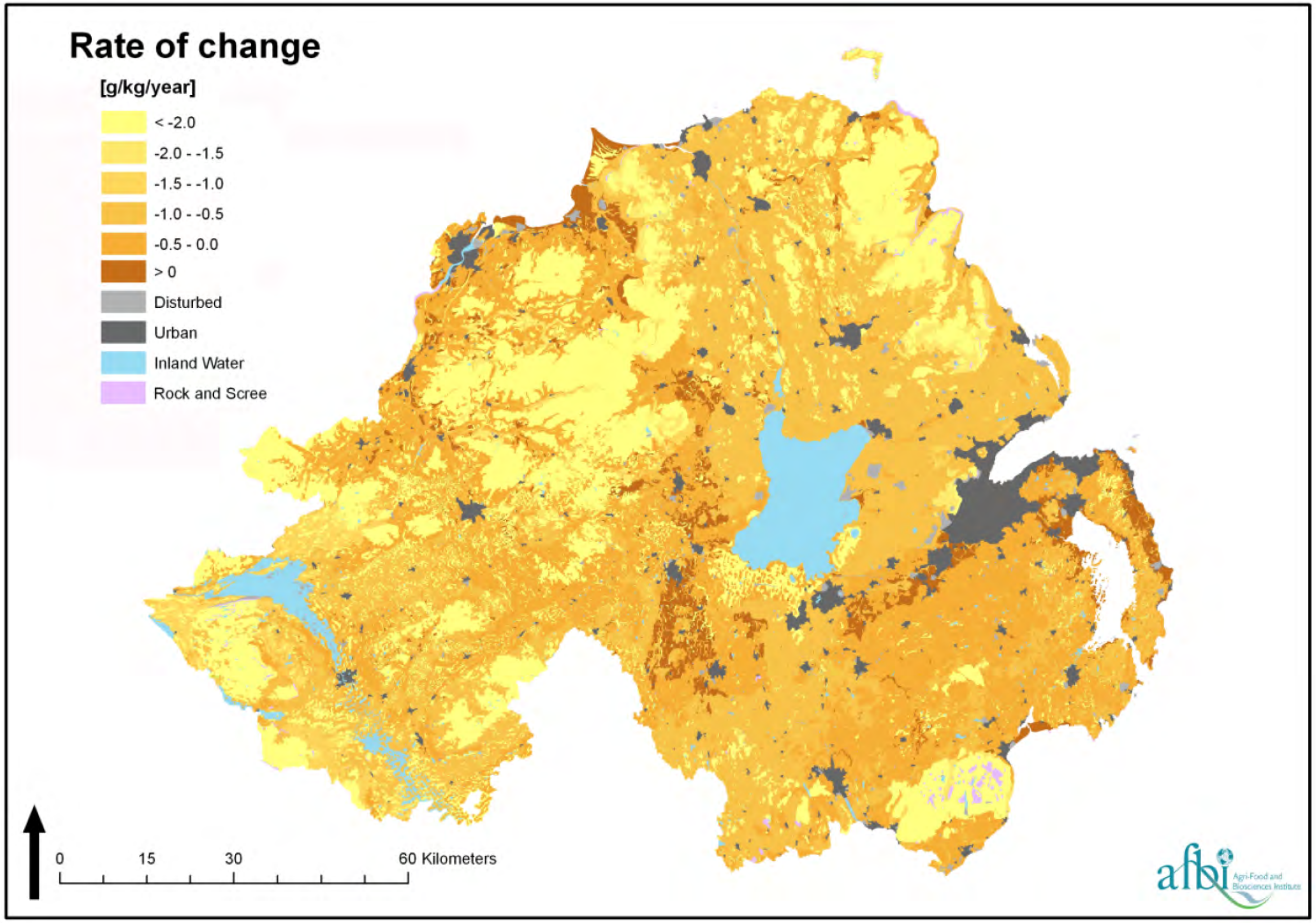


Figure 4.8 **Estimated rate of change (g kg^{-1} yr^{-1}) of topsoil carbon derived from applying Equation 4.1 to the data presented in Figure 4.7**



4.3 Conclusions

Despite the limitations of the methodology published by Bellamy *et al.* (2005), the predicted rate of change of topsoil carbon presented here highlights the importance of protecting organic and organo-mineral soils. Objectives 1 and 5 have gone some way to identifying the pressures and drivers of carbon loss that could be managed or manipulated. Under a programme of work funded by the Scottish Government, the Macaulay Institute is currently re-sampling the National Soils Inventory of Scotland. Results from this exercise should inform us as to whether topsoil carbon has changed, and if so, does the rate of change match the predictions made using Equation 4.1.

CHAPTER 5

Evaluation of land management practices and mitigation techniques

Objective 5

Evaluate options for land management practices and mitigation techniques which reduce the risk of erosion, habitat loss and DOC leaching in high risk situations.

5 EVALUATION OF LAND MANAGEMENT PRACTICES AND MITIGATION TECHNIQUES

5.1 Background

A review of the factors influencing erosion of organic and organo-mineral soils has been carried out as part of this project (Objectives 1 & 2), together with an evaluation of existing erosion models (Objective 3) and the likely response of organic and organo-mineral soils to the effects of climate change scenarios (Objective 4).

Soil erosion is a natural process which occurs in all soils to a greater or lesser extent, depending on climate, topography, soil type, vegetation and management. However, accelerated erosion is generally triggered by human activities. These may be direct (e.g. associated with engineering works) or indirect through the consequences of inappropriate soil and vegetation management. In the hills and uplands, the risk of accelerated erosion is most commonly associated with the management of domestic livestock and wild herbivores, most commonly sheep and red deer. Objectives 1 & 2 have reported on the scientific literature in relation to soil erosion in an attempt to identify the key drivers and trends in relation to erosion. The study by Grieve *et al.* (1994) was based on an analysis of erosional features observed on aerial photographs in the Scottish uplands. They found erosion features in approximately 12% of sample areas, and that in the majority the erosional features were in peat soils. Overall, they observed that the greatest concentration of peat erosional features was in the central Highlands (Monadhliath Mountains), while the most severe classes of erosion occurred in the eastern Highlands, correlating with the highest grazing and land use pressures.

This coincidence of erosion with high densities of domestic livestock and wild herbivores is of some concern to the conservation agencies and land managers. Grazing by sheep is often implicated as a factor in soil erosion in the UK hills and uplands (Birnie and Hulme, 1990; Evans, 2005). The number of sheep in Scotland rose considerably in the 1980s, due to the nature of agricultural support payments. In comparison, red deer numbers have steadily increased in all recent decades, more than doubling to approximately 400,000 between the 1960s and 2002 (Hunt, 2003), with some of the highest densities recorded in the eastern and central Highlands (Deer Commission Scotland, 2006).

In Northern Ireland, Tomlinson (1982, 1997) reported that 14% of the peatland was affected by erosion to some extent. Causal factors were considered to be climate, topography and peat cutting for fuel, while peatlands had also been lost to agricultural reclamation and commercial forestry. A similar trend to that in Scotland was evident in relation to declining sheep numbers (DARD, 2007). Although red (and sika) deer numbers are increasing, they are relatively low and are largely restricted to commercial forest areas in Counties Tyrone and Fermanagh (having escaped across the border with the Irish Republic, after being re-introduced to Co Donegal in 1891). This more recent colonisation followed a general extinction of the species throughout Ireland in the mid-1800s (Nolan and Walsh, 2005).

The key drivers identified as triggering disturbance and thus the potential for erosion of organic soils are wide ranging and include harvesting of peat, both mechanically and by hand; land drainage; recreation; wind farms and other developments on peatlands; forestry operations; burning; atmospheric pollution; the evolution of gully systems associated with water erosion; the short and longer term effects of climate and hydrological changes; and grazing, both by domestic livestock and wild herbivores (Evans and Warburton, 2007; Birnie *et al*., in prep).

5.2 Development of a geographically-specific erosion risk assessment, based on the inherent susceptibility of organic soils

The risk of soil erosion occurring in Scotland has been modelled following two different approaches. Lilly *et al.*, (2002) used a rule-based approach to identify the inherent geomorphological risk of soil erosion by overland flow, whilst Anthony *et al.*, (2006) adopted a more process-based approach integrating water balance models with understanding of soil erosion processes at the field scale. This latter approach was designed to predict sediment and phosphate movement to water bodies as part of a diffuse pollution screening tool. Both approaches integrate data on soil texture, hydrology and topography, linked to land cover datasets, to generate output in terms of erosion potential. A map showing the distribution of modelled erosion potential for soils in Northern Ireland has already been presented in Chapter 3. The soils predicted to be at greatest risk from erosion in Northern Ireland are found largely in upland areas with steep slopes, notably in the Mourne Mountains in the south-east, and associated predominantly with organo-mineral soils. In the approach adopted by Lilly *et al.* (2002), organic and organo-mineral soils were assessed into Low, Moderate and High risk categories, based on the inherent hydrological response characteristics of the soil and the steepness of slope. A map showing the inherent geomorphological susceptibility to overland flow for Scotland is also included in Chapter 3. It is important to note that this depicts the inherent risk without a vegetation cover additional work by Lilly *et al.* (2005) reassessed the risk of erosion in the uplands assuming a continuous vegetation cover and taking account of the period of time between major disturbances to that cover, for example, tree felling or heather burning.

Overall it was concluded that such models provide a useful indication of the geographic variation in erosion susceptibility, highlighting areas potentially at risk. While there are many factors at the local scale that affect susceptibility to erosion, at a regional scale the organic soils in Scotland were generally classified as being at high risk, whilst the majority of organo-mineral soils were classified as being at moderate risk. In the review of soil erosion risk models (Objective 3) the PESARA model (Pan-European Soil Erosion Risk Assessment), developed to predict soil erosion risk across Europe at 1-km cell resolution was identified as a potentially valuable tool in the further quantification of erosion from Scottish soils and the prediction of sediment yield at a landscape scale. An approach to erosion risk modeling based upon PESARA potentially provides an important advance over the earlier modeling work. As the PESERA model is process-based it can be used to assess the effect of potential changes in soil and vegetation conditions on erosion potential.

5.3 Evaluation of the key drivers of erosion and the determination of areas at highest risk

It is recognised that that the drivers of erosion may act together rather than singularly, and therefore it is often impossible to identify precise cause and effect relationships. It is also recognised that many erosional features are relatively long standing phenomena (Birnie, 1993). So what we currently observe in the landscape may not be related to present day conditions but rather to historical ones (e.g. climate cooling during the Little Ice Age; previously high levels of air pollution from heavy industry; introduction of large numbers of sheep during the early part of the 1800s). So a geographical coincidence between erosion and present day conditions cannot be assumed, necessarily, to reflect a causal relationship.

Table 5.1. Summary of the key drivers of erosion, the significance of their contribution to erosion overall, and what controls and influences are currently in place to limit their effects.

Key Driver	Geographic extent	Significance and trends	Human influence and controls
Atmospheric pollution	Acid deposition post-Industrial Revolution, notably sulphur dioxide and nitrogen deposition, affecting Scotland and Northern Ireland, particularly those areas in the vicinity of urban and industrial areas	Moderate significance, declining input of sulphur dioxide but increase in nitrogen, affecting vegetation (especially bog-forming mosses, e.g. *Sphagnum* spp.) regional patterns in deposition linked to sources of pollution and prevailing wind direction	Legislation (Clean Air Act) and improved technology, government commitment to reducing Carbon Footprint (e.g. Kyoto Protocol targets) and increase in generation of renewable energy
Burning	Controlled burning predominantly on drier moorlands in eastern Scotland, poor practice burning of larger areas and inappropriate vegetation, mostly associated with crofting, in the west and north of Scotland, and accidental uncontrolled burning largely in the vicinity of recreational areas in both Scotland and Northern Ireland	Low to moderate significance, low for small controlled burns, moderate with poor practices burning and larger wildfire burns, especially at inappropriate times of year. More intense accidental/deliberate summer fires are of particular concern, as bare soil is exposed for much longer periods.	Legislation, Best Practice guidance (The Muirburn Code) and management agreements including advice against burning wet heath and blanket bog vegetation, also public education and vigilance
Climate and hydrology	Overall influence of climate, hydrology and topography on the processes of soil formation, notably the accumulation (and loss) of organic matter	Moderate to high significance, cycles of accumulation and loss of organic matter possibly linked to long-term changes in climate and hydrology of peatlands. May be exacerbated by more recent increase in frequency of extreme events, e.g. reduced snow cover and more intense rainfall	Long-term climatic cycles may be outwith human control, but also linked to global emissions of carbon dioxide and attempts to reduce levels of atmospheric pollutants (see above key driver – Atmospheric Pollution)
Land drainage	Previously widespread in upland areas of Scotland and Northern Ireland, mostly in 1960s and 1970s, when grant-aided for agricultural improvement (resulting changes in vegetation generally not widespread and limited to immediate vicinity of drains)	Low significance overall and not currently practised, other than in very localised areas. Drains on gentler slopes tend to infill and re-vegetate., Some instances where poor practice has led to accelerated erosion of organic and mineral material	Government policy, ESAs, RSS, LMCs, Best Practice guidance for the conservation management of upland areas (e.g. GAEC), ditch blocking and peatland restoration
Forestry operations	Widespread throughout upland areas of Scotland and Northern Ireland although the Forest Service of NI no longer encourages planting on raised or blanket bog (DANI,1993), neither does FC, Scotland	Low to moderate significance, linked to ground disturbance during establishment and planting of new forests (track construction, drainage and forestry ploughing) and harvesting operations	Follow Best Practice management guidelines (e.g. Forests and Water guidelines), site-specific design of planting schemes and harvesting protocols to reduce erosion

Table 5.1 cont'd

Grazing	Widespread and extensive driver throughout upland areas of Scotland and Northern Ireland, areas at highest risk are those with current moderate to high impacts, relatively high deer densities and areas with steeper slopes	Moderate to high significance, notably higher sheep densities in recent past but now declining, red deer numbers steadily increasing in Scotland (less so in Northern Ireland and generally confined to areas of commercial forestry)	EU Common Agricultural Policy, single farm payments, LMCs, commodity prices, legislation in relation to SACs and Natura 2000 habitats (management objectives aimed at achieving favourable condition status)
Gully systems*	Predominantly found on gently sloping upland plateau areas, notably in central, eastern and northern Scotland, Shetland, and the Mourne Mountains of Northern Ireland	Moderate significance, once initiated, gully systems tend to evolve naturally and develop into extensive networks of bare eroding peat, leading to progressive loss of organic matter over time. These systems may endure for 100s of years	Blocking of gullies may be locally effective, but generally little control possible, especially where extensive systems already developed, reduction in grazing and trampling impact may be partially effective
Peat harvesting	Mechanical – localised raised bogs in the lowland areas of Scotland and Northern Ireland; by hand – crofting areas (northern and western coastal fringes and islands)	Low significance overall, locally significant on lowland raised bogs. Some evidence of localised resurgence in peat cutting for domestic fuel in crofting areas of Scotland (Carrell, 2008) and Northern Ireland but not considered to be an erosion risk	Legislation, Best Practice guidelines for harvesting and restoration of peatlands, peat cutting access rights controlled within crofting townships
Recreation	Relatively localised, restricted to well-used paths and access routes in the more popular mountain areas in Scotland and Northern Ireland, and skiing areas	Low significance overall, but locally may be moderate or high and require amelioration to minimise erosion, general trend of increasing recreation pressure leading to more erosion particularly associated with route features especially informal footpaths	Appropriate construction of footpaths and use of surface protection where necessary, visitor education, guidance and management
Wind farms and other developments	Localised but rapidly expanding number of sites on organic and organo-mineral soils throughout upland areas of Scotland and NI	Currently low significance overall but local issues with access tracks. Some examples of triggering of mass movement and debris flows (e.g. Derrybrien). Concerns related to overall carbon balance and payback times may limit future developments on peatlands	Government guidance and controls on development, EIA and Peat Landslide Hazard Risk Assessment required prior to approval, including mitigation measures to control and minimise impacts

* NOTE: Although it can be argued that gully systems are not in themselves seen as a main driver but rather a consequence of the initiation of erosion, they are included here because their development creates a chain of causation leading to further instability and erosion. So areas with a propensity for gully development are at higher risk.

The potential for both multiple drivers of erosion operating in concert, and the fact that erosional features may relate to historical conditions, does limit our analytical options (e.g. application of multivariate statistics). However, we do have a considerable body of field observations and expert knowledge (Johnson *et al*., 2001; Birnie *et al*., in prep) which we can use in a qualitative sense to develop an alternative approach to assessing erosion risk. This is one based on our understanding of the underlying processes involved, particularly with respect to vegetation changes under different levels of management. So using this underlying knowledge and as a first step, we have taken the key drivers or erosion identified in Objectives 1 & 2 and evaluated them in relation to their geographic extent and sphere of influence, the significance of their contribution to erosion overall, and what controls and influences are currently in place to limit their effects on erosion. This information is summarised in Table 5.1, with the drivers being listed in alphabetical order and not by order of importance.

5.3.1 Atmospheric pollution

The effects of increased atmospheric pollution following the Industrial Revolution and their effects on the natural environment have been well documented, notably in the Pennines of northern England and across Europe (Bower, 1960; Lee *et al.*, 1988). In Scotland and Scandinavia, research through the Surface Waters Acidification Programme (Ferrier and Harriman, 1990; Wright *et al.*, 2005) demonstrated the effects on stream and loch catchments, notably in areas with low natural buffering capacity. More recently, there has been a reduction in the deposition of acid sulphur compounds but an increase in nitrogen deposition. This may have favoured the growth of graminoid species at the expense of mosses (de Schmidt, 1995; Britton *et al.*, 2006). In Scotland and Northern Ireland, atmospheric pollution may have been a moderately significant driver in the erosion of organic and organo-mineral soils. Future trends in atmospheric inputs are likely to be influenced by how far the international community can respond to the challenges of global climate change and the need to switch from a reliance on fossil fuel usage to more renewable sources of energy.

5.3.2 Burning

Controlled burning of moorland vegetation (muirburn) is a widely used management tool to regenerate heather (*Calluna vulgaris*) for red grouse sporting management and sheep grazing. Muirburn is predominantly practiced on drier moorlands in eastern parts of

Scotland, with relatively small areas burned (approximately 0.2ha) on a rotation of approximately 15-20 years to create a mosaic of different aged stands. In this way, muirburn results in rapid re-growth of heather and has been practised for over a hundred years. Such well-managed muirburn has a low significance for erosion. Burning alters vegetation composition and structure and can affect soils, but it is not necessarily damaging. The impact of fire is dependent upon many factors including intensity, frequency and scale, vegetation and soil type. Too frequent or intense fires, fires covering large areas, burning of sensitive areas and at inappropriate times of the year, however, can all be environmentally damaging (Tucker, 2003). A temporary increase in erosion rate following muirburn was reported by Kinako and Gimmingham (1980), but with recovery of the vegetation by 15 to 20 months following post-burning. Davies *et al*. (2006) state that fires will happen regardless of management intentions, but that we can manipulate the fire regime of the British uplands to both maximize the ecological benefits and manage the threat of wildfires, which can cause massive environmental damage. Accidental uncontrolled burning, or deliberate fires often occurring during the summer months can be a notable issue where they occur on grassland, heath or blanket bog vegetation, particularly where such fires are hot enough to cause serious damage to the ground surface and lead to erosion of the surface organic layers. Legislation and Best Practice guidance, such as the Muirburn Code and supplementary guidance (Scottish Government, 2008c) include advice on appropriate burning strategies and timing, and advice against burning wet heath and blanket bog vegetation, to avoid damage to the more sensitive moorland habitats. Presently, burning is considered to be of overall low significance as a driver of erosion, but it may have been a more significant trigger in the past during episodes of forest clearance initiated by human activities in the Neolithic, Bronze Age, Iron Age and later periods of settlement and agricultural development (Birks, 1988; Stevenson and Birks, 1995). Burning of moorland was probably more casual and sporadic up until around 1800. Thereafter, the use of fire became more regular and organized with land ownership changes, an increase in sheep grazing and the development of grouse shooting (Rackmam, 1986; Tucker 2003). More formal guidance on best practice dates from an enquiry into moorland management in the early 1900s, and was based on evidence from the most productive grouse moors (Lovat, 1911).

5.3.3 Climate and hydrology

There is considerable debate as to whether cycles of accumulation and loss of organic matter over periods of thousands of years are linked to long-term fluctuations and changes in climate and the hydrological conditions characteristic of such organic soils. The process of erosion may be linked to the development of inherent instability in the accumulation of organic material, notably in relation to the extensive blanket peat deposits of Scotland and Northern Ireland. At some point in the development of such systems they may require little, if any, external factor to trigger a phase of erosion. The cause may be almost entirely due to subtle changes in climate and soil moisture conditions affecting plant growth, or structural and hydrological instability due to the forces acting on the accumulating mass of saturated organic matter, particularly on sloping terrain. There are many instances where once initiated, erosion of peatland appears to proceed to a natural end point with almost complete loss of organic matter, notably in the Monadhliath Mountains of the central Highlands, but there were also many other instances of widespread, active and advanced peatland erosion throughout central, eastern and northern Scotland, Shetland, and localities in mountain areas of Northern Ireland. In a related and ongoing study of peatland erosion in Scotland, on behalf of SNH, Birnie *et al.* (in prep.) conclude that there are few current drivers of peat erosion in the Ladder Hills (Grampian Mountains) other than those related to climate and hydrology.

5.3.4 Land drainage

Drainage of upland areas, or ‘moor gripping’ usually by widely spaced single-furrow ploughing, was a widespread and common practice carried out during the 1960s and 1970s, supported by grant-aid for agricultural development aimed at improving hill grazings. Although initially leading to more rapid run-off, the effectiveness of many of these drains has declined over time and many have overgrown and infilled naturally, particularly on more gently sloping terrain and where they have been colonised by *Sphagnum* spp. A review of the impacts of moorland drainage on vegetation (Stewart and Lance, 1983) concluded that the effects of drainage were very localised and confined to within 2-3m of the drain. Thus, the implications in relation to increased erosion risk from any change in species composition are likely to be slight. While it is acknowledged that more intensive drainage schemes would have implications, cost-effectiveness has generally ruled these out in relation to areas of organic and organo-mineral soils. In some instances, more discrete areas of peatland were drained and the converging pattern of drainage channels has led to locally increased erosion (Hulme *et al.*, 1996). The blocking of ditches has been notably effective in reversing such adverse effects (P. Hulme, pers comm.). Overall, there is little evidence that land drainage has been an initiating factor, or has lead to increased erosion of organic and organo-mineral soils. However, it is unlikely that there would be much support for such a practice in the future, due to the recognition of the importance of such areas for biodiversity and conservation management, and the requirement to maintain the integrity of such areas as natural water catchments and carbon stores, and to reduce the likelihood of rapid run-off. Legislation and government policy in relation to Environmentally Sensitive Areas (DAFS, 1988), the Rural Stewardship Scheme (Scottish Executive, 2000) and the negotiating of land management contracts have all discouraged hill drainage.

5.3.5 Forestry operations

Commercial forestry operations are widespread throughout the upland areas of Scotland and Northern Ireland and the majority of plantings during the 20th century were on organo-mineral and organic soil types (Tudor and Mackey, 1995). Potentially, the widespread disturbance caused by establishment of new forests (track construction, drainage, forestry ploughing) and during harvesting operations could have consequences for erosion of such soils. Locally, there are instances of increased erosion, but forestry operations are not generally regarded as a significant initiator of erosion in the wider landscape. Over time, the combined effects of drainage, increased ground cover and interception of moisture by trees has been shown to have an overall drying out effect, leading to shrinkage of organic and organo-mineral soils under commercial forestry (Pyatt, 1993). However, the presence of litter and brash also reduce the potential for erosion with harvesting and during the establishment of subsequent rotations. Management guidelines (Forestry Commission, 2003), first published in 1988, provide a comprehensive review of the issues involved and present guidance on minimising the effects of forestry operations on soil erosion and water quality. These include the establishment of buffer zones to limit the effects of forestry operations on stream catchments and the wider environment. A review of the evidence from recent studies in the UK designed to test the efficacy of the guidelines demonstrated that best management practices can be very effective in limiting soil erosion and the threat of diffuse pollution from forestry (Nisbet, 2001).

5.3.6 Grazing

Grazing is considered to be one of the most significant drivers of erosion of organic and organo-mineral soils in upland areas, and it is the most notable factor where land management can have a direct influence on outcomes (Sydes and Miller, 1988; Thompson *et al.*, 1995; Davidson and Grieve, 2004; Waterhouse *et al*., 2004). Grazing by domestic livestock, notably sheep, is often implicated as a factor in soil erosion in the uplands (Towers *et al*., 2006). The number of sheep in Scotland rose by almost 25% in the 1980s to 10 million, due to EU agricultural support based on headage payments. Numbers declined to 8 million following the outbreak of Foot & Mouth Disease in 2001, and this decline has continued such that the total number of sheep in Scotland is now less than 7.5 million (SAC, 2008). In comparison, red deer numbers have steadily increased in recent decades, more than doubling in numbers to approximately 400,000 between the 1960s and 2002 (Staines *et al.*, 1995; Hunt, 2003), with some of the highest densities (20-30 deer per km^2) recorded in the eastern and central Highlands (Deer Commission for Scotland, 2006). A similar trend in sheep numbers occurred in Northern Ireland as in Scotland (DARD, 2007). However, red deer numbers are relatively low and largely restricted to commercial forest areas in Counties Tyrone and Fermanagh (Nolan and Walsh, 2005).

In terms of future trends in relation to domestic livestock grazing, this notable driver of erosion is likely to be influenced by reduced densities of sheep in upland areas, due to changes in EU agricultural policy (single farm payments rather than those based on headage). The requirement to comply with Good Agricultural and Environmental Practice, inherent in new agri-environment schemes (Scottish Executive, 2000), will also be an influence, as will the effects of world commodity prices, and legislation in relation to Special Areas of Conservation and Natura 2000 habitats, notably management aimed at achieving favourable condition status of upland habitats. The latter is now becoming more of a significant issue in relation to wild herbivores, particularly red deer.

Deer have replaced sheep as the principal herbivore in many areas of high conservation value in the hills and the continued increase in numbers has led to increased culling, either through voluntary agreements between the Deer Commission for Scotland and landowners, or by imposing compulsory controls and enacting legislation to protect habitats. Such measures to protect the wider upland environment including water catchments may be required to be used more often in the future. However, organizations with conservation management objectives as a priority, such as the RSPB, National Trust for Scotland, John Muir Trust and Scottish Wildlife Trust, are increasingly becoming more important and influential landowners in Scotland and in areas under their ownership and management, there is very likely to be a decline in the importance of grazing as a potential driver of erosion.

5.3.7 Gully systems

The presence of well-established gully systems, linked to areas of already established erosion of peatlands, and influenced by climate and hydrological factors, may be of moderate significance in the on-going process of erosion. These systems are predominantly found on gently sloping plateau areas of blanket peat throughout the uplands and in the northern and Western Isles of Scotland. They tend to evolve naturally and develop into extensive networks of bare eroding peat, leading to progressive loss of organic matter over time. Blocking of gullies may be locally effective, but generally there is little effective control possible, especially where extensive gully systems are already developed. Reduction in grazing and trampling impacts by large herbivores, notably sheep and deer, may be only partially effective in reducing rates of erosion. Stabilisation and re-vegetation tend to occur on the gully floors and the species composition of the plant community often differs significantly from that of the original peatland community especially in having a relatively low moss component.

5.3.8 Peat harvesting

Mechanical harvesting of peat undoubtedly increases the potential for erosion by exposing bare peat surfaces. However, the current extent of areas being harvested is limited and these areas are invariably lowland raised bogs with level to very gentle slopes, and consequently lower risk of water erosion, although wind erosion is possibly a localised issue. Peat cutting by hand occurs over a much more widespread area but is generally limited to the crofting counties, notably in the west and north of Scotland, the Hebrides and Shetland, and is localised in Northern Ireland. Peat cutting by hand is usually limited to the crofting townships. The rights to cut peat and the ways in which it is done are highly prescribed under the common grazing regulations, and in particular the requirement to replace the top turf after the bank is cut is a standard conservation measure which minimises the surface area of bare peat that is exposed at any point in time. Domestic peat cutting was formerly much more extensive than it is at present, although there is now some limited evidence of resurgence in peat cutting due to the increase in the cost of fossil fuels. However, there is also evidence in the field and from aerial photographs that many former peat cutting areas have partially or wholly revegetated over time. Whilst there are some local exceptions to this, notably in Shetland, where due to the high population levels, domestic peat cutting has historically affected extensive areas of blanket mire on the South Mainland (Birnie and Hulme, 1990). Despite these localised exceptions, it is generally the case that such disturbance and exploitation of peatland for domestic fuel use has not been a driver of peat erosion in the past, nor is it likely to be in the future.

5.3.9 Recreation

The effects of recreation pressure on organic and organo-mineral soils are relatively localised and restricted to well-used paths in the more accessible mountain areas, and to areas developed for skiing. Locally, erosion of organic and organo-mineral soils can be a very visible issue, but there are notable instances in recent times of footpath restoration, such as on Stac Pollaidh (North-west Highlands), Schiehallion (central Highlands) and in the Cairngorm Mountains. Appropriate footpath construction and management of visitor pressure can largely overcome issues of increased erosion caused by recreational land use and visitor access in upland areas, and recreational use is not seen as a major driver of erosion (Bayfield *et al.*, 1988; Newbury, 2005).

5.3.10 Wind farms and other developments

There is an expanding network of wind farms both in place and proposed for development throughout the upland areas of Scotland and Northern Ireland. These developments, largely on organic and organo-mineral soils, are considered to be of low significance overall in relation to their effects on erosion. Government approval is dependent on a process of Environmental Impact Assessment and Peat Landslide Hazard Risk Assessment (Scottish Executive, 2007a), including proposed mitigation measures to manage and minimise impacts, leading to the submission of a comprehensive Environmental Statement. This is to safeguard against increased erosion and the possibility of creating instability on peatland sites. These controls and safeguards were largely initiated following a notable instance where poor practice and incomplete understanding in relation to the construction of a wind farm on a peatland in

Eire lead to instability, resulting in a major peat slide (AGEC, 2004). More recent concerns in relation to carbon balance and payback time may further restrict windfarm developments on peatlands (Scottish Government, 2008a). This may lead in the future to, for instance, their location on organo-mineral soils (but not necessarily on peatlands) within areas of existing commercial forestry. Such areas are likely to be of relatively low conservation and scenic value, having already been developed for commercial forestry.

5.3.11 Summary

On the basis of the above qualitative analysis, eight of the ten drivers of erosion of organic and organo-mineral soils are assessed as either of low, low to moderate or of moderate significance at a landscape scale across Scotland and Northern Ireland. The remaining two drivers, climate and hydrology, and grazing, are considered to be of moderate to high significance.

In relation to climate and hydrology, there are few practical on-the-ground control measures that can be adopted. This is due to the general scale of the processes involved and control measures have to be targeted at reducing the overall risks of climate change at an international level. Any practical mitigation strategies, therefore, have to be applied in full awareness of the fact that they may be compromised by supervening climatic or hydrological events.

There is much more opportunity for local management interventions in the case of grazing and trampling impacts on upland habitats associated with organic and organo-mineral soils, particularly in high risk areas which still have both high sheep and deer grazing densities. Here there is the possibility of reducing the effects of erosion by more direct management action. In view of this potential for management intervention a number of scenarios of possible changes in grazing regimes are explored in the following section in order to gain an understanding of how future trends may affect the balance between domestic livestock and wild herbivores, and what further land management options and mitigation measures may be required to reduce habitat loss and erosion of organic and organo-mineral soils.

5.4 Current herbivore regimes and likely changes

There is inevitably some uncertainty as to the likely future trends in grazing pressure in the hills and uplands of Scotland and Northern Ireland. A number of possible future scenarios have been elucidated and these are summarized in Table 5.2. The table outlines the various scenarios, presents evidence for and against, and summarizes the consequences of each scenario for main vegetation types (LCM2000 classes and equivalent PESERA land cover descriptions) based on predicted decrease in vegetation cover and corresponding increase in percentage of bare ground. These scenarios were used to guide the sensitivity analysis of the PESERA model to changes in vegetation cover (Chapter 3).

The methodology involved in determining the likelihood and potential impact of the scenarios, and a discussion of each potential future outcome, are presented in the following sections.

5.4.1 Possible future scenarios of grazing pressure

5.4.1.1 Methodology for the selection and scoring of scenarios

Summary data on the effects of changes in the proportion of the main vegetation types (grassland, heather moorland, montane vegetation and blanket bog), and more specifically the proportion of bare ground associated with this range of future possible scenarios of herbivore numbers, are included. These were generated as input for the PESARA soil erosion risk model to explore the effects of these scenarios on erosion risk and sediment loss.

Nine scenarios are presented, based on combinations of possible and likely predicted changes in sheep and deer numbers. These scenarios have been scored on a scale of 1-5 according to the likelihood of the scenario actually taking place in the future (1=highly unlikely, 2=unlikely, 3=less unlikely, 4=likely or 5=highly likely). The scoring is based on evidence for and against the scenarios from the scientific literature, research reviews, past and present trends and expert judgment of likely future changes.

In addition to identifying the most likely scenarios of change, an overall forecasted change in grazing and trampling impact was also estimated to quantify the potential effects of these outcomes (Table 5.2 column 5). This is weighted towards sheep compared to deer by a factor of 2, following Albon *et al.* (2007), where across eleven Deer Management Group (DMG) areas overall, it was observed that the presence of sheep was associated with the largest increase in grazing and trampling impact of all herbivores (see Appendix 3). Thus, on a scale of +3 to -3, the scenario where both sheep and deer are predicted to increase over time scores an increased predicted impact of +3, while where both sheep and deer are predicted to decrease scores -3. Assessing the scenarios in this way provides a means of comparing the predicted change in impact of one scenario against another, while allowing for the greater magnitude of the effects due to changes in numbers of sheep on the open hill. This is translated into resulting cover values for the four main vegetation types of grassland, heather moorland, montane and blanket bog, based on evidence from Albon *et al*., (2007) and the scientific literature (summarized below) relating to the effects of grazing pressure, the foraging preferences of sheep and deer, and the state-transitions of these communities when subjected to different grazing intensities. An average of the predicted cover values for these four vegetation types was calculated to guide the sensitivity analysis of the PESERA model (Table 5.2 column 9).

The vegetation types can be described in descending order of resilience as follows:

1. *Grassland* – resilient to heavy grazing and trampling impact. Effects include reduction in sward height, decreased structural diversity, increase in moss cover, particularly of 'feather' mosses, decline in accumulation of dead material in the sward base, and eventual increase in bare ground (Miles, 1988; Grant *et al.*, 1996; Milne *et al.*, 1998).

2. *Heather moorland* – less resilient. Effects of heavy grazing and trampling impact include decline in productivity of heather over time, increase in grazing-induced growth forms of heather, decrease in height and structural diversity, breakage and death of heather stems with trampling, dying out of older heather plants and uprooting of regenerating seedlings, increase in bare ground and actively eroding deer and sheep scars, reduction in height and cover of dwarf shrubs relative to graminoids, and conversion to grassland vegetation over time (Grant *et al.*, 1982; Armstrong and Milne, 1995; Hester and Baillie, 1998, Hester *et al.*, 1999; Palmer and Hester, 2000). This is influenced by soil type and nutrient status, ranging from conversion of heather moorland to *Agrostis-Festuca* on brown podzolic

soils, to *Nardus* grassland on peaty podzols or to *Molinia*-dominated grassland vegetation on peaty gleys (Bibby *et al.*, 1982). Also, interactions with management intensity and likely increase in burning may lead to an overall increase in bare ground.

3. *Montane vegetation* – dependent on whether graminoid, heath or moss species predominate, montane vegetation can be more or less resilient. Effects of heavy grazing and trampling impact include stem death of heath species with trampling, reduction in moss cover and increase in bare ground – lichens where present are very sensitive to trampling, leading to rapid loss of cover and requiring a long recovery period (Bayfield *et al.*, 1988; Britton *et al.*, 2005). However, such montane areas are usually only a preferred grazing resource for a short period in the summer months (Bibby *et al.*, 1982).

4. *Blanket bog* – This is considered to be one of the least resilient vegetation types. Effects of heavy grazing and trampling impact include decline in *Sphagnum* cover with trampling of moss hummocks and lawns, trampling of pool systems, death of older heather stems with grazing, trampling and disturbance, increase in bare ground, invasion and increase in grassy species, and increased disturbance and erosion of bare peat areas (Grant *et al.*, 1985; MacDonald *et al.*, 1998).

Table 5.2. Summary of nine scenarios of possible future trends in main herbivores and their effects on vegetation cover and bare ground. An expanded explanation of each scenario is given in the accompanying text below.

Scenario	**Overall predicted trend in relation to main herbivores in upland areas (on organic and organo-mineral soils)**	**Likelihood score (1-5) 1=Highly unlikely, 5=Highly likely**	**Evidence for/against scenario, based on scientific literature and trends**	**Overall change in impact (weighted towards sheep compared to deer by a factor of 2)**	**Consequences of this scenario for main vegetation types (LCM2000 classes and equivalent PESERA land cover descriptions -scrub) based on predicted decrease in vegetation cover and corresponding increase in percentage of bare ground. Data given are for the resulting cover of vegetation by scenario**		
					Main semi-natural vegetation types (LCM2000 classes)	**Forecasted resulting % cover of vegetation**	**Average % bare ground – used to inform PESERA sensitivity modelling**
1	Sheep = increase deer = decrease	1 = Highly unlikely	Sheep numbers are being reduced on hill due to change from headage to area-based payments (Schwarz *et al.*, 2006; Yuill and Cook, 2007; Birnie *et al.*, 2008). Also, upward trend in deer numbers reported by DCS and other authors (Clutton-Brock and Albon, 1989, 1992; Clutton-Brock *et al.*, 2004; Albon *et al.*, 2007)	+1	Grassland (COV018, COV019)	90	5
					Heather moorland (COV009, COV010)	90	
					Montane (COV011)	100	
					Blanket bog (COV008)	100	

Table 5.2 continued

Scenario	**Overall predicted trend in relation to main herbivores in upland areas (on organic and organo-mineral soils)**	**Likelihood score (1-5) 1=Highly unlikely, 5=Highly likely**	**Evidence for/against scenario, based on scientific literature and trends**	**Overall change in impact (weighted towards sheep compared to deer by a factor of 2)**	**Consequences of this scenario for main vegetation types (LCM2000 classes and equivalent PESERA land cover descriptions -scrub) based on predicted decrease in vegetation cover and corresponding increase in percentage of bare ground. Data given are for the resulting cover of vegetation by scenario**		
					Main semi-natural vegetation types (LCM2000 classes)	**Forecasted resulting % cover of vegetation**	**Average % bare ground – used to inform PESERA sensitivity modelling**
2	Sheep = increase deer = no change	1 = Highly unlikely	Evidence for sheep numbers decreasing on hill (references as above) combined with an upward trend in deer numbers reported by DCS and other authors (references as above). Also, where sheep have been removed, there is evidence of deer replacing sheep (‘vacuum effect’) and becoming the main grazer on a number of ‘sensitive’ sites (Hewison *et al.*, 2000; SNH, 2003).	+2	Grassland (COV018, COV019)	85	10
					Heather moorland (COV009, COV010)	85	
					Montane (COV011)	95	
					Blanket bog (COV008)	95	
3	Sheep and deer both = increase	2 = Unlikely	Upward trend in deer numbers = yes, but sheep numbers on the hill are going down in response to change in support payments and wider economic climate in relation to estate management (Schwarz *et al.*, 2006; Yuill and Cook, 2007; Birnie *et al.*, 2008).	+3	Grassland (COV018, COV019)	80	15
					Heather moorland (COV009, COV010)	80	
					Montane (COV011)	90	
					Blanket bog (COV008)	90	

Table 5.2 continued

Scenario	**Overall predicted trend in relation to main herbivores in upland areas (on organic and organo-mineral soils)**	**Likelihood score (1-5) 1=Highly unlikely, 5=Highly likely**	**Evidence for/against scenario, based on scientific literature and trends**	**Overall change in impact (weighted towards sheep compared to deer by a factor of 2)**	**Consequences of this scenario for main vegetation types (LCM2000 classes and equivalent PESERA land cover descriptions -scrub) based on predicted decrease in vegetation cover and corresponding increase in percentage of bare ground. Data given are for the resulting cover of vegetation by scenario**		
					Main semi-natural vegetation types (LCM2000 classes)	**Forecasted resulting % cover of vegetation**	**Average % bare ground – used to inform PESERA sensitivity modelling**
4	No change in sheep, deer = decrease	2 = Unlikely	Sheep numbers reducing on hill, while there is an underlying trend of an increase in deer numbers.	-1	Grassland (COV018, COV019)	100	0
					Heather moorland (COV009, COV010)	100	
					Montane (COV011)	100	
					Blanket bog (COV008)	100	
5	No change in sheep and deer	2 = Unlikely	Numbers are currently in a state of change, with sheep numbers decreasing on hill in response to change in support payments. Also, unlikely many estates will be able to increase deer cull without substantial increase in resources, therefore upward trend in deer numbers likely to continue	0	Grassland (COV018, COV019)	100	0
					Heather moorland (COV009, COV010)	100	
					Montane (COV011)	100	
					Blanket bog (COV008)	100	

Table 5.2 continued

Scenario	**Overall predicted trend in relation to main herbivores in upland areas (on organic and organo-mineral soils)**	**Likelihood score (1-5) 1=Highly unlikely, 5=Highly likely**	**Evidence for/against scenario, based on scientific literature and trends**	**Overall change in impact (weighted towards sheep compared to deer by a factor of 2)**	**Consequences of this scenario for main vegetation types (LCM2000 classes and equivalent PESERA land cover descriptions -scrub) based on predicted decrease in vegetation cover and corresponding increase in percentage of bare ground. Data given are for the resulting cover of vegetation by scenario**		
					Main semi-natural vegetation types (LCM2000 classes)	**Forecasted resulting % cover of vegetation**	**Average % bare ground – used to inform PESERA sensitivity modelling**
6	Sheep and deer numbers both = decrease	3 = Less unlikely	Sheep numbers decreasing -yes, but deer increasing and many estates not able to increase deer cull without substantial increase in resources, except in priority areas, or with DCS Section 7 and 8 agreements (voluntary and compulsory reductions). Some evidence of effects of conservation management (NTS, RSPB, WT, etc.) in reducing deer numbers to promote natural regeneration, but this is an individual estate management, rather than a regional effect	-3	Grassland (COV018, COV019)	100	0
					Heather moorland (COV009, COV010)	100	
					Montane (COV011)	100	
					Blanket bog (COV008)	100	
7	Sheep = decrease deer = no change	4 = Likely	Sheep numbers decreasing -yes, but overall trend is for deer increasing and unlikely that estates will have the resources to increase deer cull, or do so voluntarily unless there is more pressure brought to bear from the agencies (‘priority areas’ and Section 7/8 agreements, etc.)	-2	Grassland (COV018, COV019)	100	0
					Heather moorland (COV009, COV010)	100	
					Montane (COV011)	100	
					Blanket bog (COV008)	100	

Table 5.2 continued

Scenario	**Overall predicted trend in relation to main herbivores in upland areas (on organic and organo-mineral soils)**	**Likelihood score (1-5) 1=Highly unlikely, 5=Highly likely**	**Evidence for/against scenario, based on scientific literature and trends**	**Overall change in impact (weighted towards sheep compared to deer by a factor of 2)**	**Consequences of this scenario for main vegetation types (LCM2000 classes and equivalent PESERA land cover descriptions -scrub) based on predicted decrease in vegetation cover and corresponding increase in percentage of bare ground. Data given are for the resulting cover of vegetation by scenario**		
					Main semi-natural vegetation types (LCM2000 classes)	**Forecasted resulting % cover of vegetation**	**Average % bare ground – used to inform PESERA sensitivity modelling**
8	No change in sheep, deer = increase	4 = Likely	Sheep numbers may stabilize, while underlying trend is of an increase in deer numbers.	+1	Grassland (COV018, COV019)	95	5
					Heather moorland (COV009, COV010)	95	
					Montane (COV011)	95	
					Blanket bog (COV008)	95	
9	Sheep =decrease deer =increase	5 = Highly likely	Sheep numbers decreasing on hill in response to change in subsidy payments and wider economic conditions, also underlying trend of increase in deer numbers, partly as a 'vacuum' effect and also due to climate change, increased calving survival rates, better grazing available, low commodity price, and lack of manpower for increased culling.	-1	Grassland (COV018, COV019)	100	0
					Heather moorland (COV009, COV010)	100	
					Montane (COV011)	100	
					Blanket bog (COV008)	100	

5.4.1.2 Scenario 1 – sheep increase, deer decrease

This scenario is considered to be a highly unlikely one as there is considerable evidence that sheep numbers are being reduced on hill areas due to change from headage to area-based payments (Schwarz *et al.*, 2006; Yuill and Cook, 2007; Birnie *et al.*, 2008; Scottish Government, 2008b). Also, a consistent and upward trend in deer numbers has been reported by the Deer Commission for Scotland and other authors (Clutton-Brock and Albon, 1989, 1992; Clutton-Brock *et al.*, 2004; Albon *et al.*, 2007). While an increase in sheep numbers would result in greater competition for the hill grazing resource, it is unlikely that this would cause a decline in deer numbers. It is predicted that this outcome would lead to an overall increase in impact (score of +1), largely due to increased sheep numbers affecting grassland and heather moorland vegetation, and causing some conversion of heather/grass mosaic areas to grass dominance. This would also lead to a slight increase in the cover of bare ground (5%) with implications in terms of increased erosion of organo-mineral soils.

5.4.1.3 Scenario 2 – sheep increase, deer no change

This scenario is also considered to be highly unlikely due to the recent reductions in sheep numbers on hill areas reported by a number of authors and the upward trend in deer numbers (references as for scenario 1). Under this scenario there would be greater competition for resources, as demonstrated by Hester and Baillie (1998), Hester *et al.* (1999) and Palmer and Hester (2000), but it is unlikely that this would have an effect in the short term on the overall trend of increase in deer numbers. It is predicted that this outcome would result in an overall increase in impact (score of +2), largely due to increased sheep numbers affecting grassland and heather moorland, and causing some conversion of heather/grass mosaic areas to grass dominance, but also affecting montane vegetation and blanket bog as deer numbers remain relatively high in certain areas. It is considered that this would lead to an increase over time in the cover of bare ground (10%) with implications in terms of likely increased erosion of organic and organo-mineral soils.

5.4.1.4 Scenario 3 – sheep and deer both increase

The scenario where sheep and deer both increase is considered to be unlikely. As already stated, there is a well-established upward trend in deer numbers. However, sheep numbers on the hill are decreasing in response to changes in support payments, the wider economic climate in relation to estate management and the furtherance of conservation objectives. If this scenario was to come about, as it did during the period from 1973 to the early 1990s, it is forecasted to result in the greatest overall increase in impact (score of +3). This would be due to a combination of increased sheep numbers affecting grassland and heather moorland, and causing conversion of heather/grass mosaics to grass dominance, and also higher deer numbers affecting heather moorland, montane vegetation and blanket bog. It is considered that this would lead to a notable increase over time in the cover of bare ground (15%) with implications in terms of likely increased erosion of organic and organo-mineral soils.

5.4.1.5 Scenario 4 – no change in sheep, deer decrease

This scenario is also considered to be unlikely, due to the reported trends of decrease in sheep numbers and increase in deer. It is unlikely that many estates will be able to increase their deer cull without substantial increase in resources, therefore an upward trend in deer numbers is most likely to continue, except in priority areas covered by DCS Section 7 and 8 agreements (voluntary and compulsory reductions in deer numbers, due to damage being caused to designated habitats). In such instances, additional resources are likely to be brought to bear to reduce deer numbers. However, if there was to be a levelling out of sheep numbers and a decrease in deer overall due to increased culling, it is forecast that this would result in an overall decrease in impact (score of -1). This would be expressed in terms of reduced impact on heather moorland, montane vegetation and blanket bog. It is considered that this would have positive benefits over time in terms of the cover of bare ground (no increase predicted), with likely implications for decreased erosion of organic and organo-mineral soils.

5.4.1.6 Scenario 5 – no change in sheep and deer

This scenario is also considered to be unlikely, due to the reported trends already indicated above. Sheep and deer numbers are currently in a state of change, with sheep numbers decreasing on hill in response to change in support payments. Also, it is unlikely that many estates and DMGs will be able to increase their deer cull without substantial increase in resources, therefore the upward trend in deer numbers is likely to continue. However, if there was to be no change, with sheep and deer numbers leveling off, it is forecast to result in no change in overall impact (score of 0) and no change in terms of bare ground and the erosion of organic and organo-mineral soils, at least driven by grazing and trampling of domestic livestock and wild herbivores.

5.4.1.7 Scenario 6 – sheep and deer both decrease

A future scenario where sheep and deer numbers both decrease is considered to be less unlikely, especially in individual regions. Sheep numbers are certainly decreasing in hill areas, and despite the reported general increase in deer numbers, there is some evidence of the effects of management of estates for conservation objectives by organizations such as the NTS, RSPB, Scottish Wildlife Trust, Woodland Trust and John Muir Trust, who are increasingly becoming important landowners throughout the Highlands of Scotland. Thus, in the future, there could be a wider move to reduce deer numbers and promote natural regeneration of scrub and woodland. At the moment this is happening on an individual estate basis, but it could become a more regional trend in the future. This may happen at the Deer Management Group (DMG) scale where like-minded owners or organizations come together to manage wider landscapes for common management objectives. It is certainly a valid observation that such collaborative management operates most effectively where there are common objectives among neighbouring landowners (Nolan *et al.*, 2002) and this could become a model for the more effective regional management of red deer across Scotland. It is forecast that this would result in the greatest overall decrease in impact (score of -3), resulting in changes in structure and species composition of grassland and heather moorland (Hester and Miller, 1995) and changes in impacts on montane vegetation and blanket bog. It is considered that this would have positive benefits over time in terms of reducing the cover of bare ground (no increase predicted), with implications for likely decreased erosion of organic and organo-mineral soils. This would depend on the changes in numbers of sheep and deer at the local and regional level.

5.4.1.8 Scenario 7 – sheep decrease, deer no change

This is considered to be one of two most likely future scenarios. As stated previously, sheep numbers are decreasing on the hill through changes in support payments and it could be that increased culling, driven by conservation objectives and more effective collaborative management by DMGs, results in a stabilization of deer numbers. It is predicted that this would result in an overall decrease in impact (score of -2), resulting in changes in structure and species composition of grassland and heather moorland. It is considered that this would have positive benefits over time in terms of reducing the cover of bare ground (no increase predicted), with implications for likely decreased erosion of organic and organo-mineral soils. This would depend on the changes in numbers of sheep and deer at the local and regional level.

5.4.1.9 Scenario 8 – no change in sheep, deer increase

Conversely, it may be that sheep numbers on the hill have now largely been corrected and stabilized at a lower level, while deer numbers continue to increase steadily, continuing the long term trend evident since the 1960s. Whether this will occur is partly dependent on the management objectives and resources of individual estates, the success of collaborative management at the DMG level, and the effectiveness of partnerships with statutory organizations in meeting common goals. It is also influenced by such factors as climate change and the reduced incidence of harsh winter weather, leading to increased calving survival rates, greater shelter available with increase in woodland cover, and changes in hind to stag ratios. It is predicted that this scenario would result in an overall increase in impact (score of +1). This would be expressed primarily in terms of increased impact on heather moorland, montane vegetation and blanket bog, due to increased deer numbers affecting these habitat types. This would lead to a slight increase (5%) over time in the cover of bare ground with implications in terms of likely increased erosion of organic and organo-mineral soils.

5.4.1.10 Scenario 9 – sheep decrease, deer increase

The one scenario which is considered to be most likely to happen in the future is where sheep numbers continue to decrease on hill areas in response to changes in subsidy payments and wider economic conditions, and where there is a continuance of the underlying trend of an increase in deer numbers, seen since the 1960s. This increase in deer is partly caused by a ‘vacuum’ effect, but is also due to climate change with milder winter weather being more prevalent along with decreased snow cover, the increased availability of better quality grazings with reduced competition with sheep, increased shelter with more woodland cover, higher calving percentage and survival rates, increase in hind to stag ratios, and the lack of manpower, or the willingness of estates to respond to these positive feedbacks by increasing culling.

Where sheep have been removed in recent times, there is evidence of a ‘vacuum effect’ with deer moving in and becoming the main grazer on a number of ‘sensitive’ and priority sites for conservation (Hewison *et al.*, 2000; SNH, 2003). For this, the most likely future scenario, the overall change in impact is predicted to be -1, expressed primarily through reduced impact on grassland and heather moorland vegetation. However, on a regional level, the implications of increased deer numbers for grazing and trampling impacts, and potentially increased erosion risk on montane and blanket bog vegetation, are likely to vary considerably. This will depend on the balance of herbivore types present, the existing densities of red deer, current levels of grazing and trampling impact, and the management intensity and objectives on any particular estate.

5.5 Identification of areas most at risk of erosion

5.5.1 Grazing and Trampling Impact Assessment

While it is considered that the relationship in terms of cause and effect between present herbivore densities and the extent of erosion is not strong (the evidence in the literature and from field investigations supports the assertion that most of the erosion evident on peatland areas has been created over a timescale of hundreds of years), nevertheless the current levels of grazing and trampling impact do reflect the present herbivore regime and provide an indication of those areas most at risk of erosion.

The assessment of grazing and trampling impact on the main types of upland vegetation (MacDonald *et al.*, 1998) is based on a number of readily observable field indicators including percentage of heather shoots browsed, the presence of grazing-induced growth forms, sward height, moss cover, flowering, trampling, accumulation of plant litter, bare ground and dung. With appropriate training and experience, field recorders can readily distinguish impacts on the current year's growth, and also gain an understanding of the trends in impact over recent years from longer-term indicators, notably the morphology and prevalent growth forms of heather, and indicators such as stem breakage, presence of erosion scars, plant litter, bare ground and dung.

Examining the levels of utilisation of shoot growth is one of the primary indicators of the impact of grazing on heather vegetation. Ideally, this should be carried out in late-spring – early-summer prior to commencement of growth, when the impact of grazers over the previous twelve months on one year's growth of heather shoots can be assessed.

A combination of cutting and grazing experiments on heather in north-east Scotland have shown that young heather on dry moorland can tolerate removal by grazing of up to 40% of the current season's shoot biomass without an effect on the productive capacity of the heather in the following season. Heavier grazing, with removal of 80% of the current season's shoots, resulted in the death of some shoots, a decline in stand density, the appearance of bare areas and, after five years of such grazing, a reduction by 40-50% in the production of new shoots in a sixth, ungrazed season (Grant *et al.*, 1982). Grazing intensities which remove more than 40% of the current season's shoot biomass of heather stands in their pioneer or building phase may be assumed to be detrimental to the future productivity of highly productive dry heather moorland.

For dry and undifferentiated heath vegetation of late-building to mature stand age, dominated by intermediate and older heather, Grant and Armstrong (1993) suggested an upper limit of 10% utilisation of annual shoot production to maintain heather cover in the long-term, though experimental evidence to support this is not available. Older heather, with its lower proportion of green shoots to wood, is less tolerant of grazing than younger heather and takes longer to recover from heavy grazing. Grant and Armstrong (1993) also suggested an upper limit of 15% utilisation of annual shoot production to maintain heather cover on blanket bog vegetation.

The link with such experimental data has been made in the assessment of impacts through the field indicator for percentage of heather shoots browsed. Here the levels of 33% and 66% of heather shoots browsed, used as the boundaries between the Light and Moderate, and Moderate and Heavy categories, equate to levels of 20% and 40% utilisation of annual shoot production, respectively (Armstrong and MacDonald, 1992; MacDonald *et al.*, 1998). Thus, for younger heather, Light and Moderate impacts may be regarded as sustainable, but Moderate-Heavy and Heavy impacts may result in a decline in heather productivity and cover in the long-term. In comparison, for older heather, and blanket bog where heather is the dominant species, Light and Light-Moderate impacts may be considered as sustainable, but even Moderate impacts may result in a long-term decline in the heather resource. Moderate impacts on blanket bog may also be associated with a risk of increased erosion.

In contrast to heather, smooth and coarse grassland vegetation types are able to sustain higher levels of utilisation (60% and 30% respectively) without an adverse effect on stock-carrying capacity. Areas of smooth grassland are generally the most preferred grazing resource in any such open hill situation, attracting heavy grazing pressure throughout the year. Indeed, heavy grazing may maintain such areas in a productive state, though short sward heights are generally associated with sparse or no flowering of grasses and small herbaceous species, with a consequent reduction in the nature conservation value. In relation to coarse grassland, particularly *Nardus*-dominated areas, it is generally the more-palatable inter-tussock grasses, sedges and herbaceous species that are grazed in preference to *Nardus* (Gordon, 1988; Grant *et al*., 1996). However, where dwarf-shrub heath occurs in mosaic with grassland vegetation, impacts on the heath species may be higher than considered sustainable in the long-term.

Assessing impacts on montane vegetation presents some difficulties in that because the vegetation is generally of a suppressed nature anyway, due to the prevailing harsh climatic conditions, there are few reliable indicators that can be used. Also, areas of montane vegetation may be dwarf-shrub heath, moss and sedge, or grass-dominated, and growth and recovery from grazing and trampling is slow. Such areas may provide a useful grazing resource during the summer months, particularly when biting insects are a nuisance at lower altitudes, but heavy impacts can lead to increased risk of erosion and change from heath to grass species dominance.

5.5.2 Impacts of sheep versus deer

Grazing and trampling impact assessments have been carried out on upland habitats across Scotland since the mid-1990s to provide baseline information on the state of rangelands and to assist land managers in devising appropriate strategies based on the principles of sustainable management (Nolan *et al.,* 2003). These ‘rangelands’ in a Scottish context are areas of open hill vegetation that result from grazing and browsing, and are an important resource, managed for a number of agricultural, hunting, recreation and conservation objectives. While there has been much progress in collaborative land management in recent times, multiple objectives can lead to conflicts, including habitat degradation as a result of heavy grazing and trampling impact. The increase in sheep numbers that occurred following the entry of Britain into the European Common Market in 1973, along with a widely acknowledged increase in red deer numbers, and the growing awareness of the national and international importance of dwarf-shrub heath, blanket bog and montane habitats for nature conservation, heightened concerns about grazing and trampling impacts. The degradation of heather moorland of conservation significance at a European scale has been attributed, anecdotally, to increasing sheep and red deer populations. However, there is little quantitative evidence regarding the relative impacts of the different herbivores to inform their management. To research this issue, Albon *et al.* (2007) quantified the grazing and trampling impact of sheep, cattle, red deer, rabbits, mountain hares and red grouse on open-hill habitats in eleven DMG areas of upland Scotland, ranging from the north-west to the central, southern and eastern Highlands, and covering 8715 km^2, or approximately 20% of the open rangeland area of Scotland.

Field sampling was carried out between 1997 and 2003. Data were recorded in different years in the various survey areas because of the considerable areas being covered in this wide-ranging study. The presence of each herbivore species was attributed on the basis of signs of occupancy, notably visual sightings, evidence of recent animal presence (wool, hair, feathers, lying-up areas, animal tracks, trampling and thrashing of vegetation, burrows) and the presence of dung. The field indicators of MacDonald *et al.*, (1998) were used to generate a five-point scale of impact on sample areas of 0.25 km^2, recorded over seven habitats, with a total of 8224 records. A Bayesian regression model was used to analyse the association of herbivore species with grazing impact on the main types of upland vegetation, controlling for environmental attributes, to explore how impacts were associated with the presence/absence of the different herbivores.

Across the DMGs, deer were the herbivore most frequently recorded as present in vegetation polygon sample areas (median 90.1%, inter-quartile range 81.3-96.6%), except for one DMG (74.0%, compared to sheep 96.5%). Overall, sheep were the second most frequently recorded herbivore (median 42.5%, inter-quartile range 26.6-55.5%). Evidence of sheep and deer using the same vegetation polygons was common (median 31.0%, inter-quartile range 22.9-53.3%), but rarely were neither recorded. Cattle were an order of magnitude less frequently recorded than sheep (median 2.9%) reflecting their comparative low numbers and presently restricted range on the open hill. Grouse and hares were more frequently recorded in central and eastern Scotland, compared to the north and west, while rabbits were more locally distributed and strongly associated with lower lying enclosed land with drier mineral soils. Where smooth grassland and heath habitats occurred close to these environments, as in some DMGs in eastern Scotland, rabbit presence was recorded comparatively frequently.

Averaged across all DMGs, the highest predicted impact was associated with the recorded presence of sheep. The estimated impact of sheep was the highest of all herbivores in seven of the 11 DMGs, and significantly greater than zero in a further two.

Cattle had the second largest impact, but generally this was restricted to fewer more localised areas and habitats than sheep, notably crofting areas and restricted grazing where impacts were invariably high.

In contrast, impacts associated with wild herbivores tended to be less, and only significant locally. Although red deer presence alone was generally associated with a significantly lower impact than sheep, this impact increased with increasing deer density at both land-ownership and regional scales. For sheep there was little evidence of density-dependence. The effects of rabbits were localised and generally more discernable in DMGs in eastern Scotland, associated with smooth grassland habitats, while relatively heavy hare impacts were restricted to heath. In one DMG (Cairngorm-Speyside), the recorded presence of red deer was associated with an increase in predicted impact across a wide range of habitats.

The presence of sheep tended most frequently to have a significant impact on smooth grassland habitat across Scotland, and least frequently on blanket bog, whereas the impacts of deer tended to be more diffuse. Overall, there was a significant impact in only seven of 63 (11.1%) habitat-DMG combinations for deer, compared to 58 of 77 (73.5%) for sheep. In 40 of 63 (63.5%) habitat-DMG combinations, where both red deer and sheep impacts could be estimated, the predicted impact of the recorded presence of sheep was significantly greater than the predicted impact of deer. In contrast, in only one of all the 63 (1.6%) habitat-DMG combinations (blanket bog in Cairngorm-Speyside) was the predicted impact of the recorded presence of deer significantly greater than sheep. Where sheep and deer densities were available at the estate scale, the predicted impact associated with the presence of deer increased significantly with deer density, whereas this tended not to vary with sheep density. Thus, even at apparently low local densities, sheep had a pronounced impact compared with low densities of deer. However, at higher densities, predicted impacts of sheep and deer were similar.

The higher impact associated with sheep presence was concluded to be a reflection of their greater aggregation and limited ranging behaviour, exacerbated by sheep being herded in places convenient for land managers. Consequently, reductions in sheep numbers as a result of reform of EU farming policies, may limit the extent of their impact, but not necessarily the local magnitude. However, it was considered that reductions in sheep numbers may lead to further increase in deer densities. This may require careful consideration of just how many deer are sustainable on such sites where habitat conservation is a priority among the range of management objectives.

Where sheep are removed from an area, the reduction in grazing and trampling impact should halt further degradation of heather-dominated communities (Armstrong and Milne 1995; Armstrong *et al*., 1997). However, as red deer prefer to forage in grass patches, they may fill the 'vacuum' left by the removal of sheep, hindering recolonisation by heather (Hope *et al.*, 1996). Unfortunately, understanding of the extent to which red deer will change their foraging and ranging behaviour when sheep are removed is largely anecdotal (but see Clutton-Brock and Albon, 1992). In heath habitats, deer densities above about 15 deer per km^2 were associated with impacts of moderate or higher. Thus, pro-active deer management to constrain the rate of deer population growth may be necessary if the priority is to halt the loss of heather and reduce the associated risk of exacerbated erosion on organic and organo-mineral soils. However, the study of Albon *et al.* (2007) presents an opportunity to reconsider the issue of whether heavy grazing impact, leading to alternative plant communities, such as a replacement of heather-dominated vegetation with grassland plant communities, is an undesirable outcome rather than a dynamic process between alternative stable states (van der Wal, 2006). Light or light/moderate grazing will maintain heather-dominated habitats but grass-dominated ones require moderate or greater levels of grazing to remain stable in terms of species composition. Associated risks are that there will be a potential increase in bare ground and erosion associated with heavier impacts on such areas. Also, that there will be exacerbated erosion of adjacent habitat types particularly sensitive to trampling impact, such as blanket bog and peatlands with existing erosion.

The distribution of grazing and trampling impact scores differed significantly between the 11 DMG areas studied. Impact scores tended to be lower in DMGs in the north and west Highlands, and higher in the south and east Highlands. In three habitats (blanket bog, heath and coarse grassland), regression analysis (Albon *at al*., 2007) indicated that deer population density explained a significant proportion of the variation in mean impact between DMGs, but not so on smooth grassland and montane habitats. A series of case studies for individual DMG areas are presented in Appendix 1 to illustrate the regional differences in impacts and underlying factors that influence the areas most at risk of erosion.

5.6 Spatial distribution of areas most at risk of erosion

Figure 5.1 illustrates the distribution of polygons of 'blanket bog with erosion' according to the Land Cover of Scotland 1988 (LCS88) (Macaulay Institute, 1993), including areas where this land cover category was a primary or secondary component of a mosaic.

Figure 5.2 illustrates those areas of Scotland where deer densities are currently more than 15 per km^2, combined with where sheep are present at more than 0.5 sheep per km^2, and where grazing and trampling impacts from sample areas are Moderate, Moderate-Heavy or Heavy.

Figure 5.3 is based on the same deer and sheep data, only where grazing and trampling impacts from sample areas are Moderate-Heavy or Heavy.

The areas considered to be at greatest risk due to grazing and trampling impact in Scotland are predominantly in the south-central Highlands, also scattered localities in northern, north-west and western Scotland. This pattern reflects the strongly regional nature of reductions of sheep numbers (Birnie *et al*., 2008), where there has been considerable reduction in sheep numbers in the north and west, compared to the southern and eastern Highlands, where there are still flocks of sheep on many hill areas.

Figure 5.4 illustrates the areas of peatland with erosion features in Northern Ireland (Cruickshank and Tomlinson, 1988) and Figure 5.5 the distribution of sheep stocking density (DARD, 2007) and areas with wild red deer (EHS, 2002). Although red deer densities are generally low (Nolan and Walsh, 2005), the areas considered to be at greatest risk of erosion due to grazing and trampling impact are around the north coast of Northern Ireland and in scattered upland localities where there are higher densities of sheep associated with erosion of peatlands and organo-mineral soils.

Figure 5.1. The occurrence of "blanket bog with erosion" (including single category, primary and secondary component of a mosaic) based on the Land Cover of Scotland (1988).

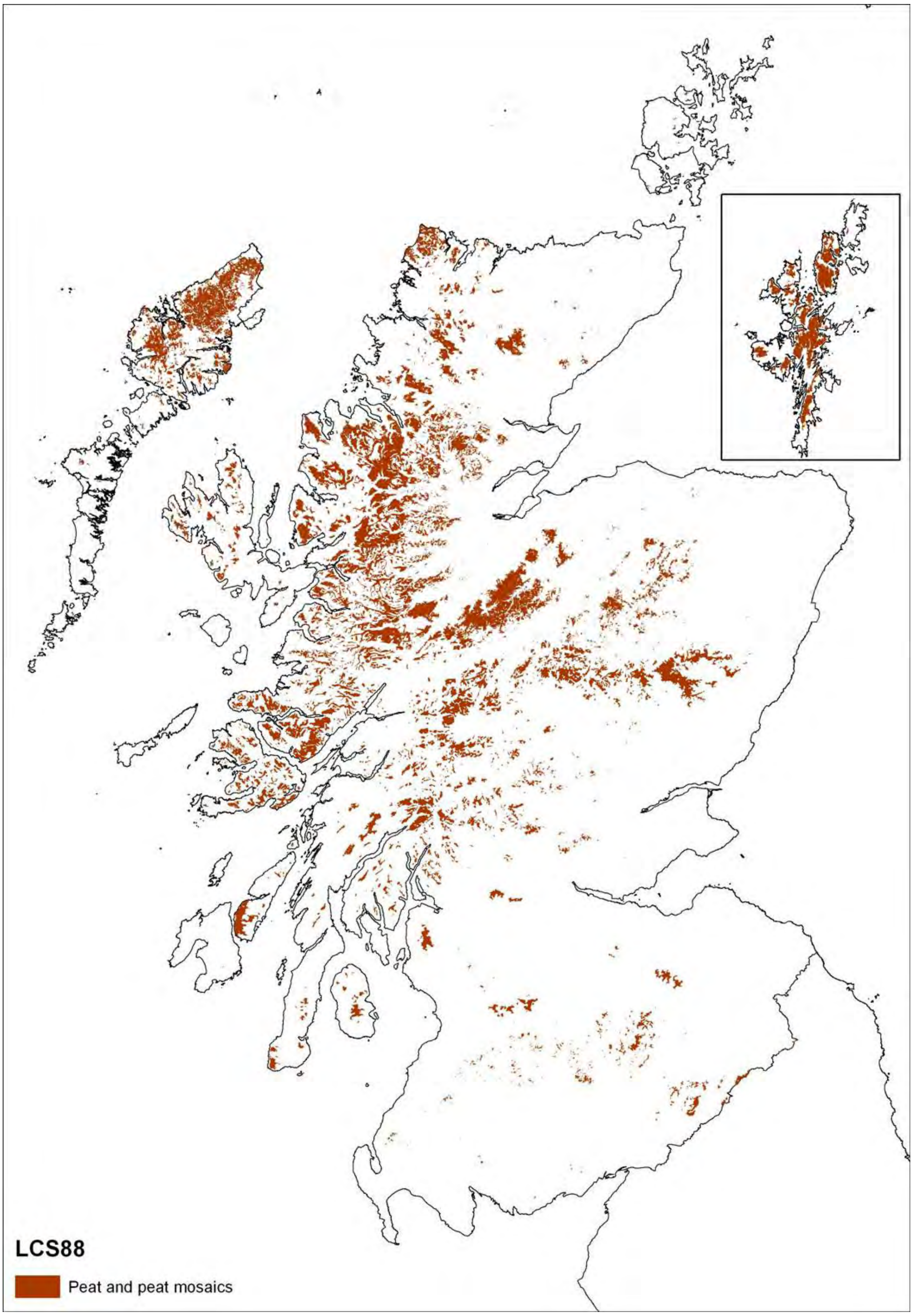


Figure 5.2. The distribution of areas of high and low deer and sheep density, combined with an overlay showing Moderate, Moderate-Heavy or Heavy grazing and trampling impacts (following MacDonald *et al.* 1998).

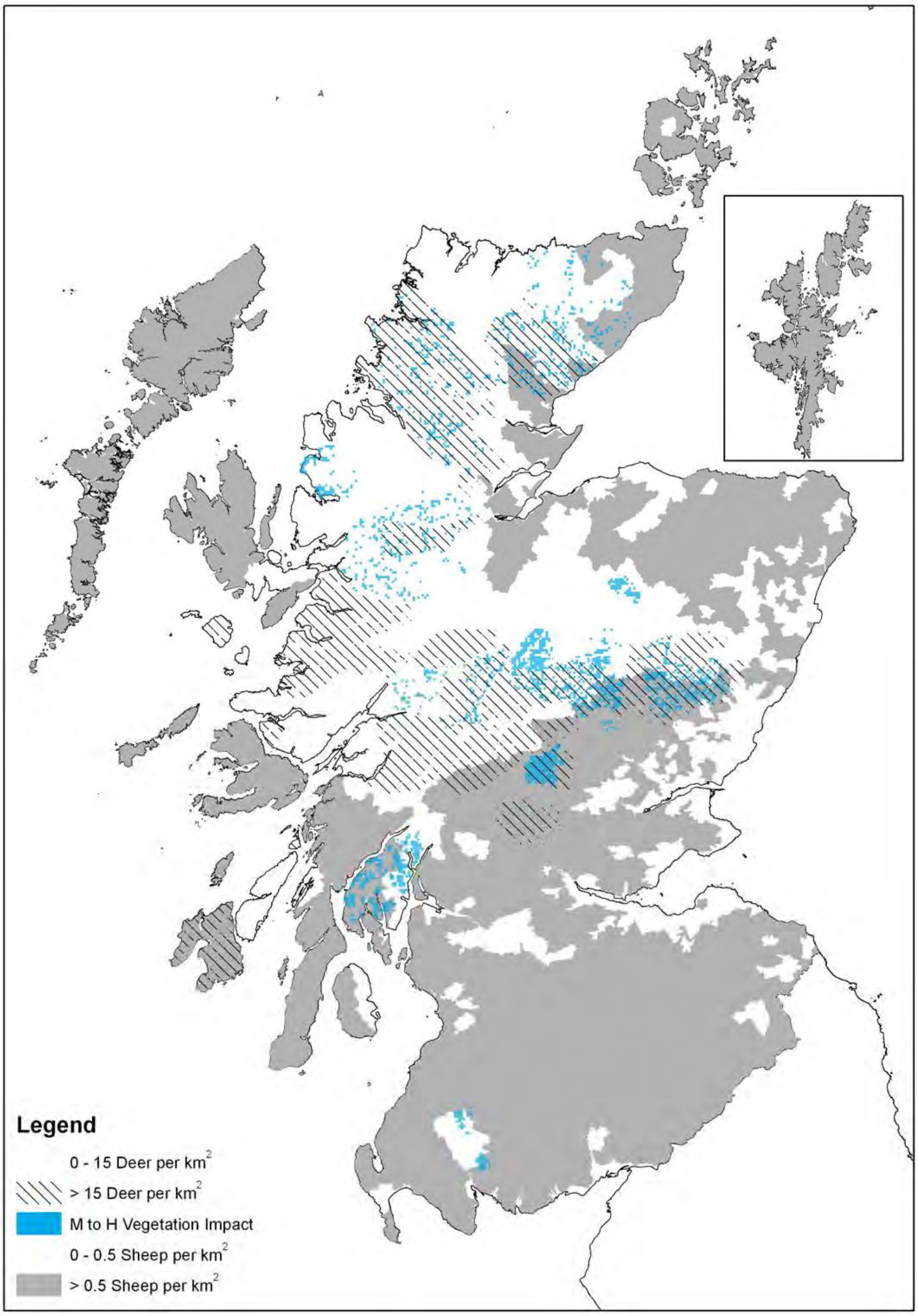


Figure 5.3 The distribution of areas of high and low deer and sheep density, combined with an overlay showing Moderate-Heavy or Heavy grazing and trampling impacts (following MacDonald *et al.*, 1998).

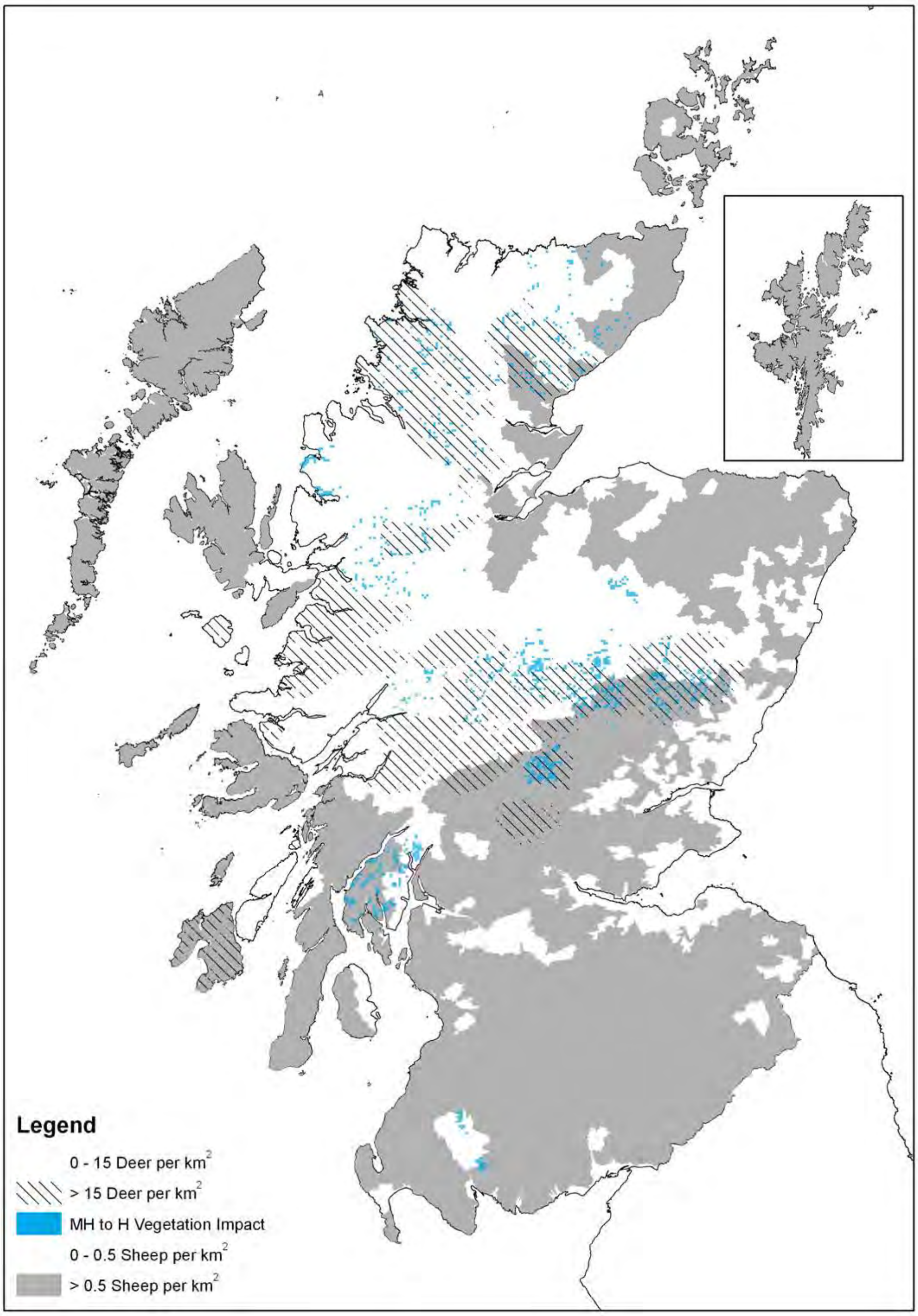


Figure 5.4. The occurrence of blanket bog with significant erosional features in Northern Ireland, taken from the Northern Ireland Peatland Survey (Cruickshank and Tomlinson, 1988).

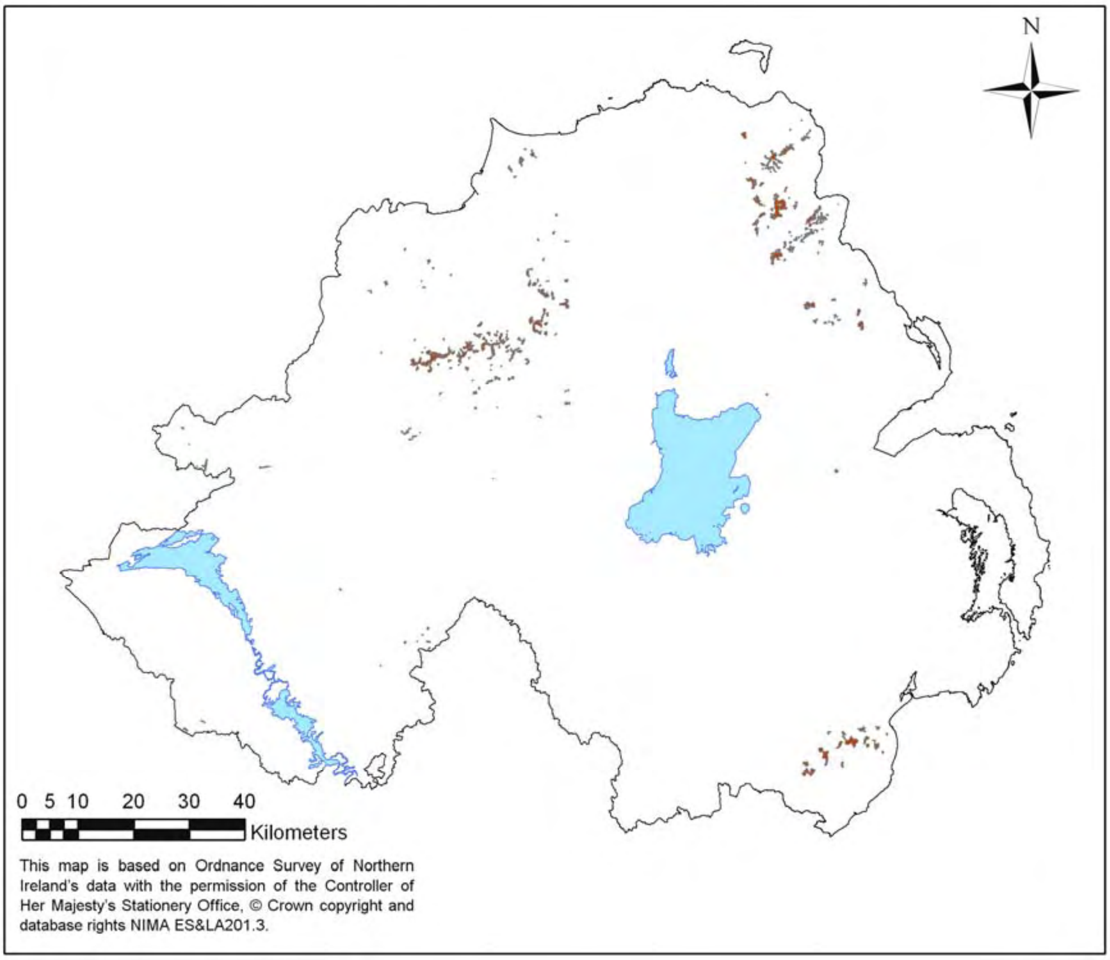
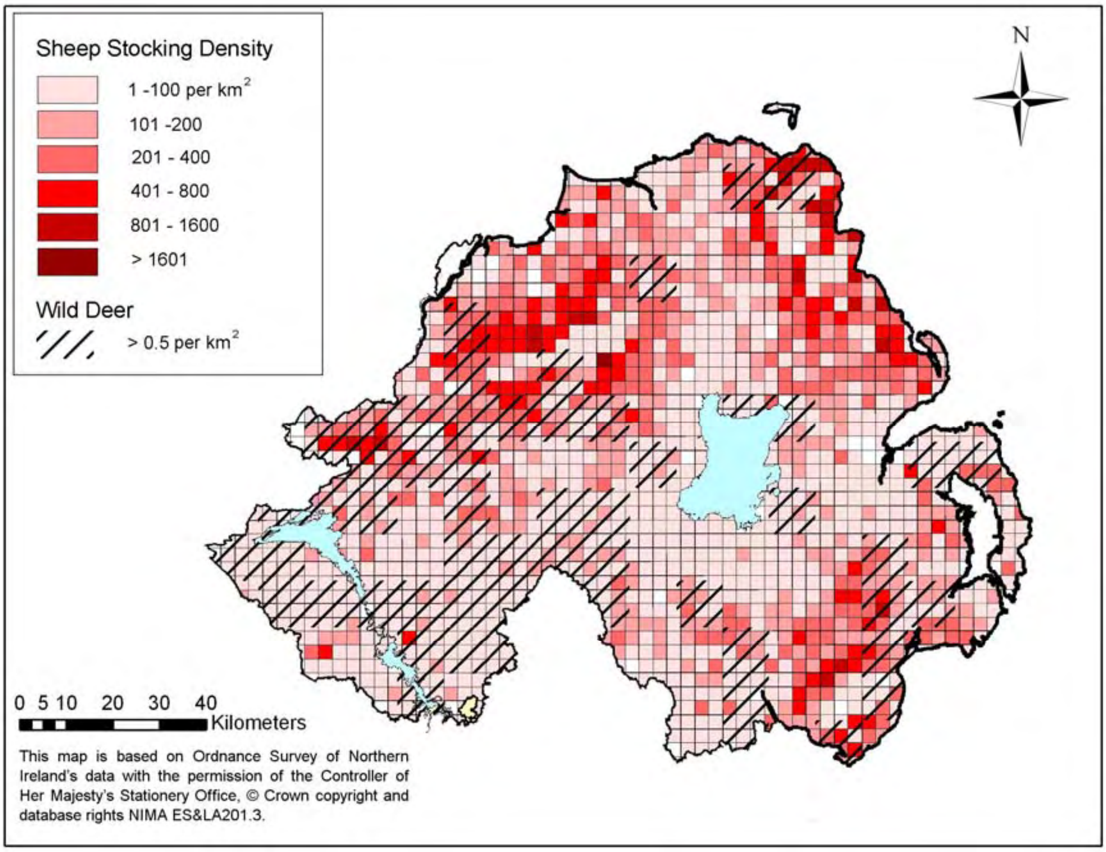


Figure 5.5 The distribution of sheep stocking density and areas of wild deer population in Northern Ireland, derived from DARD (2007) and EHS (2002) data.



5.7 Summary from case studies of areas most at risk of erosion

The case studies provide examples of impacts from representative geographic areas of Scotland across the range of deer densities and vegetation types, and with or without domestic livestock present. Over the majority of these areas, impacts were relatively light, especially on less-preferred vegetation types, including blanket bog. Only where domestic livestock were present, either as the main grazer or combined with deer or where deer densities were very high, were impacts notably heavier and associated with an appreciably greater risk of erosion of organic and organo-mineral soils. Based on the analysis of likely future scenarios, it was considered most likely that sheep would decrease in the future, while deer numbers were likely to continue to increase. Overall, it was considered that areas where deer were present at densities greater than 15 per km^2, combined with areas where sheep were still present (Parish data, RERAD 2006), were those where there was the greatest risk of increased erosion. Also, the land cover category of 'blanket bog with (existing patterns of) erosion' was considered to be the category at greatest risk of exacerbated erosion, due to increased grazing and trampling impact. However, because this increased risk is associated with grazing it is precisely these areas where there is greatest potential for management interventions.

Other drivers, notably climate and hydrology, and atmospheric pollution, while of overriding influence, are not likely to be influenced by land management practices and mitigation techniques at the local or regional level.

5.8 Recommendations

Overall, the most high-risk situations in relation to erosion of organic and organo-mineral soils are considered to be actively eroding peatland systems with existing and extensive areas of bare peat exposed to the on-going effects of a range of drivers of erosion. In relation to these drivers, the main area where there is the possibility of human intervention is that of grazing impact. Those areas considered to be most at-risk are where sheep are still present on the hill, combined with moderate to high numbers of red deer (>15 deer per km^2), and coinciding with areas where eroded peatlands are a notable feature of the topography, either as extensive areas or in mosaic with other vegetation types. Areas of eroded peat mostly occur on broadly convex and undulating, predominantly gently sloping upland terrain. The effects of rainfall, wind, alternate cycles of drying and wetting of the surface, and frost clearly affect these systems, with the predominant agent being excessive water flow, generated during periods of heavy to extreme rainfall. Grazing, and particularly trampling, impacts of herbivores on these areas can lead to exacerbated erosion and increased loss of peat sediment.

Given the range of herbivore impacts and sheep and deer numbers that currently exist across Scotland, it would appear that there is some scope for reducing the risk of erosion by making recommendations in relation to grazing. The areas considered to be most at risk are those with sheep on the hill, in addition to moderate to high deer numbers (>15 deer per km^2). In these areas, there should be consideration of off-wintering sheep on lower ground areas combined with efforts to reduce deer numbers to at or below an overall density of 15 deer per km^2. The numbers of mountain hares could also be controlled within reasonable limits. In relation to burning management, the Muirburn Code (Scottish Government, 2008c) should be strictly followed and areas of blanket mire avoided, especially where there are nearby patterns of erosion. However, it is worth noting that the removal of sheep and deer will have secondary impacts on the wider biodiversity of upland areas, as indicated by the findings of a number of recent and on-going research studies (Evans *et al*., 2006a; Albon *et al*., 2007; SNH, 2008).

It would appear that once peatland erosion is initiated in many instances, there is an inexorable tendency towards almost complete loss of the accumulated peat over time. Clear evidence of this can be seen in many areas of the Scottish uplands, such as the Monadhliaths, central Highlands, north-west Highlands and Shetland. At the same time, there is more limited evidence that under certain conditions a limited amount of 'self-healing' can occur. The exact conditions that lead to this are unknown at present and one can only speculate on possible mechanisms or how such conditions might be generated or encouraged by management interventions.

If the above analysis is correct, then there is a limit to the options that can be taken to reverse or even mitigate the situation. A possible option would be engage in a program of gully blocking. This would aim to prevent further widening and deepening of existing gullies and loss of particulate material. The hope would be that this would initiate and encourage the process of re-vegetation of gully bases, leading to a state where gullies no longer form channels for excess run-off. This approach has been used with some success in the 'Moors for the Future' Partnership, operating in the Peak District area of the south Pennines (http://www.moorsforthefuture.org.uk/mftf/main/Home.htm). However, it is acknowledged that such an approach would be very expensive, especially over such an extensive and remote area.

A more radical approach would be to actively revegetate bare peat surfaces. Again, this has been used in the Peak District National Park, within the 'Moors for the Future' program where fertilizer, grass seed and heather brash have been applied, via helicopter shipment, to exposed peat in an effort to stabilize the peat, reduce erosion and eventually encourage a more natural vegetation. This management strategy is still in its early stages though first signs are encouraging. However, it is an extremely expensive exercise, only possible by the injection of considerable financial resources.

Areas considered to be at highest risk, and where there is the greatest potential from reducing impacts, are those where overall impacts are currently moderate to high, where sheep are still currently being grazed on the open hill, and where deer densities are also moderate to high (>15 deer per km^2). These areas are predominantly in the south and east of the Highlands of Scotland.

OVERALL CONCLUSIONS

6 OVERALL CONCLUSION

The evidence from a wide range of studies suggests that erosion of surface organic horizons has had a significant impact on organic and organo-mineral soils in Scotland and Northern Ireland. At the national scale, erosion has impacted on around 14% of peatland in Northern Ireland and some 35% of peatland in Scotland.

It is difficult to quantify the specific effects of the major drivers of erosion, as some act to damage surface vegetation cover and thus increase the susceptibility of surface organic soil horizons to erosion, while others control the occurrence and rates of erosion (usually from sites with prior surface damage). In most instances, erosion is the result of multiple drivers.

The evidence suggests that overgrazing is probably the major anthropogenic driver, leading to vegetation damage and increased susceptibility of organic surface soil horizons to erosion. The evidence shows that sheep numbers have decreased in recent years but, in Scotland, there is still concern over the numbers of wild deer.

Extreme climatic events, including prolonged warm dry periods as well as intense rainfall events, are the most important triggers for specific erosion incidences. The occurrence of these is difficult to predict but most climate change scenarios suggest that the magnitude and/or frequency of extreme precipitation events are likely to increase.

In relation to organic soils, there is some evidence that degradation has been taking place for many centuries and that key climatic perturbations over this period may have triggered the development of the current gully systems. Any change in climate that increases desiccation of the ground surface is likely to make that surface more vulnerable to agents such as trampling by animals, rainfall or wind, wildfires and human trampling. Current climate change scenarios suggest that increased risk of desiccation is likely.

It is unlikely that drainage, controlled burning or air pollution act as drivers of soil erosion on any significant scale in Scotland or Northern Ireland, while the widespread adoption of the Forests and Water Guidelines has effectively reduced the risk of erosion being caused by forest operations.

It is unlikely that the increased losses of carbon from organic and organo-mineral soils, which are reflected in the increased flux of dissolved organic carbon measured in streams draining upland catchments, are driven by changing climate alone. Much of the increased Dissolved Organic Carbon (DOC) flux represents an adjustment to reduced levels of sulphate deposition following reduced SO_2 emissions over the last two decades. Modelling work would suggest that rainfall rather than temperature changes may be the key climate drivers of DOC flux in the future.

Potential new drivers of erosion in upland organic and organo-mineral soils must also be taken into account in modelling. Although there are strict development guidelines in place, the large number of proposed wind farm developments in upland areas with organic and organo-mineral soils is one example of such potential drivers.

Two process-based models were selected as being appropriate to investigate soil erosion risk in Scotland and Northern Ireland based on the availability of the required input data, the availability of support and the capability to test the impact of changes in key drivers such as land use and climate. These were PESERA (Pan European Soil Erosion Risk Assessment) and INCA (INtegrated CAtchments).

Due to a lack of validation data, PESERA should be used only to determine relative risk of erosion. The model is able to predict changes in sediment yield due to changes in land cover and climate and is sufficiently flexible that both land cover and climate change can be assessed simultaneously if required.

INCA is able to reproduce some of the observed dynamics of DOC fluxes from catchments dominated by organo-mineral soils. Fluxes of both particulate and dissolved organic carbon were positively correlated with precipitation so that increased precipitation resulted in greater losses of particulate and dissolved organic carbon from catchments dominated by organo-mineral soils.

Estimates of the rate of change of carbon content of Scotland’s soils based on published loss rate equations for England and Wales must be treated with some caution; other national studies display different trends. It would be prudent to evaluate other equations and validate against a national soil re-sampling programme currently underway.

The most high-risk situations in relation to erosion of organic and organo-mineral soils are considered to be actively eroding peatland systems with existing and extensive areas of bare peat exposed to the on-going effects of the range of drivers of erosion. Those areas considered to be most at-risk are where sheep are present, combined with moderate to high numbers of red deer (>15 deer per square kilometre).

Possible methods for reducing the risk of erosion in these areas include confining sheep grazing to the growing season (i.e. avoid year-round grazing or winter stocking of these sites) and where necessary reduce deer numbers to at or below an overall density of 15 deer per square kilometre. It is also necessary to be aware of the potential role of other herbivores, particularly rabbits, in damaging these areas.

It would appear that once upland peat erosion is initiated, in many instances, there is an inexorable tendency towards almost complete loss of the accumulated peat over time. There are limited cost-effective options available to redress this trend.

It is important to note that what can be currently observed in the landscape may not be related to present-day conditions but rather to historical ones. This is supported both by data from sediment cores and measurements of contemporary erosion rates. The latter show that the erosional processes are of the order of millimetres per annum, indicating that the processes have endured for several centuries. So a geographical coincidence between erosion and present day conditions cannot be assumed, necessarily, to reflect a causal relationship. The likelihood that multiple drivers of erosion are operating in concert, and the fact that erosional features is relate to historical conditions, does limit options for quantitative analyses of the effects of climate change and land management on the organic and organo-mineral soils of Scotland and Northern Ireland.

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7 REFERENCES

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LIST OF ACRONYMS

8 LIST OF ACRONYMS

AFBI	Agri-Food & Biosciences Institute
BADC	British Atmospheric Data Centre
BOD	Biological oxygen demand
CAP	Common Agricultural Policy
CORINE	Coordination of information on the environment
DARD	Department of Agriculture and Rural Development
DEFRA	Department for Environment, Food and Rural Affairs
DEM	Digital Elevation Model
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
DMG	Deer Management Group Area
ECHAM GCM	European Centre for Medium-Range Weather Forecasts Global Circulation Model
ECN	Environmental change Network
ECOSSE	Estimating Carbon in Organic Soils - Sequestration and Emissions
ENVASSO	Environmental assessment of soil for monitoring
FAO	Food and Agriculture Organisation
GAEC	Good Agricultural and Environmental Condition
GIS	Geographic information System
GSNI	Geological Survey of Northern Ireland
HAD GCM	Hadley Global Circulation Model
HBV	An abbreviation of the Swedish name of the department of the Swedish Meteorological and Hydrological Institute
HER	Hydrologically effective rainfall (rainfall - evapotranspiration)
HOST	Hydrology of Soil Types
HMS	Harmonised Monitoring Scheme
INCA-C	Integrated Catchments Model for Carbon
LCM2000	Land Cover Map 2000
LCS88	Land cover Scotland 1988
MI	Macaulay Institute
MLURI	Macaulay Land Use Research Institute
NERC	Natural Environment Research Council
NIRAMS	Nitrogen risk assessment model for Scotland
NSIS	National Soil Inventory of Scotland
NSINI	National Soil Inventory for Northern Ireland
NSRI	National Soil Resources Institute
OM	Organic matter
PESERA	Pan-European Soil Erosion Risk Assessment
PET	Potential evapotranspiration
POC	Particulate organic carbon

PSYCHIC	Phosphorus and Sediment Yield Characterisation in Catchments)
SOM	Soil organic matter
SMD	Soil moisture deficit
SS	Suspended sediment/solids
SSKIB	Scottish Soils Knowledge and Information Base
TOC	Total organic carbon
UKCIP02	UK Climate change Impacts Programme 2002
USLE	Universal Soil Loss Equation
USDA	United States Department of Agriculture
WFD	Water Framework Directive
WWTW	Waste Water Treatment Works

GLOSSARY

9 GLOSSARY

A horizon	A soil layer at or near the surface with an intimate mixture of humus and mineral material.
Acid deposition	Deposition of acidic substances from the atmosphere to the land surface, dissolved in rainwater, as particulate and gaseous deposition and from condensing water from mist and low cloud. These arise from emissions of sulphur dioxide and nitrogen oxide gases and their conversion to sulphuric and nitric acids in the atmosphere.
Alpine podzol	A podzolic soil (see podzol) where the characteristic podzolic features are weakly expressed due to low biological and chemical activity associated with high mountain environments. These soils are subjected to freeze/thaw conditions (cryoturbation) which further weakens the expression of podzolic features often resulting in a uniform brown topsoil rather than a distinct greyish layer. These soils may also be referred to as Oroarctic podzols.
Biological oxygen demand	A measure of the oxygen used by microorganisms.
Blaeberry	Scottish Blueberry.
Blanket bog (blanket peat)	A type of peatland where the underlying topography is masked be the development of peat. The peat is of variable thickness and develops in cold wet climates receiving nutrients primarily from rainwater and the atmosphere.
Botanical macrofossil	Preserved organic remains large enough to be visible without a microscope.

Bulk density	Dry mass of a unit volume of relatively undisturbed soil in its field, that is, aggregated state (kg m^{-3}).
Carbon stock	Total amount of carbon in the soil (often to a specified depth), expressed as mass per unit surface area (kg m^{-2}).
Digital elevation model	A digital representation of topography with information on altitude held electronically.
Dissolved organic carbon	Carbon in organic compounds dissolved in a water body, which are not retained by a 0.45 µm filter.
Ericoids	Ericaceous species.
Erodibility	See erosivity.
Erosivity	The susceptibility of a soil to erode. This term is often applied to the susceptibility of soil aggregates to break and the soil particles be transported.
Gley	Gleys are soils that are waterlogged for part of the year and become anaerobic (lack of oxygen) such that iron becomes mobilised resulting in the development of greyish patches (often on the faces of aggregates) where the iron has been reduced and removed and of orangy flecks (mottles) where the iron is redeposited during oxidation. In soils that are waterlogged for prolonged periods the subsoil layers can be greyish or bluish in colour. These soils are described as being 'gleyed'.
Graminoid	Grass species.
Gully	As an erosional feature, a gully is a small channel that is too deep to be ploughed out, that is deeper than about 30cm.
Haggs	Remnant blocks of peat in a highly eroded peatland.

Hazen unit	A measure of the colour of water.
Heathlands	Land with a vegetation cover dominated by dwarf shrubs.
HOST	Hydrology of Soil Types (HOST) is a classification of UK soils based on the dominant pathways and rates of water movement through the soil and substrate.
Humic gleys	Gley soils that have a organic-rich mineral topsoil.
Humic rankers	Shallow soils with a organic-rich mineral topsoil.
Hydraulic conductivity	A measure of a soil's ability to transmit water when subjected to a pressure gradient. Effectively the ease with which the pores of a soil permit water movement.
Hysteresis	A non linear response of a system which is perturbed in two directions, for example, a soil moisture desorption curve is different from an adsorption curve.
Mass %	Mass of a soil constituent (such as organic carbon) expressed as a percentage of the total mass of soil.
Mire	A type of peatland which is often wet with open pools of water.
Montane	When referring to vegetation, this term describes the prostrate heaths of the Scottish mountains.
Moorland	Uncultivated land with semi-natural vegetation such as dwarf shrubs, sedges and coarse grasses.
Organo-mineral soil	Organo-mineral soils have a peaty surface horizon overlying mineral subsoil horizons. A peaty horizon has more than 35% organic matter content and is less than 50 cm thick.

Peat	Peat is the remains of dead organic material which is decaying under anaerobic conditions. In the Scottish and Northern Ireland soil classification, a peat soil (strictly an organic soil) is one where the surface organic material exceeds 0.5m deep and contains more than 60% organic matter.
Pedotransfer functions	Generally these are regression equations to predict complex and difficult to measure soil properties from more readily available soil data.
Podzol	Podzols are acid soils in which iron and aluminium has been leached from the surface mineral layers and redeposited in the subsoil giving a characteristic greyish upper mineral layer and a bright orangy subsoil.
Pollen	Male sex cells of flowering plants. The outer coat of a pollen grain is highly resistant and persists in the soil. The distinctive nature of the grains allows identification of species that grew nearby.
Regosol	Immature soils with thin and weakly developed surface horizons, often developed on windblown sands.
Soil organic carbon	The carbon contained in soil organic matter (typically 50-60% of soil organic matter).
Soil organic matter	All organic material in the soil; soil organic matter is derived from plant and animal residues added to the soil (litter) which are resynthesised by soil animals and micro-organisms (the soil biomass) into complex materials which are more resistant to decomposition (humus).
Soil series	A soil classification unit where the soils have similar horizon sequences and drainage categories.

Suspended solids/sediment	Soil particles that are suspended within a river or stream.
Tellus project	A geological mapping programme in Northern Ireland.
Tg	Teragram (10^{12} grams).
Total organic carbon	Includes both particulate (POC) and dissolved (DOC) organic carbon.
Water table	Upper level of ground water; the level at which ground water pressure is equal to atmospheric pressure.

Appendixes

Appendix 1 -

Current rule-based, conceptual models used in Scotland and Northern Ireland

Appendix 2 –

Description and assessment of current rule-based erosion models

Appendix 3 -

Case Studies of Impact Assessments in relation to Individual Deer Management Group areas and other related field observations

APPENDIX 1: CURRENT RULE-BASED, CONCEPTUAL MODELS USED IN SCOTLAND AND NORTHERN IRELAND.

Scotland:

INHERENT GEOMORPHOLOGICAL RISK OF SOIL EROSION BY OVERLAND FLOW IN SCOTLAND

Factors affecting soil erosion risk in Scotland

Soil erosion risk depends on the mechanical stability of the soil, the nature and extent of vegetation cover and the occurrence of triggering events such as rainfall and snowmelt. Soil erosion in Scotland is known to be triggered by events such as rapid snowmelt (Wade and Kirkbride, 1998), high intensity rainfall (Hulme and Blyth, 1985; Davidson and Harrison, 1995; Frost and Spiers, 1996) and prolonged low intensity rainfall (Kirkbride and Reeves, 1993). This indicates that rainfall intensity is not a good indicator of the risk of soil erosion rather erosion appears to be initiated when the storage capacity of the soil is reached and runoff is initiated. With increasing slope angles, any potential runoff that is generated will have a greater ability to erode.

Soil particle detachability is a complex attribute influenced by the amount and type of clay and by the amount of organic matter. In many soil erosion models (for example, Flanagan and Nearing, 1995; Morgan *et al.*, 1998; Wischmeier and Smith, 1978) soil texture is used as a surrogate for this attribute or as a carrier of this information. As vegetation cover and the binding action of roots affect soil particle detachability, this attribute is generally determined on bare soil. As the erosion risk in this work was assessed assuming bare soil, the rule-based model determines only the inherent geomorphological risk of soil erosion by overland flow based on a consideration of potential runoff over unvegetated soils.

Development of the rule-based model

A transparent, rule-based model was developed (Lilly *et al.,* 2002) which combined slope angle and percentage runoff (Table A1.1) to give a simple ranking of the erosive power of overland flow (ranked a-g). The erosive power was then combined with soil surface texture to produce a number of erodibility classes for both mineral soils (Table A1.2) and organic surface horizons (Table A1.3). These numbered erodibility classes (1-9 for mineral topsoils and I-VIII for organic topsoils) were subsequently grouped into six erosion risk classes (low, moderate and high for both mineral and organic topsoils).

Implementation of the rules within a GIS

The model was applied to national soils and topographic datasets to produce an estimate of the erosion risk throughout Scotland. Each map unit depicted on the 1: 250 000 scale national soil map of Scotland (MISR, 1991) was allocated to a topsoil texture class and to a runoff category. Runoff was predicted from the Hydrology of Soil Types classification (Boorman *et. al.,* 1995). The slope coverage was derived from the 1: 50 000 scale Ordnance Survey digital elevation model. These derived datasets were combined following the rules to produce a map of the soil erosion risk at a resolution of 50 m (Figure 3.13).

Results and conclusions

From a total land area of approximately 77 000 km^2, over 40 000 km^2 (53.4%) of Scotland is classified as having a moderate inherent risk of erosion by overland flow and a further 25 000 km^2 (32.1%) have a high risk. A map showing the dominant erosion class in each 50 m grid cell was produced to provide an overview. As significant areas of Scotland have continuous and permanent vegetation cover, the *actual* area where erosion occurs will be less.

The classification gives a baseline estimate of the inherent geomorphological risk of soil erosion by overland flow in Scotland. Future work will aim to incorporate both land use and climate data into the rule-base, for example, rainfall seasonality, intensity and duration in relation to soil moisture contents, plant growth and land use.

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Table A1.1 Slope versus Runoff to derive erosive power of overland flow

Percentage Runoff	Slope categories (degrees)					
	<2	2-4.9	5-9.9	10-17.9	18-30	>30
<20	a	b	c	d	d	slopes
20-40	b	c	d	e	f	unstable
>40	c	d	e	f	g	

Table A1.2 Erodibility classes for mineral soils based on erosive power and soil texture

Soil texture class	Erosive Power						
	a	b	c	d	e	f	g
Fine	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Medium	*2*	*Low3*	*4*	*Moderate*	*6*	*High7*	*8*
Coarse	*3*	*4*	*5*	*6*	*7*	*8*	*9*

Table A1.3 Erodibility classes based on erosive power and soils with peaty or organic surface layers .

	Erosive Power						
	a	b	c	d	e	f	g
Peaty or humus topsoil	*I*	*II* **Low**	*III*	*IV*	*IV* **Moderate**	*VI*	*VII*
Organic soils (Peats)				***High***	*VIII*		

Northern Ireland

Potential Soil Erosion Risk Mapping in Northern Ireland

The MAFF field guide on soil erosion for farmers (MAFF, 1999a), and its accompanying advisory booklet (MAFF, 1999b), were used to map the potential risk of soil erosion by overland flow across Northern Ireland into one of five classes – very high, high, moderate, low and slight.

Using ESRI's ArcView 3.2a GIS software, including the Spatial Analyst extension, four datasets (viz. rainfall, slope, soils and CORINE land cover) were combined on a 1 km grid to predict potential erosion risk across Northern Ireland. Long-term annual average rainfall for the period 1961-90 was provided by the UK Met Office. The slope layer was derived from a 50m digital terrain model (OSNI, 1999). The soil layer was created from the national soil mapping vector dataset for Northern Ireland at 1:50,000 scale (Cruickshank, 1997). The CORINE (Co-ordination of Information on the Environment) land cover map 1990, as detailed by Tomlinson (1997), was used to allow for the effect of land cover on soil erosion risk. The risk categories and their associated criteria for soil, slope and rainfall are summarised in Table A1.4.

Table A1.4 Assessment of potential soil erosion risk based on soil texture, rainfall and slope.

Soil Textures (Risk categories 1-3)	**Steep slopes > 7°**	**Moderate slopes 3° - 7°**	**Gentle slopes 2° - 3°**	**Level ground < 2°**
Risk category 1 (sand, loamy sand, sandy loam, sandy silt loam, silt loam)	*very high (high)**	*high (moderate)**	*moderate (low)**	*slight*
Risk category 2 (silty clay loam)	*high (moderate)**	*moderate*	*low*	*slight*
Risk category 3 (other soils - mineral and organic)	*low*	*slight*	*slight*	*slight*

where average annual rainfall is less than 800 mm, the risk class in brackets applies

As they were intended for arable farmers (bare soil), the MAFF booklets only describe use of the factors in Table A1.4. However, land cover will obviously impact on the final erosion risk potential of a soil and this was modelled by incorporating a land cover layer.

The effect of land cover

The CORINE land cover grid (Tomlinson, 1997) was introduced at the final stage of the classification to allow for the ameliorating effect of land cover. Based on expert judgment, the standard CORINE land cover codes, e.g. '3.1.2 – coniferous forest', were converted to CORINE erosion risk category values, relative to bare soil, ranging from 0 = least erosion risk ('slight') to 4 = highest erosion risk ('very high') as per the lookup table below (Table A1.5).

Table A1.5 The inherent erosion risk category assigned to CORINE land cover.

Risk Category	Class	Description
4	2.1.1	Non Irrigated arable land
1	2.3.1.1	Good Pasture
1	2.3.1.2	Poor Pasture
1	2.3.1.3	Mixed Pasture
1	2.4.1	Annual crops associated with permanent crops
3	2.4.2	Complex cultivation patterns
1	2.4.3	Land principally occupied by agr\sig nat veg
2	3.1.1	Broadleaved forest
1	3.1.2	Coniferous forest
1	3.1.3	Mixed forest

3	3.2.1	Natural grassland
3	3.2.2	Moors and heathlands
2	3.2.4	Transitional woodland scrub
1	4.1.1	Inland marshes
1	4.1.2.1	Unexploited peat bogs
3	4.1.2.2	Exploited peat bogs

N.B. All other CORINE classes were assigned a value of '0' (zero).

The final potential soil erosion risk value was determined using lookup Table A1.6. For example, if the erosion risk calculated from Table A1.4 (soil type, slope and rainfall factors) was 'very high' but the risk category according to land cover was zero, the overall risk became 'none'. Likewise, an area assessed as having a 'slight' risk of erosion from Table A1.4 will increase to a 'moderate' risk if the CORINE risk category for that area is 4.

Table A1.6 Erosion Risk assessment modified for the effect of land use

	Overall Erosion Risk Categories (derived from Tables 1 & 2)				
CORINE risk category	**slight**	**low**	**moderate**	**high**	**very high**
0	*none*	*none*	*none*	*none*	*none*
1	*slight*	*slight*	*low*	*low*	*moderate*
2	*slight*	*low*	*low*	*moderate*	*moderate*
3	*low*	*low*	*moderate*	*moderate*	*high*
4	*moderate*	*moderate*	*high*	*high*	*very high*

Results and conclusions

From a land area of nearly 13,600 km^2, the areas of Northern Ireland with predicted potential risk erosion classes of 'slight', 'low', 'moderate', 'high' and 'very high' are, to the nearest 10 km^2, 7290 km^2 (54%), 3700 km^2 (27%), 1390 km^2 (10%), 370 km^2 (3%) and 6 km^2 (0.05%), respectively (see Figure 3.13c). Figure 1 illustrates, not surprisingly, that the soils predicted to be at greatest risk from erosion in Northern Ireland are found largely in upland areas with high slope, especially in the Mourne mountains (south-east of map).

The classification scheme used gives a baseline estimate of the inherent geomorphological risk of soil erosion by overland flow in Northern Ireland. However, the generalised map produced using these four datasets on a 1 km grid (Figure 3.13c) should be used for guidance purposes only as factors such as low organic matter, poor soil structure, valley features that tend to concentrate runoff and long unbroken slopes could increase the risk of erosion but are not explicitly allowed for in the current model.

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APPENDIX 2 – DESCRIPTION AND ASSESSMENT OF CURRENT EROSION MODELS

List of attribute and abbreviation used in table

Unk = unknown, pos= possible , Y = yes , N = No

Type	Type of model i.e. conceptual, physical or empirical.	C= conceptual, E = empirical, P= Physical
Spatial scale	Spatial scale that the model is appropriate for.	Farm Field Catchment
Temporal scale	Temporal scale of output eg daily, weekly, annual.	Daily Hourly yearly
Input data	The data requirements of the model. High implies that the model requires a large amount of detailed input data	H= High, L = Low, M = medium
Output data	An indication of what the model predicts.	Sed = sediment, sups sed= suspended sediment, Nut = Nutrient. Eros = erosion
Climate variation	An indication if the model can deal with changes in the climate input data	
Land use variation	An indication if the model can deal with changes in the land use input data	
Availability/ support	Is the model currently supported by the developers	Exp = expensive
Suitability for Organic soils	Can the model predict erosion in organic soils	
Rainfall/ Runoff	Can the model simulate runoff from rainfall	
Land Surface Sediment	Can the model simulate production, transport and deposition of sediment in the terrestrial environment	
In-stream sediment	Can the model simulate production, transport and deposition of sediment in streams	
Sediment-associated water quality	Does the model predict water quality parameters (i.e. nutrients, organic carbon) associated with sediment in the terrestrial and stream environment	

Acronym	name	Type	spatial scale	temporal scale	input data	output	climate variation	landuse variation	availability/ support	suitability for Organic material	Rainfall/ Runoff	Land Surface Sediment: Generation	Land Surface Sediment: Transport	Land Surface Sediment: Deposition	Gully	In-stream sediment: Generation	In-stream sediment: Transport	In-stream sediment: Deposition	Sediment-associated water quality: Land	Sediment-associated water quality: Stream
APSIM	Agricultural Production Simulator: uses modified MUSLE	C	Farm	Daily (?)	H	Eros, nut	Y	Y	Exp	Pos	Y	Y	Y	Y	N	N	N	N	Y	Y
PSYCHIC	Phosphrus and Sediment Yield Characterisation in Catchments	C	Field/ catchment	Daily	H	Run, sed, nut	Y	Y	Exp	Pos	N	Y	Y	Y	N	N	N	N	Y	Y
MEDRUSH	MEDRUSH	C	Catchment	Hourly	H	Run, susp sed	Y	Y	N	Pos	N	N	N	N	N	N	N	N	N	N
SERAE	Soil Erosion Risk Assessment in Europe model	C	Regional	Annual	M	Eros	Y	Y	N	Pos	N	Y	N	N	N	N	N	N	N	N
SWIM	Soil and Water Integrated Model	C	Regional	Daily	M	Run, sed, nut	Y	Y	N	Unk	Y	Y	N	N	N	N	N	N	Y	Y
EPIC	Erosion-Productivity Impact Calculator	C	Field	Daily	H	Run, susp sed, nut	Y	Y	Unk	Y	Y	Y	Y	Y	N	N	N	N	Y	Y
HSPF	Hydrologic simulation Program, Fortran	C	Catchment	Daily	H	Run, susp sed, nut	Y	Pos	Unk	Pos	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
LASCAM	Large Scale Catchment Model	C	Catchment	Daily	H	Run, susp sed, salt	Y	Y	Unk	N	Y	Y	N	N	N	Y	Y	Y	N	Y
STREAM	Sealing, Transfer, Runoff, Erosion, Agricultural Modification model	C	Catchment	Event	H	Sed generation and transport	Y	Y	Unk	N	Y	Y	Y	Y	N	N	N	N	N	N
SWWRB	Simulator for Water Resources in Rural Basins	C	River basin	Daily (?)	H	Streamflow, sed, nut	Unk		Unk	N	Y	N	N	N	N	Y	Y	Y	Y	Y
EMSS	Environmental Monitoring Support System	C	Catchment	Daily	L	Run, susp sed, nut	Y	Y	Unk	N	Y	N	N	N	N	Y	Y	Y	Y	N
IQQM	Integrated Water Quality and Quantity Model	C	Regional	Daily	M	Susp sed, pollutants	Y	N	Unk	Y	Y	N	N	N	N	N	N	N	N	N
AGNPS	Agricultural Non-Point Source pollution model	C	Small catchment	Daily	H	Run, susp sed, nut	Y	Y	Y	N	Y	Y	N	N	Y	Y	Y	Y	Y	Y
AGNPS-UM	Agricultural Non-Point Source pollution model, modified	C	Catchment	Daily	H	Run, susp sed, nut	Y	Y	Y	N	Y	Y	N	N	Y	Y	Y	Y	Y	Y
RillGrow 1 and 2	RillGrow 1 and 2	C	Plot	Abstract	H	Rill formation	N	N	Y	N	N	Y	Y	Y	Y	N	N	N	N	N
CAESAR	Cellular Automaton Evolutionary Slope and River model	C	Catchment/ regional	Annual-Millenia	H	Eros, sed transport	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N
WILSIM	Web-based Interactive Landform Simulation Model	C	Hillslope	Abstract	H	Eros, sed transport	N	N	Y	Pos	N	Y	N	N	Y	N	N	N	N	N
INCA-C	Integrated Catchments Model for Carbon	C	Catchment	Daily	M	Run, DOC, susp sed	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
SWAT	Soil and Water Assessment Tool	C	Regional	Daily	M	Run, sed, nut	Y	Y	Y	Unk	Y	Y	Y	Y	N	Y	Y	Y	Y	Y

												Land Surface Sediment				In-stream sediment			Sediment-associated water quality	
Acronym	name	Type	spatial scale	temporal scale	input data	output	climate variation	landuse variation	availability/ support	suitability for Organic material	Rainfall/ Runoff	Generation	Transport	Deposition	Gully	Generation	Transport	Deposition	Land	Stream
TOPMODEL	TOPMODEL	C	Hillslope	Daily	M	Sed, run	Y	Y	Y	N	Y	N	N	N	N	N	N	N	Y	Y
	Inherent geomrphological risk - Scotland	C	Regional	Steady state	M/ L	Risk	N	Y	Y	Pos	N	N	N	N	N	N	N	N	N	N
	Potential Soil Erosion Risk - Northern Ireland	C	Regional	Steady state	M/L	Risk	Po s	Y	Y	Pos	N	N	N	N	N	N	N	N	N	N
MOSES	Modular Soil Erosion System project	E	Hillslope	Annual	H	Eros	Y	Y	Unk	N	N	Y	N	N	N	N	N	N	N	N
TCRP	Tillage-Controlled Runoff Pattern model	E	Field	Abstract	L	Run, gully formation	Y	Y	Unk	N	Y	N	N	N	Y	N	N	N	N	N
WEPS	Wind Erosion Prediction System	E	Field	Daily	M	Eros	Y	Y	Unk	Pos	N	Y	Y	Y	N	N	N	N	N	N
RUSLE	Revised Universal Soil Loss Equation	E	Hillslope	Annual	H	Eros	Y	Y	Y	N	N	Y	N	N	N	N	N	N	N	N
USLE	Universal Soil Loss Equation	E	Hillslope	Annual	H	Eros	Y	Y	Y	N	N	Y	N	N	N	N	N	N	N	N
USLE-2D	Universal Soil Loss Equation 2D	E	Hillslope	Annual	H	Eros	Y	Y	Y	N	N	Y	N	N	N	N	N	N	N	N
USLE-M	Universal Soil Loss Equation Modification	E	Hillslope	Annual	H	Eros	Y	Y	Y	N	N	Y	N	N	N	N	N	N	N	N
TMDL	Total Maximum Daily Load USLE	E	Catchment	Annual	L	Sed	N	N	Y	Y	N	N	N	N	N	N	N	N	N	Y
IHACRES-WQ		E / C	Catchment	Daily	L	Run, susp sed, nut	Y	N	Y	N	Y	N	N	N	N	N	N	N	N	N
SEDNET	Sediment river network model	E / C	Catchment	Steady state	M	Susp sed, sed distribution	Y	Y	Y	N	Y	Y	N	N	Y	Y	Y	Y	Y	Y
MIKE-11		P	Catchment	Daily	H	Sed yield, run	Y	Y	Exp	N	Y	N	N	N	N	Y	Y	Y	Y	Y
EUROSEM	European Soil Erosion Model	P	Small catchment	Event	H	Sed	N	N	N	N	N	Y	Y	Y	N	N	N	N	N	N
MWISED	Modelling Within-Storm Sediment Dynamics	P	Field	Event	H	Gully formation	N	N	N	N	N	N	Y	N	N	Y	Y	Y	Y	N
PERFECT	Productivity,erosion and runoff, functions to evaluate conservation techniques	P	Field	Daily	H	Run, eros, crop yield	Y	Y	N	N	Y	N	N	N	N	N	N	N	Y	N
ANSWERS	Areal Nonpoint Source Watershed Environment Response Simulation	P	Small catchment		H	Sed, nut		Y	Unk	Pos	Y	Y	Y	Y	N	N	N	N	N	N
CREAMS	Chemicals, Runoff and Erosion from Agricultural Management Systems	P	Field	Monthly	H	Eros, deposition	Y	Y	Unk	N	Y	Y	Y	Y	Y	N	N	N	Y	N
EROSION-3D	EROSION-3D	P	Field/ small catchment	Event	H	Sed dynamics	Unk	Y	Unk	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y

												Land Surface Sediment				In-stream sediment			Sediment-associated water quality	
Acronym	**name**	**Type**	**spatial scale**	**temporal scale**	**input data**	**output**	**climate variation**	**landuse variation**	**availability/ support**	**suitability for Organic material**	**Rainfall/ Runoff**	**Generation**	**Transport**	**Deposition**	**Gully**	**Generation**	**Transport**	**Deposition**	**Land**	**Stream**
EuroWISE		P	Catchment	Event	H	Sed transport, gully formation	N	N	Unk	N	N	Y	N	N	Y	Y	Y	Y	N	N
GLEAMS	Groundwater Loading Effects of Agricultural Management Systems	P	Field	Daily	H	Sed, eros	Y	Y	Unk	N	Y	Y	Y	Y	N	N	N	N	Y	Y
GUEST	Griffiths University Erosion System Template	P	Plot	Steady state	H	Run, susp sed	Y	Pos	Unk	N	Y	Y	Y	Y	N	N	N	N	N	N
KINEROS2	Kinematic Runoff and Erosion Model	P	Catchment	Event	H	Sed yield, run	N	N	Unk	N	Y	Y	Y	Y	N	N	N	N	N	N
EGEM	Ephemeral Gully Erosion Model	P	Field	Event	M	Gully formation	N	N	Unk	Pos	N	N	N	N	Y	N	N	N	N	N
LISEM	Limburg Soil Erosion Model	P	Catchment	Event	H	Run, Sed Yield	N	N	Y	N	Y	Y	N	N	N	Y	Y	Y	N	Y
TOPOG		P	hillslope/ Catchment	Daily	H	Water logging, eros hazard, solute transport	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N
WEPP	Water Erosion Prediction Project	P	Hillslope/ catchment	Daily	H	Run, sed	Y	Y	Y	Pos	Y	Y	Y	Y	N	Y	Y	Y	N	N
WATEM	Water and Tillage Erosion Model	P	Field	Abstract	L	Sed tranport and eros	Unk	Y	Y	Pos	N	Y	Y	Y	N	N	N	N	N	N
PESERA	Pan-European Soil Erosion Risk Assessment model	P	Regional	Annual	M	Runoff and soil eros	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N
USPED	Unit Stream Power-based Erosion Deposition	P	Hillslope	steady state	M	Eros	Y	Y	Y	Pos	N	Y	N	N	N	N	N	N	N	N

Models highlighted were subsequently used in this project

APPENDIX 3. CASE STUDIES OF IMPACT ASSESSMENTS IN RELATION TO INDIVIDUAL DEER MANAGEMENT GROUP AREAS AND OTHER RELATED FIELD OBSERVATIONS.

DMG case study 1 – Northern, north Scotland

This survey was carried out in 1999 (Stolte *et al.*, 2000b). Although this DMG area is relatively low-lying, the climate could best be described as exposed, with mild to moderate winters on the coastal fringes and more severe winters on the higher lying areas (Birse and Dry, 1970; Birse, 1971). Rainfall seldom exceeds 1000 mm in this area with the exception of higher ground where averages of around 1200 mm can be expected. The Moine Thrust lies to the west of this area separating it from the more mountainous north-west highlands. A dissected plain highest in the south and sloping north to the coast makes up the region. The underlying rocks are metamorphic granulites and schists with areas of igneous granite and allied rocks. Towards the east, large areas of sedimentary sandstone appear. Soils consist mainly of peat, peaty gleys and peaty podzols. Towards the fringe of the area, non-calcareous gleys, some peaty gleys, brown forest soils and brown rankers occur on semi-improved agricultural (Futty and Towers, 1982). Overall deer density was low in this area (<10 deer per km^2).

A Summary of the distribution of Grazing and Trampling Impact Classes for the Northern Deer Management Group Area is shown in Appendix Table A2.1.

Table A2.1. The distribution of Grazing and Trampling Impact Classes, Northern DMG area, for areas grazed by red deer, red deer and sheep (and cattle), and sheep; and feeding areas for red deer and/or sheep.

	Total area	**Overall Grazing and Trampling Impact Class and % of area**				
Management Unit type	(km^2)	**L**	**LM**	**M**	**MH**	**H**
Red deer areas	548.9	59	36	5	0	0
Sheep areas	204.5	33	27	27	9	4
Deer and sheep (and cattle) areas	555.7	36	49	12	1	2
Feeding areas (sheep/deer)	8.8	0	0	36	59	5
Total area	**1317.8**	**45**	**40**	**11**	**2**	**2**

L = Light; LM = Light-Moderate; M = Moderate; MH = Moderate-Heavy; H = Heavy.

Overall impact classes of Light and Light-Moderate accounted for 85% of the area, while the Moderate Impact Class accounted for 11%, and the Moderate-Heavy and Heavy impact classes both accounted for 2%. Overall Impact Classes ranged from Light to Moderate in areas grazed by red deer only. Moderate-Heavy and Heavy impacts were more frequent in areas grazed only by sheep than in areas grazed by red deer and sheep, and were most frequent in sheep/deer feeding areas.

In general, impacts were lightest on areas of wind-clipped heath and also relatively light on blanket bog and blanket bog with dubh lochans, where they varied from the Light to Moderate. Impacts were slightly heavier on blanket bog with peat workings, and on dwarf-shrub heath, both with and without burning, while impacts were heaviest on smooth grassland, and mosaics of smooth grassland with dwarf-shrub heath.

The results of this grazing and trampling impact assessment showed that 4% of the Northern DMG area overall was in the Moderate-Heavy and Heavy impact classes. Sheep was the main herbivore in 54% of this area with the Moderate-Heavy and Heavy Impact Classes. Twelve percent of the area with the Moderate-Heavy and Heavy Impact Classes was located in feeding areas. Overall, the red deer population in the Northern DMG area was associated with Light to Moderate grazing and trampling impact on most of its range. Blanket bog, the most extensive vegetation type in the DMG area, is usually the least preferred for grazing by red deer (and sheep). However, blanket bog is fragile and impacts, in particular of trampling, can be substantial. Although Overall Impact Classes on blanket bog and blanket bog with dubh lochans were mainly assessed in the Light and Light-Moderate Impact Classes, some samples were assessed within the Moderate Class (on blanket bog and blanket bog with dubh lochans), and the Moderate-Heavy and Heavy Classes (on blanket bog). Sparse vegetation cover with bare peat showing, low *Sphagnum* cover, widespread trampling by deer (foot prints) and dried out and hard peat surface were the main characteristics of Moderate-Heavy and Heavy impacts on blanket bog vegetation. The associated grazing impact by deer was usually not substantial (few heather shoots grazed, no grazing-induced heather growth forms).

Many areas of blanket bog have been drained in the past. Here a drier form of bog or wet heath vegetation has developed with low *Sphagnum* cover, more common cotton-grass (*Eriophorum angustifolium*) rather than hare's-tail cotton-grass (*Eriophorum* *vaginatum*), deer grass (*Trichophorum cespitosum*), cross-leaved heath (*Erica tetralix)* and heather (*Calluna vulgaris*). During the summer of 1999 a population explosion of the heather beetle (*Lochmaea suturalis*) occurred in the area, causing defoliation and severe dieback of heather plants over extensive areas. The heather beetle impact was ignored when assessing grazing impact on heather in affected areas. It is likely that the grazing impact on the unaffected heather will increase until the areas affected by heather beetle have recovered.

Moderate-Heavy and Heavy impacts on blanket bog, or Moderate impact on blanket bog with dubh lochans, did occur in the south-east part of the DMG area, suggesting that the impact of red deer was heaviest in this part of the area. If the deer population is allowed to increase, it is likely that Moderate-Heavy and Heavy impacts on blanket bog will become more widespread. Grazing-induced growth forms of heather are characteristic of Moderate-Heavy and Heavy impacts on dwarf-shrub heath, and were most common in sheep/deer feeding areas. It is likely that if the current grazing pressure continues on these areas, the heather will remain in a suppressed state, or will decline in cover and be replaced by grass species or bare peat, with a higher risk of erosion.

DMG case study 2 – West Sutherland, north-west Highlands

This survey was carried out in 2000 (Henderson *et al.*, 2000). The main vegetation categories present were mosaics of dwarf-shrub heath and blanket bog (72%), and blanket bog (15%). Dwarf-shrub heath and smooth grassland comprised 7% and 1% respectively. Mosaics of dwarf-shrub heath and smooth grassland, montane vegetation and cliffs also accounted for more than 1% of the area.

The area is underlain mainly by a variety of metamorphic and sedimentary rocks. Metamorphic rocks include acidic, intermediate and basic Lewisian gneisses in the north-west which are increasingly overlain by Torridonian sandstones to the south. In the central area the foregoing rocks along with Cambrian strata (including sandstone and grit, pipe-rock and basal quartzite, serpulite grit, fucoid beds and Durness limestone) form a mountainous zone where the rocks have an extremely complex pattern of occurrence as a result of ancient thrusting and folding. Further east, more uniform quartz-feldspar granulites of Moinian Age give rise to mountains in the north-west, but more subdued undulating hilly topography largely covered by peat occurs towards the south-east. Igneous rocks are best-represented to the north-west of Ledmore and in Glen Oykel where the underlying rocks are principally granite.

The climatic divisions vary from fairly warm moist to cool rather wet in lowlands, fairly warm moist to cool wet in foothills, and, on higher hills, from cool rather wet uplands to very cold wet mountain (Birse and Dry, 1970). Rainfall generally exceeds 1600 mm and increases to 2400-2800 mm on higher ground.

The most commonly occurring soil types are peat, peaty gleys, and peaty rankers along with some peaty podzols. Where slopes are gentle, blanket peat predominates in both uplands and lowlands, while at higher altitudes subalpine and alpine soils, lithosols and regosols are prevalent (Futty and Towers, 1982). Overall deer density was moderate to high in this area (>15 deer per km^2).

The distribution of Grazing and Trampling Impact Classes for the West Sutherland Deer Management Group area and the areas of the three Management Unit types is shown in Appendix Table A2.2.

Table A2.2. The Distribution of Grazing and Trampling Impact Classes for the West Sutherland DMG area, and for Management Unit types.

	Total area	**Overall Grazing and Trampling Impact Classes**				
Management Unit types	(km^2)	**L**	**LM**	**M**	**MH**	**H**
Red deer areas	892.3					
Red deer and sheep (cattle) areas	242.1	27	16	39	11	7
Sheep areas	1.7	1	0	0	88	11
Total area	**1136.1**	**21**	**38**	**29**	**10**	**2**

L = Light; LM = Light-Moderate; M = Moderate; MH = Moderate-Heavy: H = Heavy.

Overall impact classes of Light and Light-Moderate made up nearly 60% of the area, while the Moderate impact class accounted for 29%. The Moderate-Heavy impact class occurred on 10%, and the Heavy class only on 2% of the area.

The distribution of overall Impact classes on the 80% of the area grazed only by red deer was very similar to that for the total area. In areas grazed by both deer and domestic herbivores (mainly sheep, locally cattle), the proportions in the Moderate-Heavy class were similar to the overall picture while those in the Light, Moderate and Heavy Classes were greater (27%, 29% and 7% respectively), with only 16% experiencing Light-Moderate Impact. The remaining small areas where grazing was by relatively high densities of sheep were predominantly in the Moderate-Heavy and Heavy overall impact classes.

The lighter Impacts (Light, Light-Moderate) were recorded principally on categories of blanket bog and mosaics of blanket bog with dwarf shrub heath, and also on much of the area with montane vegetation. Moderate Impacts were prevalent on drier areas of dwarf shrub heath, while mosaics of grassland and dwarf-shrub heath generally experienced more intensive grazing, and impacts ranged from Moderate to Heavy. Smooth grassland was under the greatest grazing pressure, and was assessed as having Heavy Impact for the most part.

The general pattern of overall impact was related principally to the grazing quality of the vegetation modified by the distribution of herbivores, and sometimes influenced by the presence of feeding areas and wintering grounds. However, a number of other factors affect impacts locally, especially soils, geology, slope, shelter and altitude.

Overall Impact Classes ranged widely in areas where red deer were the principal grazing herbivore. Moderate-Heavy and Heavy overall impact classes occurred on preferred vegetation categories (smooth grassland and its mosaics), and in areas with high deer densities even where the grazing resource was of poor quality (dwarf shrub heath, blanket bog and their mosaics). In such areas, there was an associated risk of increased erosion, especially on eroded peatland areas. In areas with low density and poor grazings, impacts were generally in the Light and Light - Moderate Classes.

Where sheep (and occasionally cattle) were grazing in addition to deer, densities of both herbivores tended to be relatively low and impacts were consequently rarely greater than Moderate, except on the preferred vegetation categories of high grazing value (smooth grassland and its mosaics), and also on small areas with enclosed sheep.

DMG case study 3 – North Ross, northern Highlands

The main vegetation categories present were dwarf-shrub heath and mosaics with blanket bog, blanket bog and montane vegetation (Nolan *et al.*, 2002b). Grassland and mosaics where grassland was a component account for only 3% of the area. The underlying geology is dominated by quartz-feldspar granulites of the Moinian Assemblage, with some mica schist. To the west of the Moine Thrust, notably in the Elphin area and in a narrow band north of Ullapool, contrasting rock types dominated by limestone with some Torridonian Sandstone and Cambrian Basal Quartzite occur. Also, there are large masses of granite in the Kildermorie and Inchbae areas and some Old Red Sandstone strata to the east of Strathvaich. Soil types developed on these predominantly acid rock types under a cool wet largely oceanic climate are dominated by peaty gleys, peaty podzols, peat and montane soils. Overall deer density was moderate (16 deer per km^2) and domestic livestock were present on only a small number of estates. Four management unit types were identified, namely red deer only, sheep and red deer, and sheep, cattle and red deer, and red deer winter feeding areas. Overall, in 2001-02, the grazing and trampling impact classes were found to be as follows: Light, 28%, Light-Moderate, 50%, Moderate, 16%, Moderate-Heavy, 5% and Heavy, 1% of the total area. The relationship between the ‘main herbivores’ and percentage impact in the different classes is given in Appendix Table A2.3.

Table A2.3. Overall Grazing and Trampling Impact Classes for the North Ross Deer Management Group area, and for the four Management Unit types.

			Grazing and Trampling Impact Classes and % of area				
Management Unit type	Area (km^2)	Area (%)	**L**	**LM**	**M**	**MH**	**H**
Red deer	611.3	79	24	54	17	5	<1
Sheep and Red Deer	92.2	12	60	22	6	7	5
Sheep, Cattle and Red Deer	66.8	9	9	60	22	7	2
Red Deer Winter Feeding/Semi-Improved	0.8	<1	3	4	38	55	0
Overall	**771.1**	**100**	**28**	**50**	**16**	**5**	**1**

L = Light; LM = Light-Moderate; M = Moderate; MH = Moderate-Heavy; H = Heavy.

In areas grazed principally by red deer, the Light and Light-Moderate impact classes accounted for 78% of the area, compared to 82% in areas grazed by both sheep and deer, and the Moderate class accounted for 17% of the total area, compared to 6% for sheep and deer. The Moderate–Heavy and Heavy classes combined extended to 5%, compared to 12% in areas grazed by both sheep and deer. Where cattle were present as well as sheep and deer, the patterns were similar, with Light and Light–Moderate Impact Classes combined accounted for 69%, the Moderate category 22%, and the Moderate-Heavy and Heavy categories together extended to 9% of the area.

In the very limited areas where semi-natural grassland vegetation had been improved for deer grazing, or in the immediate vicinity of where deer were fed during the winter months, impacts were generally higher. The Moderate and Moderate-Heavy Impact Classes together accounted for 93% of the total area. However, such areas extended to less than 1 km^2 of the DMG in total, predominantly in Gleann Mor, Alladale Estate.

There were indications of slightly heavier impacts recorded on the ‘undifferentiated dwarf-shrub heath’ and ‘wet dwarf-shrub heath with blanket bog’ vegetation categories where domestic stock were present in addition to red deer. For the ‘blanket bog with erosion’ category this was reversed, with 10% recorded in the Moderate and 15% in the Moderate-Heavy and Heavy Impact Classes combined. These heavier impacts on eroded blanket bog vegetation associated with deer were largely due to the physical effects of trampling and were recorded principally on the higher plateau areas of the central part of the DMG area, in many instances adjacent to steep slopes and corries often frequented by herds of red deer.

Impacts on smooth grassland and also on mosaics of heath and grassland were heavier where domestic stock were present in addition to red deer, although these vegetation categories were of limited areal extent. In common with many other parts of the country, the general pattern of impacts was related principally to the grazing quality of the vegetation and the distribution of herbivores. In some localities, this was influenced by the presence of feeding areas and deer wintering grounds. However, a number of other factors also affect impacts on the regional and local scale, notably geology, soils, slope, altitude aspect, shelter and heather burning management.

In this DMG area the pattern of impacts was broadly related to topography, with higher overall impacts on lower ground areas and in the straths. In general, it was in these areas where domestic stock were present as well as deer, and where more palatable grassland vegetation was present on better soils, often on steeper slopes, or in association with more base-rich geology. Appreciable areas of grassland vegetation were limited to the Elphin area (on limestone), and in Glen Achall, Gleann Mor and Strath Vaich. On the higher moorland and more remote mountainous areas, deer were predominantly the only large herbivore present and impacts were generally lighter on vegetation of poor grazing value, dominated by wet heath, blanket bog and montane vegetation. However, in the central part of the area, there were a number of localities where trampling impacts due to red deer on eroded blanket bog led to the classification of this vegetation category as Moderate-Heavy overall impact. Also, in a number of localities, Moderate to Heavy impacts were recorded on some of the higher sheltered slopes and in remote corries where dwarf-shrub heath vegetation and plant communities of higher grazing value such as flushes and montane grassland were present. Such higher impacts were often associated with areas of more base-rich underlying geology, such as the mica-schists in the vicinity of Gleann Beag and the Freevater Forest.

Domestic herbivores exerted an additional influence on impact levels in the areas where they were present. However, this was more often on grassland vegetation that is more resilient and able to withstand heavier impacts compared to more sensitive habitats, such as heath and blanket bog. Mosaics of heath and grassland vegetation where there were heavier impacts, and where there was the likelihood of decline in heather cover and increased erosion risk through time, occurred principally on the steep slopes of Gleann Mor, in the Elphin area, in Strath Canaird and in Strath Vaich. On the upper slopes of Ben Wyvis, Moderate and Heavy impacts were recorded on heath vegetation dominated by blaeberry in mosaic with grassland, and grazed by sheep and red deer.

The general extent and distribution of muirburn management appeared to be similar to that recorded from aerial photographs (LCS88), with only limited areas of muirburn on drier heath areas, generally on steeper terrain. Notable areas of recent burning were observed on the steep slopes of Gleann Mor, associated with Moderate to Heavy impacts on regenerating heather and some erosion of the organo-mineral soils, due to a combination of factors relating to slope, bare ground and the presence of grazers.

Of particular note recorded during the survey was the extent of damage caused by recent and severe outbreaks of heather beetle (*Lochmaea suturalis*). Most particularly, heather in wetter heath and blanket bog vegetation appeared to be the most seriously affected, with extensive areas showing severe dieback and death of heather plants. The long-term implications for the recovery of the vegetation and any associated increased erosion risk are unknown. Deer winter-feeding localities and areas where semi-natural grassland had been improved for deer grazing were characterised by Moderate and Moderate–Heavy impacts, but such areas were not extensive. Rabbits were only recorded as having a significant effect on impacts in the Elphin area, notably on steep grassy slopes, and numbers of mountain hares were very low throughout the DMG area.

Thus, impacts overall were considered to be towards the lighter end of the range, associated with moderate deer densities and the relatively limited extent of domestic livestock grazing. Management objectives in general were largely those of the traditional highland estate (a combination of sporting, agricultural, landscape, recreation and conservation objectives). It is not considered that the soils in this area are at high risk of erosion induced by grazing and trampling, other than some concerns over deer on areas of already eroded blanket bog at higher altitude, and on some of the steeper slopes associated with recent burning.

DMG case study 4 – Gairloch, north-west Highlands

The vegetation was dominated by dwarf-shrub heath, (mostly wet heath) blanket bog, mosaics of heathland with blanket bog, and montane wind-clipped heath, with only a very small proportion of smooth and coarse grassland (Stolte *et al.*, 1999a). The underlying geology consists predominantly of Torridonian sandstone, Cambrian quartzite and Lewisian gneiss. Soil types developed on these predominantly acid rock types under a cool wet oceanic climate are dominated by peaty podzols, peaty gleys and peat. Deer density was low overall (5-10 deer per km^2) and domestic livestock were generally restricted to the crofting fringes. Three management unit types were identified, namely red deer only, sheep and red deer, and sheep and cattle. Overall, in 1998, classes of Light and Light-Moderate impact accounted for 92% of the area, while classes of Moderate, Moderate-Heavy and Heavy impact accounted for only 4%, 2% and 2%

respectively. The relationship between the ‘main herbivores’ and percentage impact in the different classes is given in Appendix Table A2.4.

Light and Light-Moderate impacts accounted for 98% of the total area where deer were the predominant herbivore (66% of the total area). Moderate-Heavy and Heavy impact classes were mainly found on areas where sheep and cattle were the main grazers, predominantly associated with the crofting areas around the coast, but extending inland in some of the glens and on the surrounding hills. Areas of heath with heavier impacts were characterised by grazing-induced growth forms on heather and widespread trampling and breakage of heather stems. On blanket bog vegetation, grazing-induced growth forms of heather, widespread trampling with bare peat exposed, and damage to *Sphagnum* carpets and hummocks were notable features of areas with heavier impacts.

Table A2.4. Overall Grazing and Trampling Impact Classes for the Gairloch DMG area, north-west Scotland, and for the three Management Unit types.

			Grazing and Trampling Impact Classes and % of area				
Management Unit type	Area (km^2)	Area (%)	**L**	**LM**	**M**	**MH**	**H**
Red Deer	228.3	66	92	6	2	<1	0
Sheep and Red Deer	87.0	25	85	8	5	2	<1
Sheep and Cattle	30.2	9	38	13	18	14	17
Overall	**345.5**	**100**	**85**	**7**	**4**	**2**	**2**

L = Light; LM = Light-Moderate; M = Moderate; MH = Moderate-Heavy; H = Heavy.

Impacts overall were relatively light, as would be expected where deer densities were at the lower end of the range for Scotland, and where domestic livestock were mostly limited to the crofting township areas. Management objectives in general were largely driven by a combination of conservation and sporting objectives, and this area (along with other similar areas in northern and western Scotland) is not considered to be at high risk of erosion induced by grazing and trampling, other than on the crofting township areas, where impacts were largely driven by domestic livestock.

DMG case study 5 – Mid-West Association of Highland Estates, west Highlands

The main vegetation categories present are mosaics of dwarf shrub heath and blanket bog, along with dwarf-shrub heath, blanket bog and montane vegetation (Waterhouse *et al.*, 2003). Grassland vegetation accounted for 6% and mosaics where grassland was a component account for a further 6% of the area. The underlying geology includes a relatively wide range of metamorphic and igneous rock types. Soil types developed on these lithologies under a wet largely oceanic climate are dominated by peaty gleys, peaty podzols, peat and montane soils. Deer density was moderate overall (16 deer per km^2) and domestic livestock were present on a number of estates.

Table A2.5. Overall Grazing and Trampling Impact Classes for the Mid-West Association of Highland Estates DMG area, western Scotland.

Management Unit type	Area (km^2)	Area (%)	**Grazing and Trampling Impact Classes and % of area**				
			L	LM	M	MH	H
Overall	629.4	100	28	30	25	12	5

L = Light; LM = Light-Moderate; M = Moderate; MH = Moderate-Heavy; H = Heavy.

The overall percentage impact in the different classes is given in Appendix Table A2.5. Light and Light-Moderate combined accounted for 58% of the area, Moderate 25%, and Moderate-Heavy and Heavy combined, 17%.

DMG case study 6 – South Loch Tay, central-southern Highlands

The main vegetation categories present were mosaics of dwarf-shrub heath and grassland, dwarf-shrub heath, heath and blanket bog, and bog and grassland mosaics (Stolte *et al.*, 1999b). The underlying geology is dominated by quartz-mica schist, slate and phyllite of the Dalradian Assemblage, with intrusions of epidiorite, hornblende-shist, epidote-chlorite-schist, rhyolite and basalt. Soil types developed on these more intermediate and basic rock types under a warm to cool and less oceanic climate include humus-iron and peaty podzols, peat and montane soils. Deer density was moderate overall (15 deer per km^2) and domestic livestock were present on many of the component estates. A summary of the overall grazing and trampling impact classes is presented in given in Appendix Table A2.6.

Table A2.6. Distribution of overall grazing and trampling levels in the South Loch Tay DMG area.

	L	LM	M	LH	MH	H	Total
area (km^2)	40.97	30.32	49.82	4.48	13.52	9.21	148.32
%	**28**	**20**	**34**	**3**	**9**	**6**	**100**

L = Light; LM = Light-Moderate; M = Moderate; LH = Light-Heavy; MH = Moderate-Heavy; H = Heavy

The most commonly occurring grazing and trampling impact class was Moderate (34%), followed by Light (28%) and Light-Moderate (20%). 9% of the area had Moderate-Heavy overall impact and 6% Heavy, while 3 % had overall Light-Heavy impact. Grazing-induced growth forms of heather were characteristic of Moderate-Heavy and Heavy grazing and trampling impact on dwarf-shrub heath. These impact levels were most often found on dwarf-shrub heath occurring in mosaic with grassland. It is likely that the proportion of *Calluna* in this vegetation is declining because of long-term heavy grazing and trampling and is being replaced by grassland. This is also the case on areas where sheep are (or used to be) fed and/or wintered on the hill. It is very likely that this has also happened at many locations throughout the DMG area. Moderate-Heavy and Heavy impact levels on dwarf-shrub heath could be found on each of the six component estates. If the herbivore numbers were to be sustained in these areas, then further loss of heather in favour of coarse grassland was predicted. Improved drainage in combination with long-term heavy grazing, trampling and dunging on blanket bog in the South Loch Tay DMG area appeared to have been the cause of a loss of characteristic bog species (*Eriophorum vaginatum, Calluna vulgaris*) in favour of coarse grassland species. In the long-term this has given rise to a mosaic of blanket bog-coarse grassland vegetation, and there has been erosion of blanket bog in this general area.

Deer, sheep, cattle, mountain hares, rabbits and red grouse were the main herbivores. The total number of ¼-km^2 squares where each herbivore occurred is shown in Appendix Table 2.7. It was assumed that deer were using the whole survey area. Of the 695 ¼-km^2 sample areas, nearly all squares were grazed by deer, sheep and mountain hares, while 306 squares (44 %) had red grouse. Rabbits were less common and found in 25 % of the squares. Only 54 squares had signs of cattle grazing. The management unit types are given in Appendix Table A2.7.

Table A2.7. Management unit types in South Loch Tay DMG area. A total of 695 1/4-km^2 were surveyed.

Management Unit type	Number of squares	% of total
Sheep + deer	585	84
Sheep	84	12
Sheep + rabbits	16	2
Deer	6	<1
Rabbits	2	<1
Sheep + cattle	2	<1

A combination of deer and sheep were the main herbivores over 84 % of the area and both contributed substantially to the observed grazing impact. In 84 squares (12 %) sheep were the main herbivore, while deer were the main herbivore in only 6 squares. Impacts overall were higher in this DMG area, due to a combination of greater herbivore pressure and more intensive moorland management on vegetation with a greater component of mosaics of grassland and heather, developed on less acid soil types under a more favourable climatic regime. There was some erosion of organic soils associated with grazing and trampling impact on peatlands.

DMG case study 7 – West Grampian, central Highlands

This survey was carried out in 2002 (Nolan *et al.*, 2002a). The vegetation is dominated by dry and wet heather moorland, while at lower altitudes, on steep slopes and on the more base-rich soil types, areas of grassland and mosaics of grassland and heather commonly occur. Blanket bog vegetation is characteristic of upland peatland areas, giving way to montane heath on exposed summits and plateaux. Metamorphic rock types predominate throughout the area. To the west of Glen Tilt, the area is dominated by quartz-feldspar-granulites of the Moinian Assemblage, along with a granitic intrusion in the vicinity of the Beinn Dearg. To the east of Glen Tilt, the geology is more complex, with limestone, quartzite, quartz mica-schist, mica-schist and graphitic schist of Dalradian Age. The most commonly occurring soil types are peaty podzols, peat and peaty gleys. Some brown forest soils and humus-iron podzols are found on the lower valley slopes and on steep glen slopes. Blanket peat predominates over extensive upland areas, notably on gently sloping terrain, while at higher altitudes sub-alpine and alpine soils, lithosols and regosols are the most characteristic soil types present (Walker *et al.*, 1982). The climate ranges widely from warm moist lowlands to cold wet upland and mountain areas (Birse and Dry, 1970). Deer density was moderate to high overall (15 to 20 deer per km^2) and domestic livestock were present on only a number of estates. Six management unit types were identified, namely red deer only, deer wintering areas, deer sanctuary areas, sheep and deer, sheep, cattle and deer, and sheep winter feeding areas. The overall Grazing and Trampling Impact Classes for the West Grampian DMG area and for the six groupings of Management Unit types, based on herbivores present, are shown in Appendix Table A2.8.

Table A2.8. Overall Grazing and Trampling Impact Classes for the West Grampian DMG area and for the five Management Unit types.

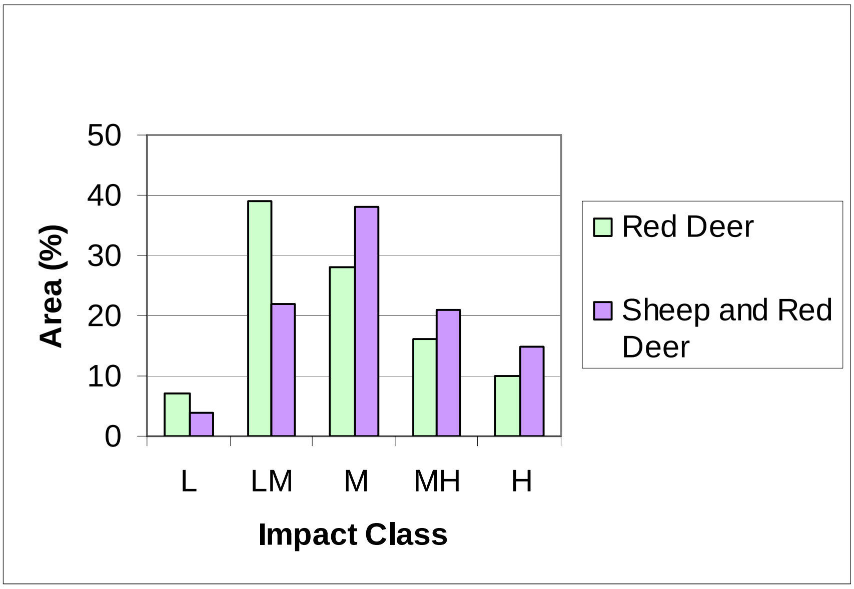
			Grazing and Trampling Impact Classes and % of area				
Management Unit types	Area (km^2)	Area (%)	**L**	**LM**	**M**	**MH**	**H**
Red Deer areas	359.1	50.6	13	33	28	19	7
Red Deer wintering areas	20.2	2.8	10	14	45	28	3
Red Deer sanctuary areas	12.5	1.8	4	32	38	26	0
Sheep and Deer areas	301.3	42.4	6	19	39	19	17
Sheep, Cattle and Deer areas	14.2	2.0	0	<1	68	2	30
Sheep wintering areas	2.7	0.4	0	9	25	0	66
Overall	**710.0**	**100.0**	**10.0**	**25.7**	**33.9**	**18.7**	**11.7**

L = Light; LM = Light-Moderate; M = Moderate; MH = Moderate-Heavy; H = Heavy.

For the management unit types combined, there was a general spread of impacts across the range with Moderate being the most extensive Impact Class. Management units designated as predominantly 'Red Deer' areas extended to 51% of the total area, with 45% of this area classified as Light and Light-Moderate combined, and 28% as Moderate. The remaining 27% was classified as Moderate-Heavy and Heavy Impacts. In the red deer wintering areas and, to a lesser extent, the sanctuary areas, impacts were generally higher, although these areas were not extensive, and the range and extent of vegetation types present were not so comparable to the other management unit types.

In areas where both sheep and red deer were present, impacts were also generally higher, with 25% classified as Light and Light-Moderate Impacts, 39% as Moderate, and 35% as Moderate-Heavy and Heavy Impacts combined (Appendix Figure A2.1). In the relatively small area where cattle, sheep and red deer were present, impacts were predominantly Moderate (68%) and Heavy (30%). Lastly, in the one management unit defined as an open hill area of sheep-wintering ground, impacts were predominantly Heavy.

Figure A2.1. The range of impact classes for areas classified as 'red deer' and 'sheep and deer' management units, West Grampian SMG area.



Heavier impacts associated with areas where domestic livestock were present in addition to red deer were most clearly evident for the 'Smooth grassland with dwarf-shrub heath' vegetation category, and on 'Montane with blanket bog' vegetation. Also, impacts were generally heavier on the blanket bog categories ('with erosion' and 'no erosion') and to a lesser extent on smooth grassland and montane vegetation where domestic livestock were present in addition to red deer.

However, less clear patterns were evident from the comparative data for the dwarf-shrub heath categories. Where domestic stock were present in addition to deer, generally heavier impacts were recorded on dry dwarf-shrub heath vegetation (no burning) but lighter impacts on undifferentiated dwarf-shrub heath (no burning). For the 'with burning' categories of these two vegetation types, Moderate followed by Heavy were the most frequent Impact Classes where domestic stock were present in addition to deer, but on deer-only areas, Moderate-Heavy was the predominant Impact Class. Various mosaic combinations of dwarf-shrub heath, blanket bog and montane vegetation also showed variation in impacts, but with a general trend towards heavier impacts where domestic stock were present in addition to red deer, and associated increased erosion risk.

Monochrome aerial photographs (approximately 1:25 000 scale) from the 1950s/1960s were compared with those from 1988 for a pilot sample of localities to examine whether any trends in heather cover were evident. Of the four sample areas examined (Dalnamein, Lude, Fealar and Glenfernate) all showed evidence of reduction in tonal contrast consistent with loss of heather cover and increase in grassland. This may have been associated with increased erosion risk, although this was not able to be detected from the photographs. However, there was also evidence of reduction in burning intensity on heather moorland between the 1960s and 1980s, which may go some way towards counterbalancing the increased erosion risk through heavier grazing and trampling impact.

In common with many other parts of the country, the general pattern of impacts in the West Grampian DMG area was related principally to the numbers and type of herbivores and the grazing quality of the vegetation, although in some localities it was also influenced by the presence of areas designated as deer sanctuary and wintering grounds. However, a number of other factors also influenced impacts on a regional and local scale, notably geology, soils, slope, altitude aspect, shelter, heather burning and deer management.

Irrespective of management, impacts were broadly related to topography, with higher overall impacts on lower ground areas and on steeper slopes and sheltered areas in the glens. In general, it was in these areas where more palatable grassland vegetation was present, often on better soils in association with more base-rich geology. This was particularly so in the area to the east of Glen Tilt on limestone and base-rich schists, where smooth and coarse grassland, and mosaics of grassland and dwarf-shrub heath, associated with heavier impacts, were commonly found. Impacts were also notably heavier on the steep sheltered slopes of Cama' Choire on Dalnacardoch and on Dalnamein, and on the lower altitude ground in the glens, for instance in Glen Garry, where the A.9 and railway act as a barrier to deer movement southwards.

On the higher moorland and more remote mountainous areas, deer were generally the only large herbivore present and impacts were generally lighter on vegetation of poorer grazing value, notably wet and undifferentiated dwarf-shrub heath, blanket bog and montane vegetation. However, in a number of localities on the blanket bog 'with erosion' category, trampling impacts due to red deer appeared to be exacerbating erosion of the exposed peat, for instance, on the northern part of Glen Bruar and on parts of Forest Lodge. This resulted in Moderate and Moderate-Heavy Impacts being recorded on this vegetation type. Also, in a number of localities, Moderate and Heavy impacts were recorded on sheltered slopes and in corries where dwarf-shrub heath vegetation and plant communities of higher grazing value such as flushes and montane grassland were present. In a number of these localities, there was an abundance of blaeberry and in many instances the morphology of blaeberry and heather plants indicated heavy and sustained grazing impact over a considerable period, notably, on Dalnacardoch, Dirnanean, Fealar and Glenfernate estates.

Impacts on grassland and heath vegetation in the vicinity of the relatively few areas of remnant native woodland areas were generally Moderate or Heavy, and in general there was little evidence of regeneration other than in stream gorges and on crags inaccessible to grazers. However, in a few instances, notably the Fealar Gorge, deer had been excluded from remnant areas of native woodland and there were abundant signs of natural regeneration.

In general, domestic herbivores exerted additional influence on impact levels in areas where they were present as well as red deer, compared to areas grazed by red deer alone. Plant species typical of grassland are able to withstand heavier impacts in the long-term without detriment through adaptations in growth and morphology. However, this is not so for dwarf-shrub species, particularly heather. Some of the heaviest impacts in the area were on mosaics of heath and grassland vegetation, and it is in these areas that there is the greatest likelihood of decline in heather cover through time and increased erosion risk. In many of these areas, the morphology of heather and blaeberry indicated heavy and long-term suppression by grazing, and there was evidence of decline in cover of dwarf-shrub species over time. This was supported by evidence from aerial photographs from the 1960s and 1980s. However, on some management units, such as Dalnamein, Clunes, Rhiedorrach and Urrard, there had been very recent removal of sheep, with the potential for reduction in impacts in the near future on a range of habitats. Where sheep had been removed 5-10 years ago, such as on Glen Bruar and Tarvie, impacts were generally Light to Moderate. The deer-fenced exclosure cages in Glen Shee give an indication of the potential recovery of dwarf-shrub heath vegetation under conditions where all large herbivores (including lagomorphs) are excluded.

The general extent and distribution of muirburn management recorded in 2002 was similar to that recorded in the LCS88 dataset, with most of the muirburn on dry and undifferentiated dwarf-shrub heath areas on terrain where heather cover was continuous. Areas where there had been heather burning, but where burning should be avoided if possible, included the higher altitude ridges and slopes to the north of Beinn Dearg on Glen Bruar and Forest Lodge. Regeneration was poor on these areas of climatically suppressed wind-clipped heath vegetation and it was evident that there had been a number of very large uncontrolled burns in the past. Generally, it is recommended that such areas above 600m are not burned (Scottish Government, 2008c).

In some localities, damage had been caused to heather by recent outbreaks of heather beetle (*Lochmaea suturalis*) notably on wet heath and blanket bog vegetation. However, these outbreaks appeared to have been sporadic in nature and limited in extent, in contrast to the extensive devastation seen in recent years in northern Scotland.

Deer and sheep wintering localities, for instance on West Hand (stags) and Dirnanean (sheep) were characterised by Moderate to Heavy impacts, but such areas were generally not extensive. Rabbits were not recorded as having a significant effect on impacts other than at one or two localities at the interface of enclosed land and the open hill, and the numbers of mountain hares were generally observed to be low throughout the DMG area during the period of field sampling.

Overall, it was concluded that in some areas, there was a likelihood of decline in heather cover through time, associated with heavier impacts of grazing and trampling on mosaics of heather. Also, there were areas of blanket bog vegetation on peatlands with heavy impacts, showing signs of increase in bare ground and erosion risk. These trends may be partially reversed with the on-going decrease in domestic livestock on a number of management units, although deer numbers may continue to rise and become more of an issue in the future.

DMG case study 8 – Angus Glens, eastern Highlands

This survey was carried out in 1999 (Stolte *et al.*, 2000a). The main vegetation types present were dwarf-shrub heath with burning (35 %), mosaics of dwarf-shrub heath and blanket bog (20 %), mosaics of dwarf-shrub heath and grassland (20 %) and blanket bog (14 %). Dwarf-shrub heath without burning, wind-clipped heath, smooth grassland, mosaics of grassland and blanket bog, and smooth grassland with rushes were also present. Winter winds tend to be from the north-east, bringing cold maritime-polar and continental-polar air. The climate can be best described as ranging from fairly warm rather wet lowlands and foothills to very cold wet exposed uplands (Birse and Dry 1970). This area receives considerably less rain than more westerly regions. Average rainfall is about 900 mm per annum in the lowland areas while the upland areas receive between 1200 – 1600 mm per annum.

Much of the area is underlain by quartz-mica-schist, grit, slate and phyllite of the Dalradian Assemblage, with intrusions of acid, intermediate and acid igneous rocks. The Highland Boundary Fault traverses the southern part of the area. Soils consist mainly of peaty podzols, humus-iron podzols, peaty gleys, subalpine soils, alpine soils and areas of eroded blanket peat (Walker *et al.*, 1982). Overall deer density was moderate (15 deer per km^2).

A summary of the distribution of Grazing and Trampling Impact Classes for the Angus Glens Area as a whole is shown in Appendix Table A2.9.

Table A2.9. The distribution of Grazing and Trampling Impact Classes for the Angus Glens DMG area, for areas grazed by red deer, red deer and sheep, and sheep.

	Total area	Overall Grazing and Trampling Impact Class					
	(km^2)	L	LM	M	MH	H	Total
Management unit type		%	%	%	%	%	%
Red deer areas	260.9	10	49	22	16	3	100
Sheep areas	39.12	3	22	41	25	10	100
Sheep and deer areas	320.18	4	33	36	22	4	100
Overall	**620.2**	**6**	**39**	**30**	**20**	**4**	**100**

L = Light; LM = Light-Moderate; M = Moderate; MH = Moderate-Heavy; H = Heavy

Impact Classes of Light and Light-Moderate together accounted for 45% of the Angus Glens DMG area, while the Moderate Impact Class accounted for 30%, the Moderate-Heavy Impact Class 20%, and the Heavy Impact Class 4%. Moderate-Heavy and Heavy Impact Classes were more frequent in areas grazed by sheep than in areas grazed by red deer. Moderate-Heavy and Heavy Impact Classes accounted for 35% in areas where sheep were the main herbivores, 26% in areas where sheep and red deer were the main herbivores, and 19% were red deer were the main herbivores.

The results of the impact assessment suggested that in 24% of the Angus Glen area, overall impacts were either Moderate-Heavy or Heavy. These impact levels are not considered sustainable for heather-dominated vegetation. Visual comparison of vegetation patterns and boundaries assessed during this field survey (1999) with those assessed from the aerial photographs from 1988 (LCS88), clearly showed some areas where loss of heather cover had taken place during the intervening period.

Suppressed growth forms of heather (topiary and drumstick) and fragmentation of heather (increasing areas of grassy vegetation within heather moorland), were observed frequently on dwarf-shrub heath occurring in mosaic with grassland and were mainly associated with grazing and trampling impact by sheep and rabbits. However, in some areas suppressed heather and heather loss appeared to be associated with red deer impacts. The decline in heather cover was accompanied by an increase in the proportion of coarse or smooth grassland species, blaeberry, or bare ground. It was concluded that if herbivore numbers were maintained, further loss of heather and the likelihood of increased erosion, particularly on reas of blanket bog, was likely to occur.

During 1994-1999, considerable effort has been put into reducing red deer numbers in the wider East Grampian Deer Management Group in general and in the Angus Glens sub-area in particular. This was reflected in the biennial red deer counts of 23,935 in 1994, 21,257 in 1996 and 18,676 in 1998. However, due to the increased stalking efforts and an increase in recreation activity by hill walkers, the behaviour of the red deer appears to have changed. Instead of foraging in small groups they have formed large herds of sometimes more than 1000 animals. These groups are easily disturbed with large groups of red deer frequently moving through the area over distances of several kilometers, with associated trampling damage. This is particularly the case at higher altitudes where the vegetation consists predominantly of blanket bog, often actively eroding, wind-clipped heath, and mosaics of blanket bog and dwarf-shrub heath. Impacts of trampling and grazing were locally high and not considered to be sustainable in the long-term on these relatively fragile and sensitive habitats.

Another contributory cause of the higher impacts on these vegetation types at higher altitude is the exclusion of red deer from part of their lower altitude traditional wintering ground by deer fencing. Thus, deer are now forced to winter higher on the hill. An additional factor could also be the wintering of large numbers of sheep on traditional deer wintering ground in the glens.

Case study 9 – Assessment of Impacts, Caenlochan Glen, Angus

This investigation was carried out for the Deer Commission for Scotland to describe the status of semi-natural habitats in the Caenlochan Glen, Angus (Hewison *et al.*, 2000). The work principally involved a detailed on-site recording of the impacts of grazing and trampling on the range of habitat types present that qualify the area as a candidate Special Area of Conservation, notably calcareous grasslands, flushes, tall herb vegetation, sub-arctic willow scrub, dwarf-shrub heath and blanket bog.

The assessment of impacts, determined from a range of field indicators for each habitat and impact type, was divided into three classes – low, moderate, or high. These indicators focus primarily on the directly observable effects of current impacts. Vegetation recording focussed primarily on five areas within Caenlochan Glen that supported a wide range of the important habitats. The sampling was based on a 100m x

100m grid, with additional targeted sampling along transects between grid points. Dung count data, species of herbivore responsible and the numbers of larger herbivores present on-site during the field investigation were also recorded, such that the relative impacts of red deer and sheep could be assessed. The current state of habitats was considered in relation to targets for 'favourable condition' status, bearing in mind the nature conservation value of the designated habitats in this area (Member States are required to maintain such Annex 1 Habitats in a state of 'favourable condition' across the European Union as a whole).

A total of 128 individual areas of vegetation were assessed for grazing and trampling impacts, covering ten of the fifteen habitat types for which this area qualifies as a candidate Special Area of Conservation:

1. *Alpine and sub-alpine calcareous grasslands* – All samples were assessed as 'moderate' overall impact, with a greater amount of bare ground due to trampling than would be considered as appropriate for 'favourable condition' status. Sward height was consistently shorter (<6 cm) than the target range for 'favourable condition' (5-10 cm).
2. *Species-rich Nardus grasslands* – All samples were assessed as 'moderate' or 'heavy' overall impact, with a greater amount of bare ground, in general, than would be considered as appropriate for 'favourable condition' status. Sward height was consistently shorter than the target range for 'favourable condition'.
3. *Alpine pioneer formations (flushes)* – The majority of samples were in the 'moderate' category, although 36% were assessed as 'high' overall impact. In relation to poaching damage, 64% of flushes were assessed as being above the level considered appropriate for 'favourable condition', i.e. having >50% of the flush surface disrupted by hoof prints. Also, a similar proportion of samples exceeded the recommended level of grazing on sedge and grass species, which should be no more than 'light'.
4. *Tall herbs* – The results for tall herb stands were the most variable of all the habitat types. This was a reflection of their accessibility, with samples on relatively accessible ground being classified in the 'high' overall impact category, and less accessible areas being classified as 'low' or 'moderate'. The more accessible stands did not meet the targets for 'favourable condition' status.

5. *Sub-arctic willow scrub* – As with the previous habitat, impacts were closely related to accessibility. In situations accessible to surveyors (and herbivores) the majority of willow stands were classified in the 'high' overall impact category, with almost all samples subject to heavy browsing and not meeting the target for 'favourable condition' status. Willow scrub in less-accessible areas appeared to be more vigorous with no obvious browse-line.

6. *Blanket bog* – All samples of this habitat were classified in the 'high' overall impact category. Current trampling pressures are at a level where they are actively leading to increasing erosion. This habitat is in a highly un-favourable condition.

7. *Alpine and sub-alpine heaths* – Impacts were classified as 'high' overall for all samples. This was the only habitat where sheep and mountain hares as well as deer were considered to be responsible for impacts. Sedges and dwarf shrubs were assessed as heavily grazed/browsed. For such habitats to be in a 'favourable condition', overall grazing and trampling impacts should be absent or 'light'.

8. *European dry heaths* – Browsing and trampling impacts were found to be particularly severe on dwarf-shrub heath overall, with 85% of the samples classified in the 'high' overall impact category. All samples were classified as exhibiting chronic heavy browsing-induced growth forms of dwarf shrub species, notably blaeberry. For such habitat to be in a 'favourable condition' at least 90% of vegetation samples should show full expression of dwarf-shrub growth form. In this context, not one of the 36 samples of dry heath vegetation recorded would meet this criterion. In addition, the habitat should be no more than lightly browsed, and again not a single sample was classed in this category. The only area in Caenlochan Glen where these targets may be achieved is on very steep rocky terrain with negligible herbivore accessibility. Trampling damage and the amount of bare ground was also a notable feature of this habitat type.

9. *Eutric scree* – Grazing impact on fern species, tall herbs and dwarf-shrubs varied according to accessibility. In general, tracking development was low or moderate.

10. *Siliceous scree* – Grazing impact varied with accessibility and the physical nature of the individual areas of scree assessed. However, as far as physical damage and tracking is concerned, the majority of samples exceeded the target of less than 5% disturbance, set as a maximum for the habitat to be in a 'favourable condition'.

It was concluded that all designated habitats assessed fell short of targets for 'favourable condition' status with respect to at least one of the criteria in the guidelines. Dung count data and visual counts of herbivore occupancy indicate that red deer were responsible for the great majority of impacts that were recorded. Calculations based on dung counts give rise to very high rates of deer occupancy in the area, equivalent to >50 deer per km^2 on an annual basis. Evidence of sheep occupancy was recorded on the slopes below Glas Maol and it is likely that they are contributing to impacts in this part of the site. The intensity of many of the impacts that were recorded is likely to have already led to a reduction in the extent and biodiversity of nationally scarce habitats that support a number of rare species. Without a reduction in impacts, this deterioration in the natural heritage value is likely to continue, diminishing the nature conservation status of the site.

Case study 10 – Ladder Hills Peat Erosion study

Field data collection was carried out in the Ladder Hills SAC in 2008 to provide information on a related project for SNH, aimed at determining the drivers of peatland erosion in Scotland (Birnie *et al*., in prep), notably related to a number of specific objectives:

a) To provide ground truth information to inform the process of image analysis and validate the semi-automated classification of eroded peat areas.

b) To assess the relative impacts of wild and domestic herbivores and ascertain whether it was apparent that grazing was limiting recovery.

c) To determine whether the current apparent activity of erosion was balanced, increasing or decreasing.

d) To evaluate the potential for restoration and likely methods to promote this.

To achieve these objectives, field data was recorded systematically from a total of 25 sample sites from within six sample areas of the study site, selected as broadly representative of the topography and patterns of peat erosion across the area. This included the following:

1. A record of the sample point and 12-figure O.S. Grid Reference (Garmin-12 GPS)

2. Site photograph (with signboard ID)
3. Ground truth information related to the image classification (bare mineral, bare peat, grey/brown/green and shadow tones, depth of eroded peat, width of banks, etc.)
4. Veg type (NVC type, dominant species)
5. Topography (slopes, patterns of erosion related to ground features, break points, etc.)
6. Impacts (animal presence, tracks, dung, wallows, sheep/deer scrapes, human impacts, burning, ditching, overall impact assessment (after MacDonald, *et al.*, 1998)
7. Apparent state of erosion (active, increasing or decreasing, also whether grazing was limiting recovery)
8. Summary notes related to restoration potential and methods to promote this.

Sample area 1

This area is located approximately 0.5 km to the south of Carn Liath (792 m altitude), towards the southern part of the main Ladder Hills ridge. This area is gently sloping and broadly convex. Data were recorded from three specific locations. The area is dominated by relatively extensive areas of bare peat, eroded down to the mineral substrate in places, with a mean peat depth of approximately 1.5 m. There were also some relatively extensive areas of bare peat material that had been eroded by water and re-distributed as level areas of peat sediment. Tonal patterns of the eroded areas on the aerial photographs included both darker brown colours, related to the darker more humified lower peat layers, and lighter pinkish-brown tones, related to upper layers of less-decomposed *Sphagnum*-rich peat. Peat banks between eroded areas were dominated by lichen-rich *Calluna-Eriophorum* mire (M19c). The contrast in tonal patterns on the aerial photographs between the lighter grey exposed mineral areas, bright green tones of vegetated blanket mire, paler light yellowish green tones of lichen-rich blanket mire, and the darker bare eroded peat areas were very striking, and the image classification of eroded peat areas was generally very accurate. Grazing was not considered to be limiting recovery from erosion and there were only very localised areas of re-vegetation evident where *Empetrum nigrum* and *Deschampsia flexuosa* had colonised bare peat adjacent to exposed substrate mineral material, also some areas of *Empetrum nigrum* and *Calluna vulgaris* expanding out from remnant peat banks.

The overall impact was Light with very few signs of animal or human impact evident. Mountain hares were encountered relatively frequently, but there were only very localised areas where the grazing impact approached Moderate. There was very little sign of sheep occupancy or grazing, no evidence of grazing or disturbance that could be attributable to deer, very few animal or human tracks evident and no burning. Peatland erosion was considered to be active and in a relatively advanced stage and was concluded to be largely climatically-induced through the agents of rainfall, wind and frost, although it was difficult to infer any cause and effect, or rates of erosion. Based on the overall evidence observable in the field, such processes were considered to have been operating over a relatively extended period of time, perhaps hundreds of years.

Sample area 2

This area is located approximately 0.5 km to the east of Carn Liath (792 m altitude). The area includes the gently to moderately sloping broad summit ridge and the steeply to very steeply sloping terrain to the north. The area was not recorded in detail, due to constraints of time, but observed from the opposite hillslope. The more gently sloping summit of the broad ridge is characterised by relatively intact blanket mire. A number of eroded bare peat gullies become evident as the slope gradually increases, leading to the upper part of the steeper slope which is dominated by an area of bare eroded peat, dissected by downslope gullies. The steepest upper part of the slope includes an area of exposed bare mineral material, where peat may have formerly occurred. Below this, the main part of the slope is characterised by dense heather, part of which has recently been burned. Again, there were clear tonal contrasts on the aerial photo image and the image classification of eroded peat areas was generally considered to be very accurate. Peat erosion was considered to be active and in a relatively advanced stage, and was considered to be largely due to the interaction of topography, notably the steepness of slope, and climatic factors, operating over an extended period of time.

Sample area 3

This area is located between Carn Liath (792 m altitude) and Carn Mor (804 m altitude), the latter being the highest point on the Ladder Hills ridge. This area is gently to moderately sloping, broadly convex and undulating with a distinct eroded peat gully system. Data were recorded from three specific locations. The area includes intact blanket mire on the gently sloping ridge to the west, an area of largely eroded peat (the focus of the area of interest) and a system of broadly parallel to diverging eroded peat gullies extending eastwards and downslope. Peat depth was around 1.0-1.5 m, with erosion down to the mineral substrate in places. Again, tonal patterns of the eroded areas on the aerial photographs included both mid-brown colours, related to the darker more humified lower peat layers, and lighter pinkish-brown tones, related to eroded and exposed upper layers of less well humified peat. Peat banks between eroded areas were dominated by notably lichen-rich *Calluna-Eriophorum* mire (M19c). The contrast in tonal patterns on the aerial photographs between the light grey exposed mineral areas, yellowish green tones of lichen-rich blanket mire, and the darker bare eroded peat areas was very notable, with minimal shadow effects. The image classification of eroded peat areas was generally very accurate, although some of the lighter pinkish-brown tones, related to eroded and exposed upper layers of less well humified peat, were misinterpreted as non-eroded. Grazing was not considered to be limiting recovery from erosion. There were localised areas of re-vegetation evident, with *Empetrum nigrum, Calluna vulgaris*, *Deschampsia flexuosa and Polytrichum* sp. colonising both bare mineral and peaty areas.

The overall impact was Light with very few signs of animal or human impact evident. Mountain hares were encountered relatively frequently, but there were only very localised areas where the grazing impact was Moderate. There was very little sign of sheep occupancy or grazing, no evidence of grazing or disturbance by deer, very few animal or human tracks evident and no burning. Peatland erosion was considered to be active and in a relatively advanced stage and was considered to be largely climatically-induced through the agents of rainfall, wind and frost, although it was difficult to infer any cause and effect, or rates of erosion. In some localities, erosion was being somewhat counter-balanced by re-vegetation of mineral and peaty/mineral areas post-erosion.

Sample area 4

This area is located on Broom Knowe (691 m altitude), a broad spur extending southwards from the main Ladder Hills ridge. This area is relatively level, occupying a saddle on the broadly convex ridge. Data were recorded from eight specific locations. Dominated by extensive areas of bare eroded peat, areas of bare grey slaty mineral substrate and level areas of bare re-distributed peat, the most notably eroded terrain coincides with the level saddle part of the ridge. Peat depth was approximately 1.5-2.0 m. Tonal patterns on the aerial photograph were relatively clear, including light grey exposed mineral areas, light yellowish green areas of lichen-rich blanket mire, and a range of darker brown and lighter greenish-brown tones, representing eroded peat areas and possibly re-vegetated areas. In the field, the image classification of eroded peat areas was found to be relatively good, but a proportion of the total actual eroded area (approximately 25%) and specifically the lighter brown areas, were found to correspond to areas of bare peat. While these areas appeared at first glance on the aerial photograph to be possibly re-vegetated surfaces, they were actually level areas of redistributed peat with contrasting surface texture, moisture characteristics and light-reflecting properties to those of the adjacent sloping and eroded peat banks. Peat banks between eroded areas and remnant islands of the former intact blanket mire were dominated by lichen-rich *Calluna-Eriophorum* mire (M19c). Grazing was not considered to be limiting recovery from erosion and there were only very localised areas of re-vegetation evident, with *Empetrum nigrum* and *Calluna vulgaris* colonising some bare peaty areas adjacent to remnant peat banks.

The overall impact was Light with very few signs of animal or human impact evident. Mountain hares were encountered relatively frequently, but there were only very localised areas of grazing. There was very little or no sign of sheep occupancy or grazing, no evidence of grazing or disturbance that could be attributable to deer, very few animal or human tracks evident and no burning. Peatland erosion was considered to be active and in a relatively very advanced stage and was considered to be largely climatically-induced through the agents of rainfall, wind and frost, although it was difficult to infer any cause and effect, or rates of erosion. Based on the overall evidence observable in the field, such processes were considered to have been operating over a relatively extended period of time, perhaps hundreds of years.

Sample area 5

This area is located just to the east of Dun Muir (754 m altitude) on the broadly convex and undulating main ridge of the Ladder Hills. The area includes the gently to moderately sloping broad summit ridge and the more steeply sloping terrain to the east. The area was not recorded in detail, due to constraints of time, but observed from the south. The more gently sloping summit of the broad ridge is characterised by relatively intact blanket mire. Downslope to the east is an area of eroded peat, banks and gullies.

Tonal patterns on the aerial photograph were far less contrasting than for the previous four sites. The image had an overall greenish-brown appearance, and while the peat banks and relatively more intact areas of blanket mire were broadly recognizable, bare peat areas were far from clear. Also, the classification of eroded peat areas was made more problematic by the pronounced shadows evident on this image. On the ground, the pattern consisted of bare eroded peat surfaces and remnant peat banks. The intact mire surface and peat banks between eroded areas were dominated by lichen-rich *Calluna-Eriophorum* mire (M19c). Grazing was not considered to be limiting recovery from erosion.

Peat erosion was considered to be active and in an advanced stage, and was considered to be largely due to the interaction of slope and climatic factors, operating over an extended period of time.

Sample area 6

This area is located on the broadly convex and undulating main ridge of the Ladder Hills, approximately 0.5 km to the west of Dun Muir (754 m altitude). Data were recorded from eleven specific locations. The area is dominated by extensive areas of bare peat, eroded down to the mineral substrate in places, with peat depth of around 1.5-2.0 m and remnant peat banks. Again, tonal patterns on the aerial photograph were far less contrasting than for the previous sites. The image had an overall greenish-brown appearance, and while the peat banks and relatively more intact areas of blanket mire were generally recognizable, bare peat areas were very indistinct, due to the overall greenish-brown appearance of the photograph. In addition, the recognition of eroded peat areas was made more problematic by the pronounced shadows evident on this image. In contrast, field validation revealed the pattern on the ground was very clear and striking, almost exclusively consisting of widespread bare eroded peat surfaces and remnant peat banks. The peat banks between eroded areas and smaller remnant islands of the former blanket mire surface were dominated by lichen-rich *Calluna-Eriophorum* mire (M19c). There were virtually no areas of re-vegetation evident, only very rarely were there instances of *Empetrum nigrum* and *Calluna vulgaris* colonising bare peaty areas adjacent to remnant peat banks.

The overall impact was Light with very few signs of animal or human impact evident. Grazing was not considered to be limiting recovery from erosion. Mountain hares were rarely encountered and there were only very localised areas of grazing. There was very little or no sign of sheep occupancy or grazing, no evidence of grazing or disturbance that could be attributable to deer, very few animal or human tracks evident and no burning. Peatland erosion was considered to be active and very advanced. This was considered to be largely climatically-induced through the agents of rainfall, wind and frost, although it was difficult to infer any cause and effect, or rates of erosion. Based on the overall evidence observable in the field, such processes were considered to have been operating over a relatively extended period of time, perhaps hundreds of years, resulting in extensive areas of >75% and up to 90% bare peat.

Summary

While the areas selected for study were those showing the most active erosion from the aerial photography, other areas on the Ladder hills showed greater evidence of past erosion surfaces becoming gradually revegetated. This varied from fair to good vegetative cover of the gully bottoms, through to almost complete re-vegetation of even vertical faces and a cessation of active erosion. In one case it was unclear, apart from clues in the surface topology, whether the area had undergone erosion or not.

Overall, the peatland areas studied were considered to be actively eroding with extensive areas of bare peat exposed to the on-going effects of a harsh climate. This erosion was considered to be in an advanced or very advanced state. Grazing was not considered to be limiting recovery on any of the sites investigated, with only light impacts attributable to human and animal influences. There was very little evidence of current grazing or disturbance by domestic or wild herbivores, with very few tracks or hoof prints in bare peat, no trampling damage of vegetated surfaces and *Sphagnum* areas, and very little herbivore dung other than hare pellets recorded. There was also very little burning in the immediate vicinity of eroded peat areas, although there was some muirburn of adjacent heather-dominant vegetation on steeper slopes lower down where fires had burned out upslope in the transition from heath to blanket mire.

Areas of eroded peat mostly occurred on the broadly convex and exposed summit ridges of the Ladder Hills around 600-800 m altitude. The effects of rainfall, wind, alternate cycles of drying and wetting of the surface, and frost were clearly evident. Surface flow in channels and gullies appeared to be the most erosive agent and, indeed, water was still flowing in some channels though the weather had been clear. There was also limited evidence of subsurface flow in cracks and/or 'pipes'. While water was visibly responsible for maintaining the erosion process, it was very difficult to speculate on the agent initiating the erosion in the first place. Most peat surfaces were actively eroding, with very little re-vegetation or colonisation by moss or algae. In some areas, up to two metres of peat had eroded over time and the underlying bare mineral substrate was exposed at the surface.

The probable factors responsible for on-going erosion on the six sites were considered to be principally climate (three sites) and climate and topography (three sites).

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Scottish Natural Heritage is a government body responsible to the Scottish Government.

Statement of principles:

Scottish Natural Heritage – the government body that looks after all of Scotland's nature and landscapes, across all of Scotland, for everyone. Our 5 strategic priorities are:

- Caring for Scotland's nature and landscapes
- Helping to address climate change
- Delivering health and well being
- Supporting the Scottish economy
- Delivering a high quality public service

Find out more at **www.snh.org.uk**

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Scottish Natural Heritage
All of nature for all of Scotland