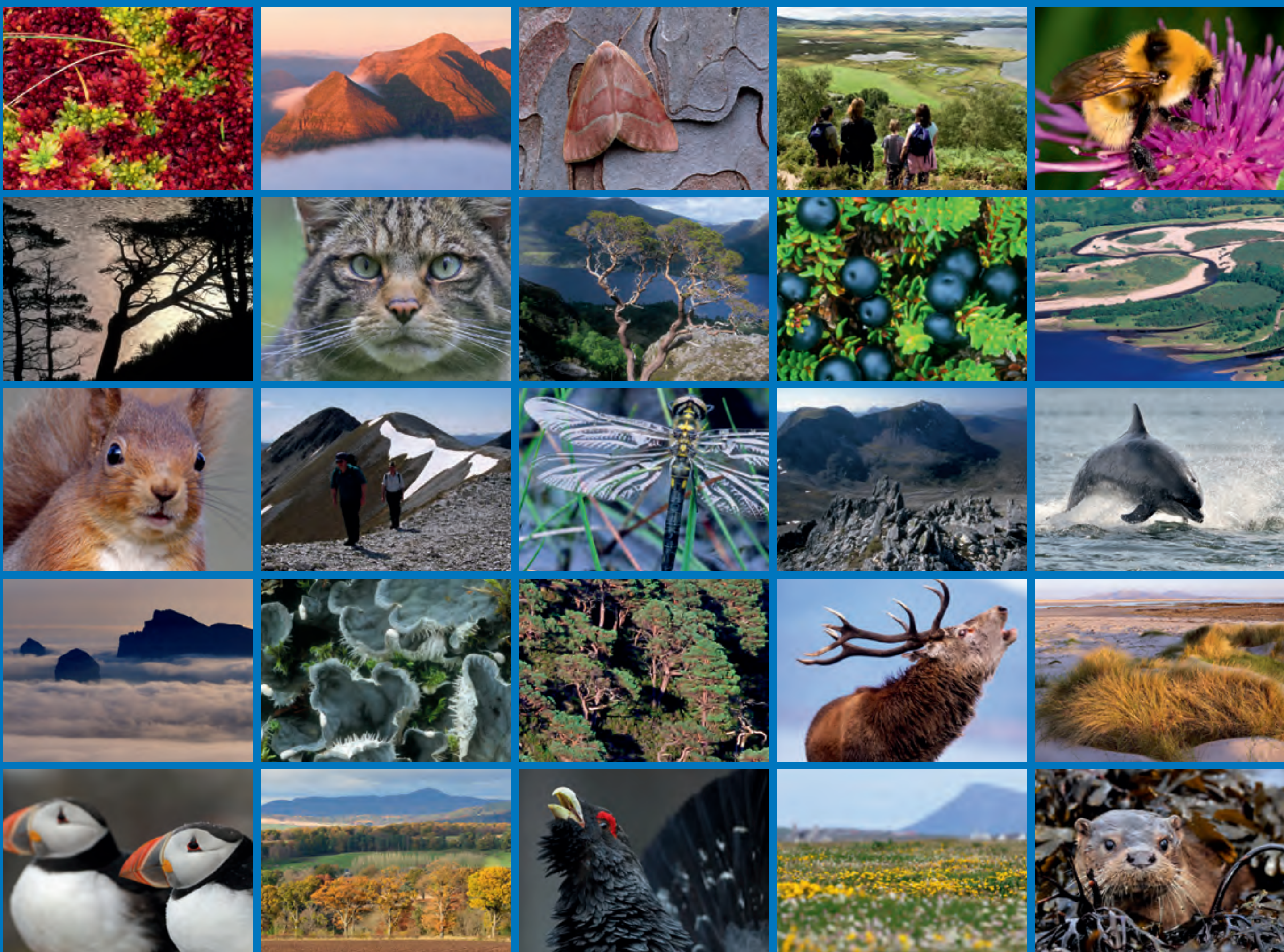
Scottish Natural Heritage
Commissioned Report No. 410

Peat erosion and the management of peatland habitats



COMMISSIONED REPORT

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Peat erosion and the management of peatland habitats

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COMMISSIONED REPORT

Summary

Peat erosion and the management of peatland habitats

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Background

Scotland is unique for its blanket bog habitats of high conservation value. It supports some 10% of the global resource, including many sites designated under the EC Habitats Directive. Their sustainable management is vital not only for the intrinsic value of these habitats and the species they support, but also for their role as carbon stores. Peat and other organic soils cover about 66% of Scotland and contain over 50% of the UK's soil carbon stocks. Erosion is a widespread feature of Scotland's blanket bog. In part this is a natural process but it may be accelerated by human activities, such as land management, and potentially by the impacts of climate change.

This project aims to evaluate the role of different factors known to influence erosion and recovery, including (but not confined to) the impacts of grazing and trampling by herbivores. It also considers the possible implications of future changes in climate. The roles of several drivers were assessed for Scotland as a whole and those most likely to have an impact were then examined in detail in three selected regions of high conservation value selected by SNH staff. The outcomes of this study aim to support the development of advice for the management of blanket bog habitats and soils to secure their favourable condition and to safeguard – and where possible to enhance - their function as carbon stores. In doing so, it is informed by a parallel joint-SNH/SNIFFER project (Lilly *et al*., 2009) investigating the broader patterns and factors underlying erosion in organo-mineral soils in Scotland and Northern Ireland. In particular, the current project aims to provide results that will lead to improved guidance for evaluating the condition of blanket bog sites which are experiencing, or have experienced, erosion.

MAIN FINDINGS

Methodology review

1. Methods for measuring changes in the extent and pattern of peat erosion, erosion risk and the role of different drivers were compared against a common set of criteria to evaluate their suitability for detecting the extent and severity of peat erosion. The methods differed in their accuracy, costs, spatial and temporal scales, sensitivity, and security and stability on site. Many methods were judged to have low sensitivity or no applicability in either the vertical or horizontal dimension. Temporal sensitivity was generally high for field methods while LiDAR was considered to have the greatest potential among the remote methods.

2. The research team considered that field-based measurements required less skill and training and were less expensive than remote sensing methods, for which data acquisition may have to be specially commissioned.

3. The review highlighted difficulties of resolution and registration when imagery taken at different times or from different platforms is used to assess detailed changes in erosion extent and severity. As a result, it was decided to take a correlative approach to assess the impact of different drivers relative to current erosion.

National results

4. Data for the whole of Scotland were used to examine the relationships between eroded peatland vegetation and various parameters of potential drivers, including climate, geography and the densities of sheep (Agricultural Parish returns, 1986-2006) and red deer (counts by Deer Commission Scotland, 1987-2002).

5. Data were acquired for all 250 x 250 m squares centred on the OS 1 km intercepts where peatland vegetation was recorded in Land Cover Scotland 1988 (LCS88). The number of squares eventually analysed had to be reduced from over 15 000 to about 1 000 due to high levels of autocorrelation in the data.

6. After allowing for spatial autocorrelation, regression analyses indicate that mean monthly rainfall, altitude, latitude and exposure are the most important explanatory variables of eroded blanket bog vegetation (LCS88 class '*blanket bog and other peatland vegetation: eroded*'. Note: no criterion is stipulated for the extent of eroded bare ground present).

7. No significant relationships were identified between the area of eroded peatland vegetation and the densities of large herbivores across Scotland as a whole but this may be an artefact of the density data. Although the best available data were used, they may still be too coarse, in both space and time, relative to the extent of erosion.

8. There was a negative relationship between the area of eroded peatland vegetation in sample squares and the area of land designated as a Site of Special Scientific Interest (SSSI). This result probably reflects the policy for selecting areas that are in 'good condition' for SSSI designation. Importantly, it also suggests that the results from the SSSIs selected for detailed studies (below) are unlikely to be typical of eroded blanket bogs in general.

Selected sites

9. Detailed studies were made of erosion in the following three study areas of high conservation value:

    (i) Ladder Hills SSSI;

    (ii) Monadhliath SSSI; and

    (iii) a group of four sites in the Caithness & Sutherland Peatlands SAC: Grudie Peatlands, Srath an Loin and Beinn Sgreamhaidh SSSIs (these three adjacent sites are referred to collectively as 'Grudie Region'), and the Knockfin Heights SSSI.

10. Twenty high resolution (25 cm) airborne digital images were purchased for each study area, each image covering 0.25 km^2 and taken in 2004-2006. The images were distributed between sub-catchments (referred to as sites) that were selected for having varying types of erosion and covering as wide a range of potential drivers as possible.

11. It is important to recognise that the sites were selected deliberately and are not a random selection of land within a study area. Therefore extreme caution is required before making any extrapolations of the results to whole SSSIs or the wider countryside.

12. Detailed studies focused on the relationships between potential drivers of erosion and the area of bare peat, which is a more precise estimate of erosion *per se* than 'eroded vegetation' as used for the national assessments. To minimise subjectivity, an image analysis protocol was developed which identified bare peat from a supervised classification of the red:green spectral balance in the imagery.

13. In the Ladder Hills and Monadhliath study areas, 80% of the area of bare peat occurred on slopes of 10^o or less. The equivalent figure for the Grudie region/Knockfin study area was 4^o, but slopes generally were less here than in the other two study areas.

14. In all three study areas, the mean slope of bare peat areas in the sample squares was less than that of vegetated ground. However, the mean differences were less than 2^o and, though statistically significant in the Ladder Hills and Monadhliath study areas, are clearly too small to be of much practical value for land managers.

15. Analyses of different types of erosion were conducted for the Ladder Hills only and showed that anastomosing erosion systems tended to occur on shallow slopes (mean 6^o) and were mostly associated with exposed sites. Dendritic systems were on similarly gentle slopes (mean 7^o), whereas the mean slope of gully erosion - usually ascribed to localised, high-energy waterflows - was 12^o. Four examples of slippage were recorded, the slopes ranging from 6^o to 32^o (mean 17^o).

16. Apart from slopes, it was inappropriate to conduct formal statistical analyses for most potential drivers of erosion because the data were relatively homogeneous within sites and, where there were differences, sample sizes were small. Inspection of the data from individual study areas revealed no consistent evidence of single or multiple relationships between climatic drivers and areas of bare peat.

17. Similarly, there was no clear evidence to indicate that densities of large herbivores were associated with the incidence, severity or type of erosion, either in the sample squares as a whole or in individual patches of erosion, where numbers of animal paths were used as an indicator of usage. If herbivores are a main driver of erosion, it is possible that this is due to local concentrations of animals that are detectable only by detailed field studies (e.g. using dung deposition counts to assess animal densities).

18. The routes of paths indicated that animals tended to avoid crossing deeply eroded systems. Wide and apparently heavily-used animal paths had developed between pools in some systems in the Knockfin Heights site.

19. Recolonisation was rarely detected either in the imagery or during field validations in the Ladder Hills study area. It was commonly associated with areas where severe erosion had exposed mineral surfaces, suggesting that most bare peat is currently unsuitable for recolonising seedlings. Knockfin Heights was an exception where there were signs of recolonisation on what appeared to be former pools that had dried out. It was not possible to assess if herbivores were a limiting factor in recolonisation.

20. There were few occurrences of burning, recreation or vehicle tracks detectable in the imagery of any of the sample squares and none of these factors was particularly associated with areas of erosion. This does not preclude the possibility that burning carried out 15 or more years previously could have had an impact.

Evidence-based management recommendations

21. The above results provided no firm evidence on which to base management recommendations for individual sites. Either relationships do not exist or are not

detectable using the available data – this cannot be resolved without more localised data on the different likely drivers of erosion. Some site-specific information was available but could only be used to provide background context because of its temporal frequency or spatial scale, or because it was not quantitative.

22. Another possible reason for the apparent lack of relationships might be that sites are inconsistent in their responses to drivers, either individually or in combination. Therefore it is recommended that managers should visit and assess sites individually before deciding on management options. Generalised prescriptive measures could have a low success rate.

23. Climate appeared to be the principal driver of erosion. Possible methods to ameliorate its impacts - based principally on the extensive (and expensive) work in the Pennines - include blocking of gullies, mechanical reprofiling (with or without geo-textiles), spreading of heather mulch and the use of nurse crops to assist natural regeneration.

24. Application of these methods needs to be assessed on a site-by-site basis. Success rates are likely to be greater on slopes of 6^{o} or less. At least half of the area of bare peat in all three study areas was on slopes below this limit.

25. Any management to promote recolonisation must take into account local populations of herbivores (including hares) because they are attracted to the nutritious grazing provided by young plants.

26. High densities of animal paths, particularly in the Knockfin site, indicated that there were some large local concentrations of animals, considerably out of proportion to overall stocking rates. When determining acceptable densities of animals for an area, this should be based on the condition of these vulnerable sites. Other studies show that high-altitude sites are particularly vulnerable, even when animal densities are low.

27. The much quoted maximum densities of 15 deer per km^2 or 0.5 sheep per ha may be used as pre-emptive management guidelines. To be fully effective, it is essential to make site visits to determine (a) if there are any local concentrations of animals, (b) how sensitive the vegetation is likely to be to animal impacts and (c) to assess other ground characteristics that could affect the susceptibility of a site to erosion.

Common threads and their wider applicability

28. The image analysis methodology developed for the detection and measurement of bare peat is widely applicable but, to be cost-effective, LCS88 or similar data should be used to help filter out key areas when assessing areas of several square kilometres or more.

29. A common thread throughout all three study areas was a lack of suitable quantitative data to assist in making informed decisions, especially for the management of deer and sheep but also for localised influences of climate and hydrology. Therefore management decisions must be made on a local basis after local assessments of impacts.

30. There is a range of practical management techniques to ameliorate the impacts of climate. They involve varying degrees of disruption and none is cheap, especially when applied to large areas. Policy decisions may be required about trying to identify and safeguard high quality sites (i.e. currently with little erosion present but potentially vulnerable) or to treat sites that already have considerable erosion present but where management would produce more tangible results.

31. It is unrealistic to try to recreate peat-forming vegetation due to the very long timescale involved. Apart from pool systems, there were few sites where raising water levels *per se* would be the primary aim. Management would usually be targeted at controlling flow rates and direction, and promoting revegetation.

32. The likelihood is that multiple drivers of erosion are operating in concert and some of the current areas of bare peat may be related as much to historical conditions as to more recent impacts. It is highly unlikely that these effects can be readily differentiated, so a 'precautionary principle' approach to management will often need to be employed. Clearly it will be important to monitor the impacts of any management.

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1. INTRODUCTION

1.1. Background

Scotland is unique for its blanket bog habitats of high conservation value. It supports some 10% of the global resource (Lindsay *et al*., 1988), including many sites designated under the EC Habitats Directive. Their sustainable management is vital not only for the intrinsic value of these habitats and the species they support, but also for their role as carbon stores. Erosion is a widespread feature of Scotland's blanket bog. This is partly a natural process, but it can be accelerated by human activities and potentially by the impacts of climate change.

One of the initial aims of this project was to analyse historical and current patterns of accelerated blanket bog loss and peat erosion on selected study areas but this proved to be impractical due to difficulties of resolution and registration when imagery taken at different times or from different platforms is used to assess detailed changes in the extent of erosion. Instead, it was agreed with the Steering Group that the project would use correlation techniques to incorporate currently available data and recent high definition satellite imagery to assess processes of erosion and evaluate the role of different factors known to influence erosion and recovery. These included, but were not limited to, the impacts of grazing and trampling by herbivores. The possible implications of future changes in climate under different scenarios were also considered, informed by a parallel joint -SNH/SNIFFER project investigating the broader patterns and factors underlying erosion in organic soils in Scotland and Northern Ireland, which the Macaulay Institute and Stirling University were undertaking as part of a wider consortium (Lilly *et al*., 2009).

The outcomes of the project aim to support the development of advice for the management of blanket bog habitats and soils to secure their favourable condition and to safeguard and, where possible, enhance their function as carbon stores. In particular, the outcomes would provide guidance for evaluating the condition of blanket bog sites which are experiencing, or have experienced, erosion, and help to inform the options and objectives for their sustainable management and recovery.

1.2. Objectives

The original aims of this project were to assess the factors causing and propagating accelerated erosion in selected peatlands of high conservation value and to evaluate management options for mitigation and to promote recovery. The project was to build upon existing research and overviews of the causes and drivers of peat erosion and was to focus on land of high conservation value.

The specific objectives were:

Objective 1. Review and assess appropriate methodologies and techniques to measure changes in the extent and pattern of peat erosion, erosion risk and the role of different drivers in three study areas. This will include an assessment of the accuracy and scale of changes that can be reliably detected by different methods.

Objective 2. Evaluate the role of different drivers of peat erosion, individually and in combination, in the three study areas. This should include an assessment of the possible links between herbivore impacts and peat stability thresholds. If it is appropriate, it is anticipated that the study will include, but not be limited to, the use of air photographs from different dates.

- Collect and analyse information on the evidence for historical and current patterns and rates of blanket bog loss and peat erosion in the study areas.
- Collect and analyse information on the evidence for historical and current patterns and rates of blanket bog loss and peat erosion in the study areas.
- Collect and analyse information on the factors likely to influence past, current and future patterns of accelerated blanket bog loss and peat erosion and recovery in the study areas. The study will include, but not be limited to, the geomorphological and environmental context of the areas, records of past land-use, indications of past deer/sheep numbers, information on encroachment by livestock, fire events, air pollution and climatic factors, where appropriate.

Objective 3. Prepare evidence-based recommendations relating to the site condition and management of eroding peatland habitats for the studied areas. These will be based on a critical assessment of the issues, processes and pressures. Management solutions for each area will be proposed, including:

- the potential for restoration;
- guidance on evaluating site condition for peatland habitats prone to natural erosion, informed, where possible, by a longer-term perspective of their history and dynamism.

Objective 4. Identify common threads between the areas, which could be used for the development of management prescriptions and restoration guidance applicable to other areas under similar pressures.

The study did not involve *in-situ* experimental measurements or monitoring of erosion processes but did include site visits, where necessary, to provide contextual information to the results.

Revisions to objectives

Following preliminary investigations and discussions with the Steering Group, it was agreed that it would be impractical (perhaps impossible) to plot historical changes in the extent of erosion at a suitably fine scale due to the limitations of the available aerial photography (Objectives 2 and 3) and rates of erosion that could be very slow. Therefore it was decided that the project should examine erosion in terms of the erosion system and processes and use correlative techniques to assess the impact of different drivers. Detailed information was required at the sub-catchment level and this would be the basic spatial unit or site.

2. REVIEW AND ASSESSMENT OF METHODOLOGIES AND TECHNIQUES TO MEASURE CHANGES IN THE EXTENT AND PATTERN OF PEAT EROSION, EROSION RISK AND THE ROLE OF DIFFERENT DRIVERS

2.1. Methods to measure changes in the areal extent and spatial patterns of peat erosion

There have been several attempts to quantify the spatial extent of peat erosion for areas ranging in size from individual catchments to sample squares to the whole of Scotland. Areal extent and spatial patterns are most commonly determined using either ground survey methods or by interpretation of remotely sensed imagery, mainly aerial photographs.

2.1.1. *Ground survey methods*

Presence or absence of soil erosion is often recorded as part of soil survey procedures. During the National Soils Inventory for Scotland (NSIS), presence or absence of erosion features was recorded at 2845 locations throughout Scotland. When the location of erosion features was compared with the area of peat in Scotland, more than 30% of the peat sites had erosion features. NSIS provided the first truly national estimate of the extent of such features based on objective sampling. However, the area of land affected and the depth of features at each site were not recorded, and the severity of erosion cannot therefore be determined from NSIS data. The usefulness of the data is also limited by the 10 year time interval over which the data were collected.

A number of soil maps produced by the Soil Survey of Scotland differentiated and delineated eroded peat from non-eroded peat. This was not done systematically and tended to reflect the relative importance that eroded peat had in different areas. Additionally, eroded peat was not strictly defined in terms of the density of drainage channels or haggs present, so there was a degree of subjectivity involved in its delineation. Nevertheless, these maps do represent the first attempt to identify and map eroded peat over large areas and in the case of 1:63 360 soil maps, at a detailed scale. Although the method used was field survey, the mapping was carried out using 1:25 000 and 1:10 000 scale air photography, enabling a much more accurate delineation than using hard-copy paper maps.

McHugh *et al.* (2002) used ground-based methods in a survey of the extent of soil erosion in the upland areas of England and Wales commissioned by DEFRA. This study set out to estimate volumes of eroded and deposited soil and visited 399 field plots, each 50 m in radius and located using a grid sampling system. Individual erosion features were measured at each site and the area of degraded soil and volume of eroded material were determined. The area of degraded soil was estimated at 2.46% of the area sampled (313.4 ha). This figure represents the area of soil eroded and cannot therefore be compared directly with the NSIS estimates which quantify percentage of sites with evidence of erosion. McHugh *et al.* (2002) also indicated that many eroded sites were revegetated and no longer subject to accelerated soil loss at the time of sampling. The total volume of soil eroded from large scale blanket degradation in upland England and Wales was estimated at 0.242 km^3.

The ground-based survey methods used to estimate the extent of soil erosion in upland England and Wales have important limitations (Warburton *et al.*, 2003). The sampling plots were too small to encompass upland erosion features properly. The definition of the field survey methods was not sufficiently robust to allow reliable re-sampling. In particular, measurements of depth of erosion features implicitly assume that the pre-erosion surface can be objectively identified. Timescales of erosion were also not taken into account, as many features in the Pennines have a complex history of triggers and episodes of erosion over periods of hundreds of years (Warburton *et al.*, 2003).

At a more localised scale, Evans (2005) used ground survey methods in a study of effects of changes in grazing pressure on soil erosion in the Peak District over several decades. The initial estimate was made in 1966 from field observations in randomly located squares covering 10% of the catchment. Scars caused by sheep were the major features identified and these appeared to be eroding most rapidly. Field measurements of the extent and condition of 32 major scar features were repeated at intervals between the late 1960s and 2001 and used to assess the impacts of changes in grazing pressures on erosion (Evans, 2005).

2.1.2. *Use of remotely sensed imagery*

2.1.2.1. Aerial Photographs

The aerial photographs flown to make the Land Cover of Scotland 1988 (LCS88; MLURI, 1993) map have been used in two assessments of the spatial extent of erosion in Scotland. LCS88 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 two categories of land cover: eroded blanket bog and eroded montane vegetation.

The LCS88 dataset shows that just less than 6% of Scotland had 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. 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 6% of the total area. This also holds true for calculations based on the NSIS.

In an independent assessment using the same set of aerial photographs, Grieve *et al.* (1994) quantified the spatial extent and severity of erosion in the Scottish uplands. Using a stratified random sampling scheme, they selected 144 5x5 km squares, a total area of 3600 km^2 or 20% of the defined upland area. Areas affected by erosion were identified by photo-interpretation and outlined on overlays. Eroded areas were grouped in one of three severity classes:

1. narrow, well-defined gullies often with dendritic drainage pattern;
2. broad gullies often eroded down to underlying mineral soil and flanked by bare peat banks; drainage pattern generally not as clear as class 1;
3. remnant peat blocks standing as isolated tables, probably the remains of a formerly more extensive peat cover.

Overlays were captured using a high-resolution video camera and image analysis was used to quantify eroded areas. Although the photographs were not ortho-rectified, overall errors were found to be around 1.5%. In total, approximately 12% of the sampled area had erosional features, with peat erosion accounting for the greatest extent. 6% of the sample area was classified as eroded peat. This figure is very similar to the area of eroding blanket bog found in both the original classification of the LCS88 aerial photographs and in the NSIS ground survey measurements. It must be emphasized again, however, that these data do not indicate that 6% of the upland area of Scotland has been lost to erosion, 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.

By estimating erosion as a percentage of defined sample areas and stratifying sampling on a regional basis, Grieve *et al.* (1994) also provided some assessment of the likely drivers of erosion. This was done through measurements of environmental and land management variables for each sample square and spatial correlation of these with areas of erosion and severity of erosion. This approach highlighted: (a) the Monadhliath Mountains as having the greatest occurrence of peat erosion (20% of the sample area); and (b) the large areas of erosion in the most severe category in the eastern Grampians, possibly linked to grazing and burning pressures (Grieve *et al.*, 1995).

Wishart & Warburton (2001) used a combination of aerial photographs, ground survey and historical sources to map and classify peat erosion in the Cheviot Hills. Comparison of aerial photographs from 1951 and 1983 revealed no change in the pattern and dimensions of dissection systems apart from the development of an obvious scar along a footpath. They suggest that changes in gully development are not detectable from aerial photography over these timescales. Aerial photographs were most useful in classifying erosion forms. Wishart & Warburton (2001) successfully mapped peat erosion as linear, dendritic, anastomosing or slides, and in combination with topographic analysis found that dendritic types dominated the mid-slopes, whereas anastomosing types were almost always confined to the flatter ground above 800 m elevation.

Conventional aerial photographs at scales of 1:25 000 or smaller thus enable the quantification of erosion at a suitable scale for making national and regional assessments of areas affected. However, the resolution of aerial photographs is usually insufficient for measuring change in individual gullies, either as headward extension or as widening. More modern sensors offer possibilities of improving the quantification of changes in erosion features using remote sensing, in particular changes in gully depth rather than extension.

2.1.2.2. Satellite remote sensing

Vreiling (2006) has reviewed the use of satellite remote sensing for assessing water erosion features. Sensors include those detecting reflected radiation in the visible, near-IR and thermal IR bands and imaging radars which transmit microwave pulses and record the reflected signal. The former are far more common and range in spatial resolution from 80 m for the first Landsat satellites to 0.6 – 1 m for the more modern Quickbird and IKONOS satellites. Satellites can detect both specific features and areas of erosion and also the consequences of erosion such as sediment plumes in receiving waters. The resolution of data from older satellites is insufficient to map erosion features, although very large gullies can be detected. High resolution satellites are capable of detecting and monitoring features, although results have not yet been reported in the scientific literature (Vreiling, 2006).

Visual interpretation of satellite images has been widely used to map eroded areas such as badlands, although aerial photographs still allow a better determination of different gully types. Automated classification of satellite images using both supervised and unsupervised techniques have also been used successfully to map eroded areas and different stages of erosion. Digital elevation models can be derived from radar satellite data and, provided the spatial resolution is sufficient, this has great potential for erosion detection and mapping (Vreiling, 2006).

Stove & Hulme (1980) reported on the use of multi-level and multi-band aerial photography in classifying Landsat MSS imagery for peat resource mapping on Lewis. They used 1:27 000 scale panchromatic OS aerial photography to produce 1:12 500 scale base maps using photogrammetry. Their distinction between eroded and intact peat was primarily based on the pattern and development of channels on the peat surface. Whilst they argued that several distinct “stages of erosion” could be identified, they restricted their classification to identifying “moderately eroded” and “severely eroded peatland”. Using this approach, the minimum channel width on the moderately eroded peat was approx 0.6 m, with channel spacing on average from 3-5 m. On severely eroded peat the channel widths exceeded 5 m, with a range of 10 -14 m and commonly with a spacing of 25-35 m. Using 1:60 000 scale photography, they were only able to detect the severely eroded peatland. It was not possible to detect channels less than 0.75 m at this scale. They backed up this detailed photogrammetric work with a stratified random sample of quadrats on the ground. The abundance of plant species was assessed on a ten point Domin-type scale. Their results showed that the relevés from moderately and severely eroded sites were closely related in vegetation terms. This suggests that once an erosion system begins to develop, a characteristic vegetation community develops whose composition changes little as the erosion progresses. These initial vegetational changes reflect changes in the local soil moisture conditions which tend to be drier around the eroding sites. They noted that *Erica cinerea* was a characteristic species of free-draining, relatively dry, eroded peatland areas, with *Cladonia* species also abundant. Where erosion was most active, the peat was generally devoid of plant cover.

Using very simple image classification methods on the Landsat MSS image data, Stove & Hulme (1980) were able to compare the classifications they obtained with those obtained from the photogrammetry. They showed that there was a high correlation between the areas measured from the photogrammetrically-derived maps and those measured from the satellite images for some classes. As would be expected, the highest correlation was 0.945 (significant at 1% level) for the open water category. The lowest correlation was 0.78 (significant at 1% level) obtained for the erosion category. Bearing in mind the fact that this study used Landsat MSS (56 m x 79 m ground resolution) and that the digital image processing facilities available were very limited, this study demonstrated the potential value of satellite data for peat mapping when used as part of a multi-level approach.

The most relevant initiative related specifically to peat was the development by Scottish Natural Heritage of the Scottish Blanket Bog Inventory (SBBI) (Reid *et al.*, 1997). This initiative was founded on the idea that it was not possible to use the field-based National Vegetation Classification (NVC) over large areas of Scotland. The SBBI uses a methodology developed specifically for mapping the extent, variability, condition and hence the conservation interest of the blanket mire (a wetland that supports surface vegetation which is peat forming). It makes no attempt to map other land covers. The method was founded on Landsat TM data because they were less expensive than aerial photography, and because they were already in digital form they could be easily combined with other spatial datasets. It was also felt that the spatial resolution of TM (30 m) was appropriate to mapping such an extensive habitat and that any gaps in detail could be filled by supplementary ground surveys.

A detailed methodology was provided by Reid *et al*. (1997) and comprised 3 stages:

1. automated classification used to target sites for ground reference survey;
2. satellite data processing using ground reference data and masking out the areas that are known to be outside the area of blanket mire;
3. quantitative analysis of the resulting classification.

This approach yielded 7 peatland classes which comprised a varying proportion of the two main NVC blanket mire types (M17 *Scirpus cespitosus* – *Eriophorum vaginatum*; M19 *Calluna vulgaris* – *Eriophorum vaginatum*) and the two sub-communities (M17a *Drosera rotundifolia* – *Sphagnum* spp; M17b *Cladonia*) The statistical analysis yielded an overall class accuracy of 77% (range 64-90%) for the Lewis and Harris area. This was felt to be acceptable given the continuous nature of the landscape and vegetation (i.e. intergrades between classes). The results for Lewis and Harris are reproduced here as Table 1. The SBBI has now been completed for the whole of Scotland. The overall accuracy specifically for the eroded classes is thought to be less than 70% (A. Coupar, pers. comm.) and there is therefore scope for improving the quality of the data in this inventory. The image classification associated with the creation of the SBBI, and other work, suggests that severe and extensive areas of blanket peat erosion can be detected using LANDSAT TM data. However, the accuracy is limited (quoted at below 70%). Comparison with higher spatial resolution data suggests that there is systematic under-representation of narrower gully systems. It is known that these can be recognised using large scale (1:12 500) aerial photography but clearly judgements need to be made about the extra costs associated with that technique and the benefits that might accrue.

Table 1 Summary of the peatland classes and their relative areas/% derived from classification of Landsat TM data for Lewis & Harris and used in the National Blanket Bog Inventory (after Reid et al. 1997, Table 1). The letters refer to the National Vegetation Classification (NVC) class.

Spectral Class Name and Brief Description	**Area of each class (ha)**	**% of total area**
1. **M17/a/b** mixture (high quality peatland vegetation class)	14716	7
2. **M17** with microbroken peat surface	29610	15
3. **M17a** with smooth peatland bog surface and water level across bog (high quality class)	13653	7
4. **M19** drier community, *Calluna vulgaris* dominated	21339	11
5. **M17b** with an eroded peatland surface	32022	16
6. Marginal peatland with thin peat surface	7092	4
7. Bare peat	22165	11
8. Rocky ground	11134	5
9. Grassland	11272	6
10. Woodland	1544	1
11. Sandy soils/dunes	2670	1
12. Land over 200 m - masked from imagery	23151	11
Other non-peatland classes	10113	5

There is no further evidence in the literature of systematic surveys using remote sensing applied to peat in Scotland. There has been more recent research work, particularly focussed around the Southern Pennines by teams from the Universities of Leeds, Manchester and Durham. Early work using Landsat TM suggested that it was inadequate for providing high quality habitat maps (McMorrow & Hume, 1986). Mehner *et al.* (2001) reported on the use of IKONOS data for habitat monitoring in the Northumberland National Park, but Cutler *et al.* (2002) noted that whilst these sensors had higher spatial resolution they still had “relatively poor spectral coverage” (p. 22). With a specific interest in differentiating between exposed peat with differing degrees of humification, Cutler *et al*. (2002) and McMorrow *et al*. (2004) have investigated the potential uses of hyperspectral resolution sensors such as AVIRIS (Airborne Visible and Infrared Imaging Spectrometer) and HyMap. Hymap is an airborne multispectral scanner that acquires data in 128 contiguous narrow spectral bands, in the range 450-2480 nm (visible to short wave infrared) and at a spatial resolution of either 3.2 or 4.5 m. These systems are seen as test-beds for the next generation of satellite-based hyperspectral missions such as ENVISAT. Early results of this work suggest that it will be possible to provide information on surface peat composition across large areas with these technologies.

In conclusion, there has been considerable research and development related to the use of aerial photography and satellite remote sensing technologies to map peat and peatland habitats both in Scotland and the UK more generally. In addition to the National Soils Inventory for Scotland, there are national inventories for land cover and a national inventory of Scottish Blanket Bogs (SBBI). All of these contain some information about peat erosion, and the latter is entirely based upon the supervised classification of Landsat TM imagery. Whilst the SBBI appears to include a significant amount of information on peat erosion, the data are not easily available at the moment. Doubts have been expressed about their reliability (A. Coupar, pers. comm.), and the relevant reports and data are consequently not available directly from the SNH website and may only be made available on request. Recent work using airborne hyperspectral data is yielding some interesting results on detecting the degree of humification of surface peats.

The existing studies are based on the use of LANDSAT MSS (at 80 m spatial resolution) and LANDSAT TM (at 30 m spatial resolution) data. They suggest that the eroded peat can be detected with an accuracy of around 70%. The multi-level study done by Stove and Hume (1980) showed that it was possible to detect small channels of less than 1 m across on large scale (1:12 500) aerial photography but this was not possible on 1:60 000 photography. Given the relatively coarse spatial resolution of the LANDSAT sensors, it is likely that there is systematic under-representation of the narrower gullies, and that the ability to detect wider gullies will be strongly influenced by sub-resolution pixel mixing effects. These effects are likely to be less of an issue with sensors with higher spatial resolutions such as SPOT (10 m) and IKONOS (4 m).

ADDENDUM:

The latest development in the use of earth observation (remote sensing) is presented in:

"Assessing the Extent and Severity of Erosion on the Upland Organic Soils of Scotland using Earth Observation: A GIFTSS Implementation Test: Final Report".

Available online only: http://www.scotland.gov.uk/Publications/2009/11/06110108/0

2.2. **Methods to quantify rates of peat erosion**

2.2.1. *Catchment sediment budgets*

Rates of erosion can be calculated from changes in the spatial extent of features measured over a defined period of time. However, determination of the areal extent of features is often insufficiently accurate for measuring change. Quantification of rates also requires accurate measurement of the depths of features, so that volume (and hence mass) of material lost can be calculated. For reasons such as these, Warburton *et al.* (2003) concluded that reliable estimates of erosion are best derived from detailed analysis of sediment budgets at the catchment scale.

Net erosion rates for entire catchments can be calculated from the sediment load carried by the river draining the catchment (Collins & Walling, 2004). These are usually derived from continuously measured river discharge and discrete measurements of suspended sediment concentrations from samples taken at regular intervals. Suspended sediment concentration and discharge are usually positively correlated and the regression equation linking the two is frequently used to estimate river load over extended periods of time. The relationship between suspended sediment concentration is not linear (usually log-log) and this can lead to significant underestimation when loads are calculated from regression equations (Ferguson, 1986).

Sediment budgets for entire catchments simply provide an estimate of the net flux of sediment leaving the catchment over a period of time. Net sediment loss from catchments masks significant variations in sediment mobilisation and deposition within the catchment system and hence in more localised damage to the peatland system. Evans and Warburton (2005) and Evans *et al.* (2006) present in-depth analysis of sediment fluxes within two contrasting Pennine catchments, which neatly illustrates the complexity of the sediment delivery system in blanket peatland catchments. Evans *et al.* (2006) give mean annual export of 31.2 Mg km^{-2} sediment from the Rough Sike catchment in the northern Pennines and 195.2 Mg km^{-2} from the more degraded North Grain catchment in the southern Pennines. However, erosion rates measured from bare peat surfaces were much more similar in the two catchments, with mean gully wall retreat rates of 19 and 34 mm yr^{-1}, respectively. The major difference between the two catchments was in the deposition and storage of sediment in channels due to extensive natural revegetation in the less degraded north Pennine system. Clearly measurements of erosion rates must be treated with some caution as not all the detached material is exported off-site and is simply redistributed elsewhere in the gully system. The complexity of the sediment delivery system does, however, mask the variability in erosion within the catchment, and total sediment output may not therefore provide the best index of damage to the peat system within the catchment.

2.2.2. *Erosion pins*

Rates of peat erosion at a more localised scale within catchments have been most frequently quantified using erosion pins to determine the rate of retreat of exposed bare peat surfaces. Published rates of retreat for peat surfaces in England and Wales have been summarised by Holden *et al.* (2007a) (Table 2).

The only comparable use of erosion pins to measure retreat rates for peat surfaces in Scotland is by Birnie (1993) for bare peat surfaces at two hill-top sites in Shetland between 1982 and 1987. Mean erosion rates were between 10 and 40 mm yr^{-1}, very similar to the range reported for sites in Northern England and Wales. Again such values represent near worst-case scenarios, in this case bare peat on very exposed sites.

Erosion rates reported in the literature for bare peat surfaces in the UK determined by erosion pins are remarkably consistent, with most published values in the range 15-40 mm yr^{--1}, but these apply only to exposed surfaces and cannot be taken as representative of the system as a whole. As Evans *et al.* (2006) have shown, catchments with very different net erosion rates can have very similar erosion rates locally on bare surfaces within the catchment.

Table 2 Published rates of retreat for peat surfaces in England and Wales (from Holden et al., 2007a).

Location	**Surface**	**Erosion ($mm\ yr^{-1}$)**
Moor House, N. Pennines	Gully walls	19.3
Upper N. Grain, S. Pennines	Gully walls	14
Plynlimon, Mid-Wales	Gully walls	30
Moor House, N. Pennines	Gully walls	7.8
Moor House, N. Pennines	Gully walls	10.45
Holme Moss, Pennines	Low angle peat margin	33.5
Holme Moss, Pennines	Peat margin	73.8
Harrop Moss, Pennines	Bare peat surface	13.2
Snake Pass, Pennines	Peat margin	5.4
Mid-Wales	Ditch walls	23.4
N. York Moors	Low angle bare peat	40.9
S. Pennines	Low angle flats	18.4-24.2
Cabin Clough, S. Pennines	Low angle eroded face	18.5
Doctors Gate, S. Pennines	Low angle eroded face	9.6
Plynlimon, Mid-Wales	Peat faces	16

2.2.3. *Reservoir sedimentation rates*

Further insights into erosion rates at the catchment scale over longer time periods can be gained from analysis of sediment deposition in lakes or reservoirs. Comparison of surveys of the bottom sediments at different dates and estimates of sediment volume based on augering or coring of bottom sediments provides estimates of volume of deposition over known time periods, and these can be converted to mass per unit catchment area if sediment bulk density is known. Yeloff *et al.* (2005) tabulated overall sediment yields from a large number of reservoir sedimentation studies from catchments with significant areas of upland peat and found total sediment yields ranging from 25 to more than 200 $Mg\ km^{-2}\ yr^{-1}$.

Mean erosion rates for catchments in Scotland are:

North Esk reservoir: 25 Mg km^{-2} yr^{-1} (Ledger *et al.*, 1974)

Hopes reservoir: 26 Mg km^{-2} yr^{-1} (Ledger *et al.*, 1974)

Glenfarg reservoir: 26 Mg km^{-2} yr^{-1} (McManus & Duck, 1985)

Glenquey reservoir: 31 Mg km^{-2} yr^{-1} (McManus & Duck, 1985)

Earlsburn reservoir: 68 Mg km^{-2} yr^{-1} (Duck & McManus, 1990)

North Third reservoir: 205 Mg km^{-2} yr^{-1} (Duck & McManus, 1990)

Carron Valley reservoir: 142 Mg km^{-2} yr^{-1} (Duck & McManus, 1990)

Analysis of reservoir sedimentation provides an overall rate of erosion for the catchment over a much longer time period than analysis of stream discharge and sediment concentrations, and the greatest contribution that such determinations can make is quantifying changes in net erosion rates over long periods of time. Yeloff *et al.* (2005) reported variations in erosion rates over time from reservoir sedimentation in the March Haigh reservoir catchment in the southern Pennines. The reservoir was completed in 1838 and its catchment ranges from 330 to 482 m altitude. The upper slopes are dominated by blanket peat soils with bare peat and a well developed system of gullies. Erosion rates were estimated from multiple cores of the bottom sediments and dating was established by correlating magnetic properties of cores with a master core dated by ^{210}Pb and ^{137}Cs. Mean erosion rates were found to be low from the mid-19th century until the early 1960s, but increased markedly after 1963 and peaked during the late 1970s and early 1980s. Rates of total sedimentation ranged from 2 to 28 t km^{-2} yr^{-1}. Silt traps within the feeder streams during the early life of the reservoir and sediment removal by scouring may have contributed to these low net erosion rates. However, the occurrence of greater erosion rates measured in the post WW2 period is supported by increases in the extent of gullies seen when aerial photographs from 1948, 1964 and 1988 are compared (Yeloff *et al.*, 2005).

Erosion rates calculated from reservoir sedimentation are more likely to underestimate actual erosion rates because not all sediment will be trapped by the reservoir. As with estimates of catchment erosion rates from stream discharge and sediment concentrations, erosion rates estimated from reservoir sedimentation provide an overall catchment mean and mask spatial variations in sediment mobilisation and deposition from specific soil types within the catchment system. The method cannot therefore provide reliable estimates of peat erosion except for cases where peat soils cover the entire catchment.

2.2.4. *Horizontal mass flux gauges and mass flux samplers*

Warburton (2003) reported a piece of work that for the first time quantified the significance of wind action in the erosion of peat in a UK upland environment. A network of passive horizontal mass flux gauges and two vertical arrays of BNSE mass flux samplers were set up. This combination of instrumentation is designed to capture both the volume and weight of detached peat transported by the prevailing wind (the passive gauges) and at different heights above the ground (the BNSE samplers) The main finding were that the sediment flux was between 3 and 12 times greater on the windward side and that most of the peat transport was close to the ground surface. Very little was found above 0.3 m. For two years the average annual horizontal net erosion flux was 0.47 t/ha.

2.2.5. *Changes in the morphology of landforms from an initial surface or form over time through repeated topographic measurement*

Objective ground-based surveys can show changes in eroded areas and volumes of eroded material over time, provided the survey methods are sufficiently well defined. McHugh (2007) reported the results of a resurvey of 139 sites from the DEFRA survey of erosion in upland England and Wales in 2001/02 (McHugh *et al.*, 2002). Increases in the areal extent of erosion were found at 52% of the sites surveyed, representing 705 m^2 of newly exposed soil. Significant revegetation of bare soil was also recorded at these upland sites, resulting in a decrease in net eroded area at 63% of the sites. However, McHugh noted that the greatest changes in area of erosion occurred on dry mineral soils, whereas the greatest changes in volume were on wet peaty mineral soils. The change in volume at the 59 peat sites visited was estimated at 40.6 m^3, a mean loss of 0.69 m^3 from the 7850 m^2 (50 m radius) plots. This is equivalent to a mean surface lowering of 0.09 mm over 2-3 years. Although this result is the mean of varying depths of erosion, the overall change is relatively small, and so it is clearly important to have stable benchmarks at sites if accurate assessments of changes are to be made, especially over relatively short timescales.

2.2.6. *Use of environmental radionuclide (^{137}Cs) tracer techniques*

Traditional approaches to measuring erosion rates involve many deficiencies and limitations, including reliability, cost, spatial representativeness and the need for extended periods of measurement. The use of environmental radionuclides, and more particularly caesium-137 (^{137}Cs), offers an effective alternative means of assembling such data.

Evidence of absolute rates of soil erosion over longer time periods is available from studies using the caesium isotope ^{137}Cs as a tracer. ^{137}Cs was added to soils from atmospheric testing of atomic weapons and events such as the Chernobyl incident in 1986. The isotope is strongly adsorbed to soil clay particles. Redistribution of soil particles following ^{137}Cs deposition provides an estimate of absolute rates of soil redistribution during the last 40 years. Bowes (2003) mapped soil losses from soil ^{137}Cs inventories in 25 m square cells along transects across cultivated fields on sandy soils in east central Scotland. Net annual soil redistribution in all the fields sampled ranged from losses of 3 kg m^{-2} to gains of 6 kg m^{-2}. However, it must be stressed that these losses apply to small areas. Field boundaries effectively trap much of the eroded soil within the field and net losses from the field were much lower. This may partly explain why ^{137}Cs estimates of erosion rates are often greater than data obtained from surveys of larger spatial units (Brazier, 2004).

Studies that involve this technique have been confined to mineral agricultural soils (e.g. Walling & Quine, 1991; Zhang & Walling, 2005). The method is likely to be of less use in eroding blanket bog as adsorption of ^{137}Cs to organic colloids is weaker, but this should be tested in the field.

2.3. Suitability of methods for quantifying peat erosion in Scotland

The methods reviewed above differ in their accuracy, costs, spatial and temporal scales, sensitivity and security and stability on site. Here we compare the methods against a common set of criteria to provide an overall evaluation of the suitability of each for the present survey. As far as the authors know, no similar previous comparison has taken place and there is relatively little information in the literature that provides a critical analysis of these methods, either individually or collectively.

2.3.1. *Methods reviewed*

1. Erosion pins
2. Sediment traps
3. Horizontal flux gauges and samplers
4. Changes in the morphology of landforms over time through repeated topographic survey
5. Measurement of exports of sediments (both suspended and bedload) from catchments at river gauging sites
6. Reconstruction of erosion rates from sediment accumulation at storage sites such as lakes or reservoirs, dated by pollen analysis or ^{14}C or ^{210}Pb methods
7. Budgets of environmental radionuclides (^{137}Cs)
8. Use of existing black and white or colour vertical air photographs (repeated at different dates)
9. Use of existing high resolution satellite imagery such as Landsat TM, SPOT or IKONOS (repeated at different dates)
10. LiDAR (Light Detection and Ranging) technology

2.3.2. *Criteria for comparison*

The methods summarised above were assessed against the following criteria by five members of the project team working independently. Each method was scored using the classes below, based on evidence from the published literature and supplemented by personal experience where possible.

a. Sensitivity in the horizontal plane (<1 m **score 3**, 1-20 m **score 2**, > 20 m **score 1**; if method does not measure size of feature **score 0**).

b. Sensitivity in the vertical plane (1-5 mm **score 3**, 6-50 mm **score 2**, > 50 mm **score 1**, if method does not measure depth **score 0**).

c. Operator skill (requires little prior knowledge of equipment or training **score 3**, requires some basic understanding and training **score 2**, requires high degree of training **score 1**).

d. Scale of analysis (across a major part of a bog (> 10 hectares) **score 3,** across within a network of gullies/peat flats **score 2**, within individual gullies/peat flats **score 1**).

e. Temporal sensitivity (able to identify annual changes **score 3**, able to identify decadal changes **score 2**, timescales greater than decadal **score 1**).

f. Security and stability on site (very robust and proven in adverse conditions, **score 3,** vulnerable to damage in adverse conditions **score 2**, has known and unresolved problems in adverse conditions **score 1**).

g. Installation and operating costs, including staff and data processing time (Cheap **score 3,** Moderate **score 2**, Expensive **score 1**).

h. Does it measure extent, degree (severity) or form of erosion features or any combination of them? (all three **score 3**, two **score 2**, one **score 1**).

i. Reproducibility of data when measurement is repeated at the same site/time (within 5% **score 3**, 5-20% **score 2**, >20% **score 1**).

An additional class (score 0) was used under criteria (a) and (b) for cases where the method did not provide the information assessed under that criterion.

Table 3 gives a matrix of median scores from the 5 observers for each method and criterion. There was generally close agreement among observers; where there were substantial differences the range of values is tabulated. Several members of the team felt their knowledge of two methods (horizontal flux gauges and radiocaesium budgets) was insufficient to provide a secure assessment. Scores for these methods are therefore based on two team members only.

Erosion pins, field topographic survey and LiDAR scored higher than the other methods, while flux gauges, radiocaesium budgets and catchment and lake sediment measurements scored less. Remote methods tend to be more secure and provided information over larger areas than field-based methods such as erosion pins and sediment traps. It was assumed by most of the team that field-based measurements required less skill and training and were less expensive than remote sensing methods, but the cost of remote sensing varies depending on the imagery purchased and on whether imagery needs to be specially commissioned.

Many of the methods were judged to have low sensitivity or no applicability in either the vertical or horizontal dimension. Temporal sensitivity was generally high with field methods, although LiDAR has the greatest potential among the remote methods. Some methods require prior knowledge from using other methods; LiDAR, for example, provides very sensitive height measurements but cannot identify peat erosion *per se.*

Evans & Warburton (2007) compared two field-based methods, erosion pins and sediment traps, against each other. They suggest that erosion pins have four main sources of error; movement of the pins, changes in surface elevation, influence of the pin on erosion and human interference. In their opinion, erosion pins are better suited to measurement of surface retreat at low temporal resolutions. Because sediment traps aggregate erosion from an area of the peat face rather than at a point (in the case of pins), they are of the opinion that they provide reliable data at much higher resolution than the point measurements of erosion pins. Sediment traps, however, have been used much less often and they should be tested and compared more widely with erosion pins to test Evans and Warburton's view.

Table 3 Median scores from 5 observers on aspects of different methods of measuring erosion.

Median scores from 5 observers	A: **sensitivity – horizontal** (<1 m **= 3**, 1-20 m **= 2**, > 20 m **= 1**, n/a = **0**)	B: **sensitivity - vertical** (1-5 mm = 3, 6-50 mm = 2, > 50 mm = 1, n/a = 0)	C: **operator skill** (little knowledge or training = 3, basic = 2, high degree = 1)	D: **scale** (> 10 ha = 3, network of gullies/ flats = 2, individual gullies/flats = 1)	E: **temporal sensitivity** (annual changes = 3, decadal = 2, > decadal = 1)	F: **security and stability on site** (robust & proven = 3, vulnerable = 2, unresolved = 1)	G: **Costs incl. staff and data time** (Cheap = 3, Moderate = 2 Expensive **= 1**)	J: **Extent, severity or form?** (all three **= 3**, two **= 2**, one **= 1**)	K: **Repeatability** (< 5% **= 3**, 5-20% **= 2**, >20% **= 1**)
Erosion pins	0	3	3	1	3	2	3	1-3	2
Sediment traps	0	3	3	1	3	2	3	1-3	2
Horizontal flux gauges *	0	2	3	1	3	2	3	1	2
Changes in morphology by topographic survey	3	2	1	2	2	3	1	3	2
Catchment sediment exports (river gauging)	0	0	2/3	3	3	2	2	1	2/3
Catchment sediment exports (accumulation in lakes or reservoirs, dated by pollen, ^{14}C or ^{210}Pb)	0	0	1	3	3	2	2	1	3
Radionuclide (^{137}Cs) budgets *	0	3	1	1/3	1	3	1	1	2
Existing air photographs (different dates)	2	0	1	3	1	3	2	3	2
High-resolution satellite imagery (different dates)	1	0	1	3	1	3	1	3	2
LiDAR (Light Detection and Ranging)	3	2	1	3	2	3	1	3	3

**Small sample of comments on these methods.*

The commentary below provides a brief resumé of the major strengths and weaknesses of each method:

Erosion pins

Cheap and little expertise needed. Applicable to a range of scales from spot to significant areas depending on number deployed. Excellent vertical and temporal sensitivities but not suitable for assessments of spatial dimensions of erosion features.

Horizontal flux gauges

Insufficient expertise to comment fully but more suitable for assessing wind erosion or wind-driven rain erosion than for an assessment at the national scale.

Morphology changes by topographic survey

Excellent spatial sensitivity, good vertical and temporal sensitivities and capable of assessing a wide range of erosion elements. Major drawbacks are cost and applicability to limited spatial scales.

Sediment budgets from river or lake sediments

Biggest advantages are scale of application, repeatability and temporal sensitivity. No information on different types of erosion, the spatial/vertical dimensions of features or the spatial distribution of erosion within the catchment. Not sufficiently specific to erosion of peat soils.

Radionuclide budgets

Not proven for organic soils.

Aerial photographs and satellite remote sensing

Good spatial sensitivity and excellent scale of application and range of aspects measured. Major disadvantage is lack of vertical and temporal sensitivity and need for skilled interpreters. Satellite imagery provides a wider spatial scale but with less sensitivity and also shorter time period over which historical data are available.

LiDAR

Very promising but is coverage available for Scotland? Potentially good sensitivity in all dimensions, but expensive to obtain data and no historical data for comparison.

2.3.3. *Conclusions*

The ground survey methods reviewed above would not provide an assessment of peat erosion rates sufficiently quickly at the national scale, but may be useful for more detailed measurements of erosion at specific sites. Rates of erosion are best assessed from sediment budgets for catchments with significant coverage of peat soils, although erosion pins offer a rapid method for obtaining data at a more localised scale within catchments.

It has been noted above that estimates of peat erosion from remote sensing are constrained by their limited vertical resolution and lack of temporal sensitivity. Despite these limitations, remote sensing methods are likely to be the most appropriate for assessing peat erosion at the national scale. For the spatially explicit measurements required in the present study, we conclude that analysis and interpretation of aerial photographs will provide the most appropriate data and we propose that these be used in the present study. However, we note that for future monitoring serious consideration should be given to LiDAR surveys of defined areas.

2.4. Methods to measure the role of different drivers of peat erosion

Peat erosion results from the complex interaction of climatic and anthropogenic influences acting over a long period of time. Considerable debate surrounds the processes that underpin the development of peat erosion, but there is a growing consensus that it is not a recent phenomenon and that climatic shifts in the last millennium may have initiated the erosion. Other factors now operate to perpetuate the erosion processes. It is therefore often difficult to identify with any certainty what the initial and subsequent drivers actually are.

Many of the studies on peat erosion and on the role of the various drivers that trigger or exacerbate the process have taken place in the Southern Pennines. This area lies in a marginal climate in relation to peat formation and it has been subject to a range of intense anthropogenic impacts (e.g. acidification, grazing and more recently recreational activities). Any extrapolation of findings from these studies to Scotland must be treated with some caution but they do provide the best evidence base available.

2.4.1. *Climate*

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 likelihood of it being eroded and the proportion of it that is eroded (Grieve *et al.*, 1994). This suggests that the current climate, as well as past climates, is also a factor in peat erosion. The positive correlation between altitude and severity of gully erosion has long been recognised, suggesting that climatic factors including the incidence of frost, high winds and more frequent and heavier rainfall events are important. Although some areas of eroding peat are found as low as sea level, it is usually in very exposed situations such as Lewis, Shetland and the western seaboard of Scotland. Analysis of a number of sites from throughout the UK and Ireland suggests that climatic influences may be the most important influence in causing erosion (Rhodes & Stevenson, 1997).

Within this project, further examination of the distribution of eroded peat with altitude and climatic variables was undertaken in order to gain a better understanding of this relationship.

2.4.2. *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 that can 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 CAP (Holden *et al.*, 2007a).

Heavy grazing by sheep causes a decline in the cover of dwarf shrubs, including heather and other ericaceous species, and their replacement by tussock-forming grasses and sedges. Changes can be assessed by quantification of vegetation composition in plots under different grazing regimes (e.g. Worrall *et al.*, 2007). *Nardus* in particular has short rhizomes and poor soil binding qualities; peat soils supporting a *Nardus*-dominated vegetation are thus more prone to erosion (McKee & Skeffington, 1997; Waterhouse *et al.*, 2004). Effects of sheep can also be quantified by repeat surveys of geomorphological features explicitly linked to sheep activity, such as scars and scrapes (Evans, 2005). In their comprehensive review, Holden *et al*. (2007a) cite unpublished data from Zhao and Holden, that "have shown that sheep tracks are important hydrological agents, providing direct connectivity across slopes for water, sediment and pollutants". This is because sheep tracks are compacted and infiltration capacities reduced so that infiltration-excess overland flow becomes more common". Where grazing occurs, the hydraulic conductivity and infiltration rate are much lower across the hill-slope than where grazing has been restricted. Just five years without grazing is enough to allow the system to recover towards that of a system that has had no grazing for over 40 years. These changes in hillslope hydrology could be manifest in changes in river flow and indicate that cessation of grazing may well be a useful tool in reducing flood risk.

Apart from experimental studies, assessments of grazing animal numbers - whether by visual counts or agricultural parish returns - have rarely been made at a suitable scale or over a long enough period to correlate them with the relatively slow process of peat erosion. More recent visual counts of red deer by the Deer Commission Scotland (DCS) are usually made annually and so do not encompass the diurnal and seasonal variations in density that could seriously influence peat erosion (e.g. red deer aggregating to use or create wallows when they move to higher altitudes in the summer). Recent animal occupancy at a local level is commonly monitored using counts of the deposition or volume of dung (e.g. Welch, 1985). Large herbivores can be identified by their dung and estimates can be made of 'animal.days' occupancy by measuring dung deposition rates over a fixed period of time. In free-ranging situations (and excluding resting areas), the results are broadly related to local grazing impacts and trampling effects. Both of these factors vary according to vegetation type and ground conditions, but nevertheless dung counts do provide a simple baseline for assessing and comparing the recent impacts of different densities of herbivores within and between much smaller localities than is possible with, for example, agricultural parish data or the annual counts of deer by the DCS.

The major difficulty in linking severe erosion of blanket peat to contemporary grazing pressures lies in the fact that gully systems in areas such as northern England can be many hundreds of years old, and 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 & Stevenson, 1997). Data from historical sources and palaeoecological analysis is required to unravel the complexity of land-use history at such sites. Based on pollen and macrofossil evidence preserved in peat deposits in mid-Wales, Ellis & Tallis (2001) found that the initiation of peat growth and peat erosion was linked to changing climate during the later Holocene. Some current erosion was initiated more than 1400 years ago and can be linked to prehistoric forest clearance in the uplands and associated increases in grazing (Ellis & Tallis, 2001).

2.4.3. *Drainage*

Many apparent effects of grazing on erosion are complicated by the effects of artificial drainage of hill land to improve the quality of grazing. Using government statistics, 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. Effects of drainage have been quantified by measurement of runoff and suspended sediment concentrations for catchments before and after drainage. Bragg (2002) linked drainage of blanket mires in Scotland to a decrease in runoff response time following precipitation events and more flashy river regimes, and Robinson (1986) and Robinson & Blyth (1982) documented similar changes following drainage of an upland forest catchment. Blocking of drains can significantly reduce rates of sediment output. Holden *et al.* (2007b) monitored sediment yields from blocked and unblocked drains and showed that blockage could reduce sediment yield from drains from 30 to 50 Mg km^{-2} to less than 1 Mg km^{-2} in a Pennine catchment. Holden *et al.* (2007a) also showed that where hill drains in the Yorkshire Dales were not maintained, they tended to revegetate and infill naturally on slopes of less than about 4°.

Based on personal observational evidence from the project team, drainage of peat bogs is not viewed as a major factor in stimulating or exacerbating peat erosion in Scotland. Many of the extensively eroded bogs have no drainage channels at all. Likewise, many areas that have been drained show no firm evidence of erosion features.

2.4.4. *Burning*

Interpretation of aerial photographs has been used to map the spatial extent of moorland burning in both Scotland and England and Wales (Hester & Sydes, 1992; Yallop *et al.*, 2006). Yallop *et al.* (2006) found that aerial photographs could be used satisfactorily to identify areas of controlled burning particularly in areas of dwarf shrub vegetation. Identification was more difficult in grassland areas. The method was sufficiently sensitive to calculate average burn frequencies for areas and to identify a significant change in burned area over a 30 year period. However identification of controlled burns was partly based on patterns of burning, and aerial photographs may not be as suitable for mapping uncontrolled burns (wildfires).

If best guidance is adhered to, the Muirburn Code (Scottish Government, 2008) should prevent any future burning of blanket mires or peats. The exception to this is peat where heather constitutes more than 75% of the vegetation cover but this is extremely rare. Percentage cover of *Calluna* is normally much lower than this due to site wetness, and on many bogs *Calluna* is very scarce.

2.4.5. *Recreation*

Assessment of the absolute level of recreational pressures is best made by ground-based counts of walkers on footpaths (Watson, 1991). Watson (1984) used aerial photographs to document the changes in footpaths in the Cairngorms, an area of increasing recreational pressures, while Lance *et al.* (1991) used ground-based measurements to quantify impacts on footpath width in the same area. In a comparison of aerial photography flown in 1951 and 1983, Wishart & Warburton (2001) identified changes including a marked loss of vegetation and incision along the lines of major paths such as the Pennine Way in the Cheviot Hills. Grieve (2000) linked truncation of soils in areas of excessive disturbance by human trampling to a significant loss of carbon storage in these upland soils.

2.4.6. *Atmospheric pollution*

Acid deposition has been implicated as one of the causal factors of peatland erosion, in particular in the Southern Pennines, and might be one explanation for the severity of the problem in that area. Skeffington *et al.* (1997) suggested that acid deposition since the start of the Industrial Revolution about two centuries ago may be one of the causal factors for peat erosion in the Southern Pennines. *Sphagnum* has almost completely disappeared from these bogs, thereby reducing further accumulation of organic matter at the soil surface; although the reason for this loss is not well understood, it is thought to be linked to acid deposition. Another aspect of acid deposition on blanket bogs and whether it has caused a reduction of fertility of these systems is the leaching out of base cations. In a comparison of 8 bogs across the UK from NW Scotland to SW England, there is some evidence, that the two Southern Pennine peats have lower exchangeable Mg and K than the others. Exchangeable Ca is lower at one of the sites. However, none of the levels of base cations correlated significantly with sulphur deposition. It may be that atmospheric deposition does not cause erosion *per se*, but the huge loss of *Sphagnum* spp. due to acid deposition provided the impetus for other factors to take effect. Cresser *et al*. (1997) suggest that further work is required on the possible effects that acid deposition has had on the physical properties of peat.

Nitrogen deposition onto 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 providing a stabilizing influence (Evans & Warburton, 2005).

The UK's emissions of SO_2 peaked in 1970 and have declined by almost 70% since 1990 (Fowler *et al.*, 2005). Although N deposition has only yet shown small reductions, these may increase as car engine technology improves and the use of N fertilisers decreases (Fowler *et al.*, 2005). The influence of acid deposition in peat erosion processes will have been much less in the past in Scotland and is likely to be of minimum effect in the future.

3. EVALUATING THE ROLE OF DIFFERENT DRIVERS

3.1. Terminology

- Aerial photography, digital or otherwise, is referred to as ***imagery***.
- The basic sampling units are images of 0.25 km^2 areas, referred to as ***sample squares*** or simply ***squares****.*
- Contiguous groups of squares within a sub-catchment constitute a ***site***.
- Each SSSI (or group of SSSIs in the case of the Caithness and Sutherland Peatland SAC) along with any sampled adjacent ground outside the SSSI, is referred to as a ***study area****.*
- Unless stated otherwise, ***eroded vegetation*** will be used as shorthand for 'blanket bog/peatland vegetation with erosion features present'.

3.2. Background

The aims for this objective were: (a) to examine broad scale relationships between eroded peat and the possible drivers of erosion across Scottish peatlands as a whole; and (b) using this information to examine the principle drivers in more detail at three study areas of high conservation value selected by SNH staff*.*

For reasons of spatial scale given in Section 2, along with problems of the timescale of available imagery and difficulties with registration of different imagery, it was impractical within the resources available to assess *changes* in the extent of erosion*.* However, to confirm these conclusions, the historical imagery of at least one 0.25 km^2 square in each of the three study areas was examined, both visually and by overlaying within the GIS. The results are discussed below.

In the light of those results, it was agreed that a correlative approach should be adopted, relating recent assessments of the extent of peat erosion, in terms of the erosion system and processes, to levels of different drivers.

3.3. Assessments of historical images for determining changes in peat erosion

The results were consistent for all three study areas and are illustrated by the following information from two sites in the north-east of the Monadhliaths study area (Figure 1a & 1b), which was the most intensively examined study area. For each site, the figures show: (a) two historical monochrome aerial photographs, taken originally at about 1:24 000 scale; and (b) a composite of the modern colour images (25 cm pixels) for all 0.25 km^2 squares in the study area, along with two small representations of the historical images for comparison.

Figure 1a shows a comparison between aerial photograph images on the gently to moderately sloping and undulating dissected montane plateau to the north of Carn Ban (942 m). Figure 1b shows a comparison from the same years for a site in Gleann Ballach in a contrasting landscape setting of the upper glaciated valley to the east of Carn Dearg at 600-700 m altitude. When the scale and definition of the different sets of imagery are taken into account, both sites show very little discernible change in the patterns and extent of peat erosion over time. The scale of the historic photography is too small to detect the relatively small changes that might have occurred over periods of 15-20 years, and immediate post-war 1:10 000 imagery would have to be acquired to make better comparisons. While this would be a better scale and would extend the time period, it would not overcome the problems encountered with the overlaying process which emphasised the problems of spatially registering imagery from different times and sources. This is common when dealing with older imagery, and across all three study areas some mis-registrations exceeded 50 m, commonly associated with steep-sided valleys. Precise measurement of change is clearly not possible under such circumstances and within a reasonable budget.

It is not possible to quantify any change in peat depth by visual inspection of these images, but it appears that almost all bare peat surfaces were present over the 42 year time period; any changes were relatively small and generally maintained a very similar pattern of erosion. Details of all the historical imagery examined are given in Appendix 1 Table A1.6.

3.4. National-scale relationships between eroded peatland vegetation and drivers

While there are benefits in the *ad hoc* selection of study areas with a well-documented history and where some work has already been undertaken, there is a major drawback in that they may not be representative of the full range of potential drivers of erosion (both natural and anthropogenic) present at other sites in Scotland. Consequently, any generic conclusions about drivers – and subsequent recommendations for remediation and management - would not necessarily be robust when extrapolated to areas outside the selected study areas.

Therefore it was agreed that Scotland-wide data would be used to try to identify the principal drivers of erosion across the country. The initial proposal was to use the following objective approach, based on GIS analyses, and this would provide the basis for the subsequent selection of three specific study areas for detailed examination:

(i) SNH’s Scottish Blanket Bog Inventory (SBBI) and MLURI’s Land Cover Scotland 1988 (LCS88) dataset - derived from aerial photos - would be combined in a GIS and areas of blanket bog and bare peat filtered out. It was thought that this would provide a more robust dataset of these features than either dataset on its own.

(ii) The dataset would then be combined with:
- locational data (e.g. latitude, longitude);
- physiographic data (e.g. altitude, aspect, slope);
- climatic data (including exposure and rainfall);
- datasets on herbivore densities.

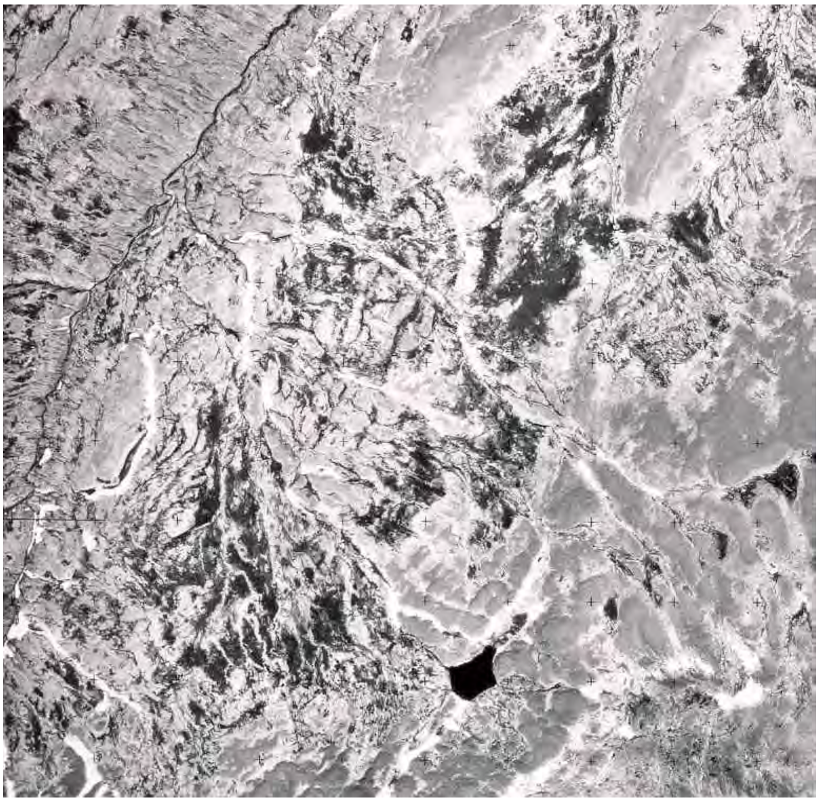
(iii) The resultant Scotland-wide dataset, which would contain relevant geophysical and environmental attributes associated with each area of blanket bog and bare peat, would then be subject to multivariate cluster analyses. From the analyses we would determine if the data clustered according to broad combinations of these attributes, thus indicating different principal drivers (or combinations thereof) acting on different sites across Scotland.

(iv) Depending on how the data clustered, three or possibly four study areas would be selected, each in a different cluster, so that the effects of the different drivers could then be examined in more detail. Study areas of high conservation interest would be filtered by using the GIS to overlay coverages of SACs and SSSIs.

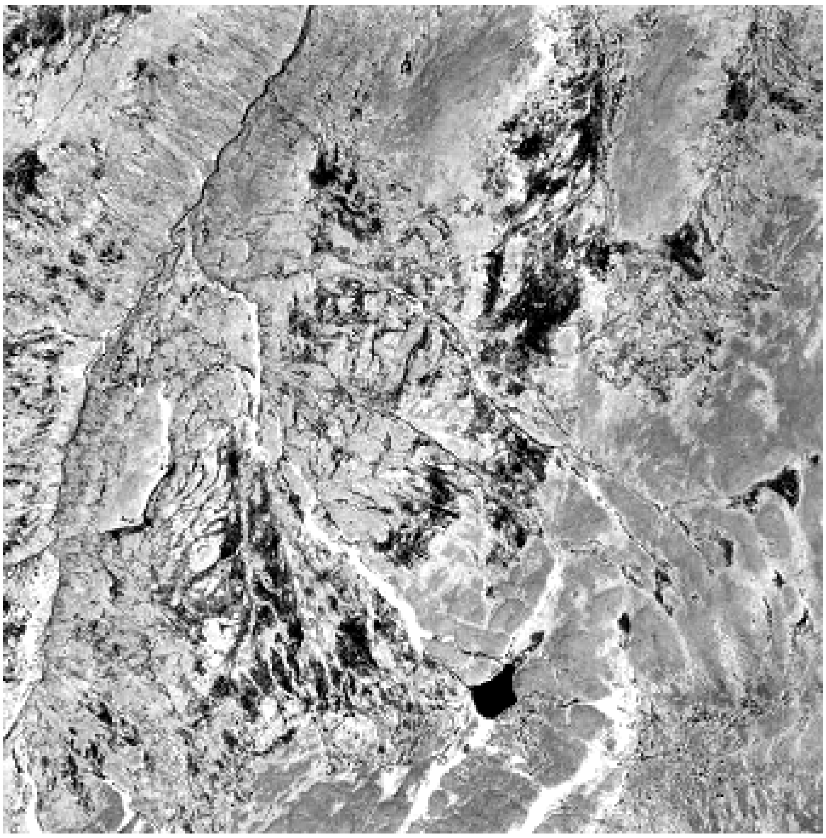
It was considered that this approach would allow a potentially more robust extrapolation of the findings from the study areas (as required in Objective 4) because peatland areas with similar characteristics would have already been identified by a robust statistical approach.

Figure 1 Comparisons of past and present aerial photography

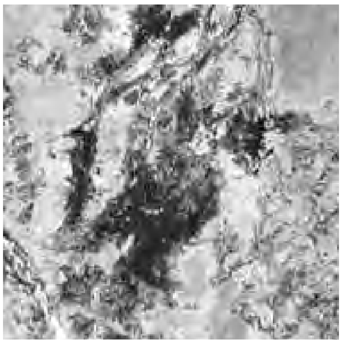
a. Monadhliaths north-east group, north of Carn Ban



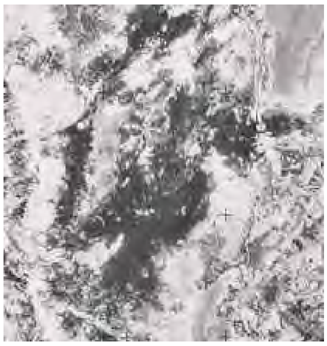
1963

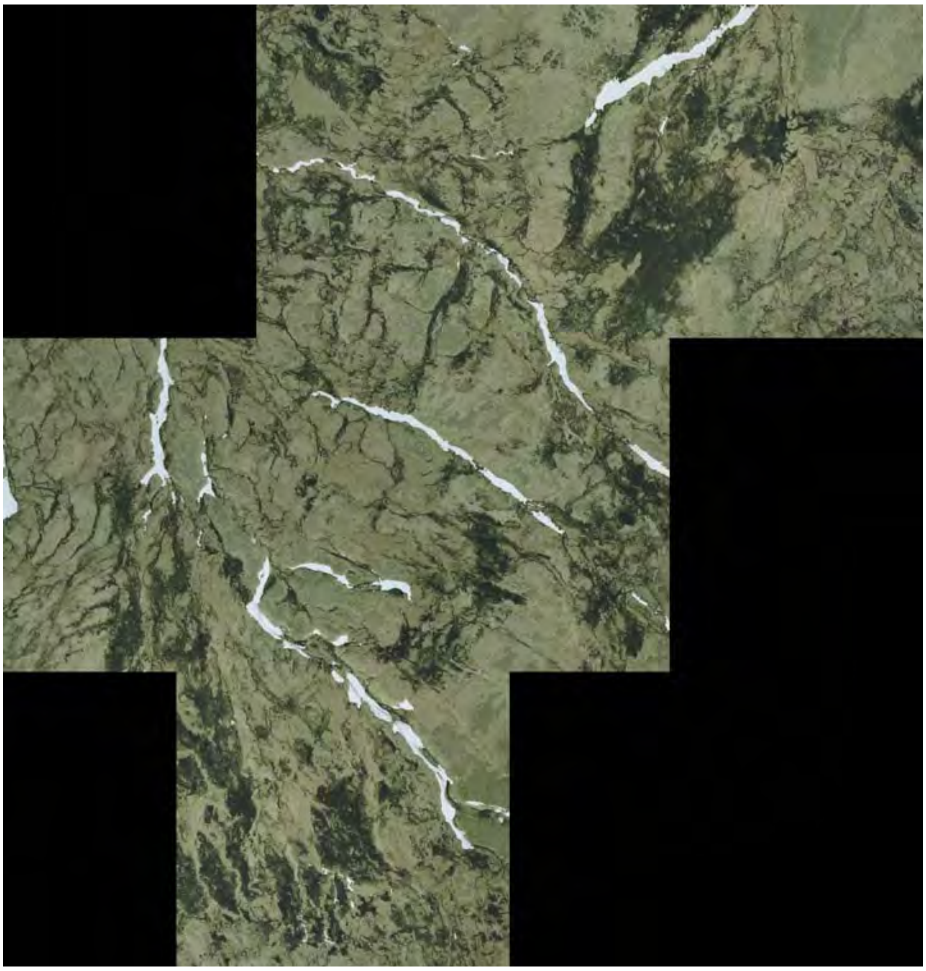


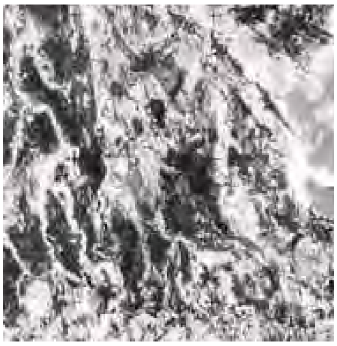
1989



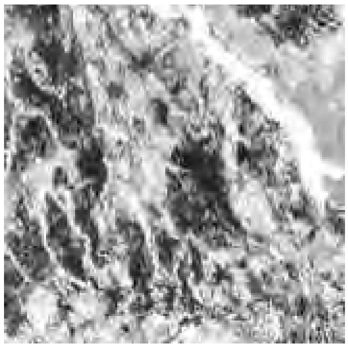
Comparison of aerial photos of top right square of colour image: 1963 (left), 1989 (right) and 2005 (below)



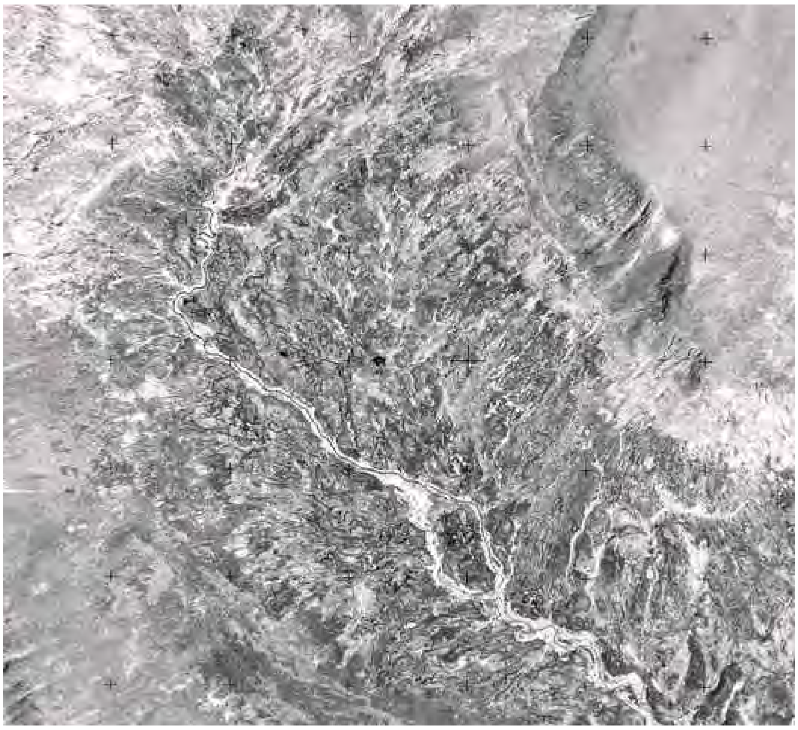




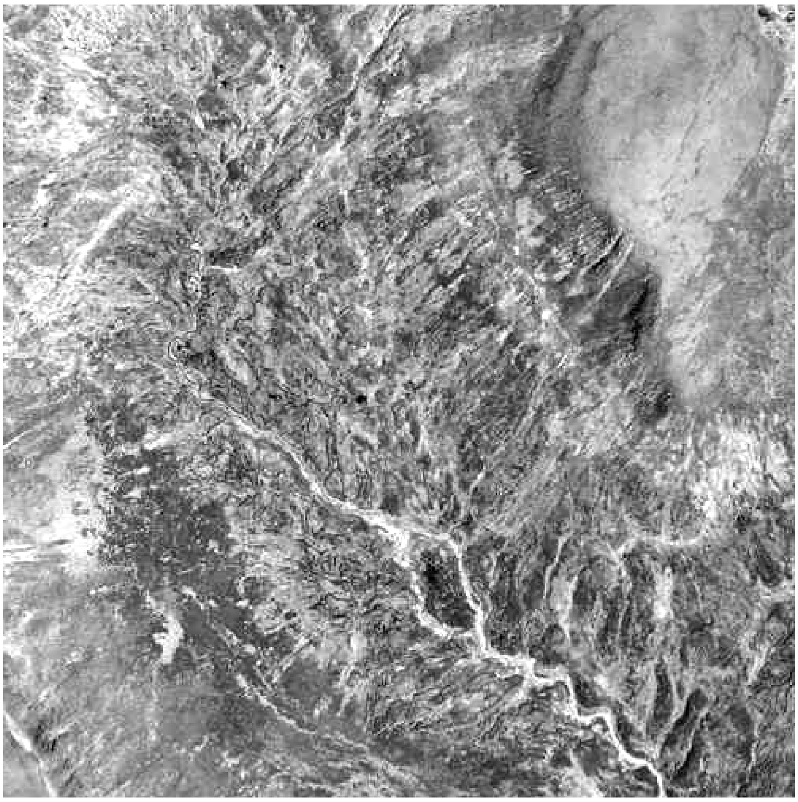
Comparison of aerial photos of bottom square of colour image: 1963 (left), 1989 (right) and 2005 (above)



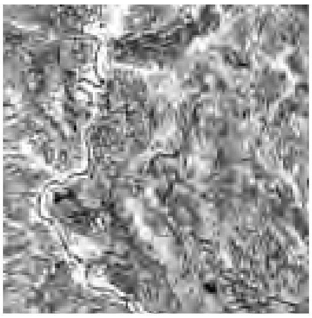
b. Monadhliaths north-east group, Gleann Ballach



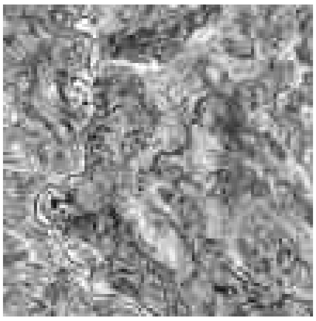
1963

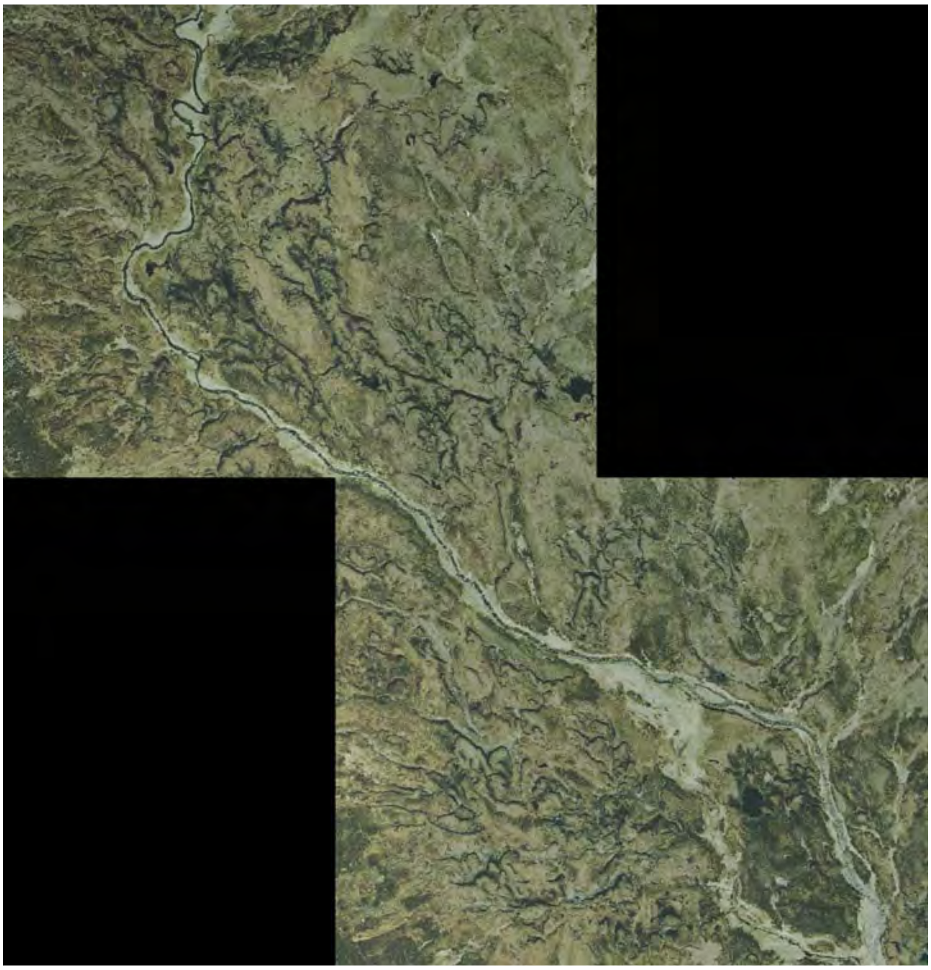


1989

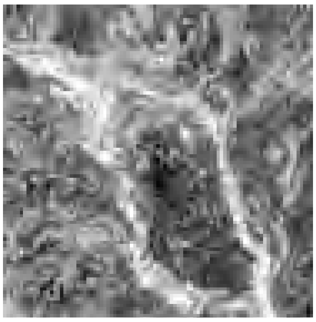


Comparison of aerial photos of top square in colour image: 1963 (left), 1989 (right) and 2005 (below)





Comparison of aerial photos of bottom square in colour image: 1963 (left) 1989 (right) and 2005 (above)



However, following preliminary examination and analyses of the available data, the above procedure had to be modified because:

(a) the scale of the SBBI, derived from Landsat satellite data, was too coarse to be useful and so had to be abandoned;

(b) there was a high degree of correlation between several of the potential drivers of erosion which meant that any clustering of the data was unlikely to be clearly interpretable and could be misleading.

As a result, statistical advice was that the Scotland-wide assessment of drivers should be undertaken using regression techniques.

3.4.1. *Regression analyses*

3.4.1.1. Sampling structure

To obtain an unbiased sample of peatlands, data were obtained for all 250 x 250 m sample squares centred on each of the 80 443 one-kilometre OS intercepts in Scotland. This 1/16 ha sample area was chosen as being large enough to pick up areas of erosion but small enough to provide relatively discrete values for the different attributes of the area to be analysed (Table 4). Areas larger than this were likely to encompass too wide a range of variation to provide sensible values for the sample squares, especially in areas of high relief. When the LCS88 data were overlaid on these sample squares, 15 833 squares contained peatland vegetation.

The response variable for the analyses was the proportion of each sample square that was recorded as the LCS88 class 'blanket bog/peatland vegetation: eroded'. Of the independent variables, deer and sheep densities in the SEERAD and DCS datasets, respectively, were recalculated for those LCS88 vegetation types where the animals were usually present (i.e. excluding occasional incursions). Example areas excluded were built land, commercial forestry, wetlands and arable land.

In summary, a first run of the analyses showed two key results:

a) Results from different sample squares at 1 km spacing were often not independent, probably because the underlying data were from large-scale areas covering several sample points. Consequently, sampling was reduced to 4 km spacing. This reduced the sample size of peatland areas from 15 833 to about 1000 (the actual number varied slightly as there were missing values for some of the attributes in the component datasets).

b) The scale of mapping in LCS88 meant that there were relatively few sample squares that contained both eroded and uneroded peatland vegetation, so the proportions of eroded peat in a square tended to be 'all' or 'nothing'.

These points are discussed in more detail in Section 3.4.2.

Table 4 Attributes of the 15 833 one-km OS grid ref intercepts in Scotland where peatland vegetation - whether eroded or not - occurs in a 250 x 250 m square centred on the intercept.
('y' indicates attributes selected for initial regression for assessment of drivers.)

y	**X** - X coordinate of 1 km grid (i.e. westing)
y	**Y** - Y coordinate of 1 km grid i.e. (northing)
y	**GridID** - combined X and Y coordinates (abbreviated)
	PC_SAC - % of Special Area of Conservation in 250 m grid square. Not used in regressions as too recent to affect management in 1988
y	**PC_SSSI** - % of Special Site of Scientific Interest in 250 m grid square
y	**EXPN** - Birse Exposure number - indication of exposure from Birse's climatic maps (6 classes)
y	**FRON** - Birse Frost number - *ditto* accumulated frost (5 classes)
y	**DCA_Km_LCS**[1,2] - Deer density - DCS 1987-2002 data converted to mean count per sq km; data set informed by LCS88 for likely presence/absence of deer
y	**SheepHa_86** - Sheep per hectare in 1986, calculated from parish data - data set informed by LCS88 presence /absence sheep
	SheepHa_06 - Sheep per hectare in 2006, calculated from parish data - data set informed by LCS88 presence/absence sheep. Not used in regressions
y	**Aspect** - aspect of slope at centroid of square.
	AreaNonEro - Area of non-eroded peatland vegetation in 250 m grid square from LCS88 data
	AreaPtErod - Area of eroded peatland vegetation in 250 m grid square from LCS88 data
y	**PCPeatErod** - area of eroded peatland vegetation as % of total peatland area in 250x250 m grid square
	Ht_Min - minimum altitude value in 250 m grid square (derived from the 25 values at 50 m intervals of the OS grid)
	Ht_Max - maximum altitude value in 250 m grid square (using a 50 m grid)
y	**Ht_Range** - maximum minus minimum altitude value in 250 m grid square (using a 50 m grid) - a broad surrogate for a wider measure of slope
	Ht_Mean - mean altitude value in 250 m grid square (using a 50 m OS grid)
y	**Ht_STD** - standard deviation of altitude values in 250m grid square (using a 50m OS grid) - an indicator of evenness of altitude (e.g. might help differentiate more even plateaux from slopes)
y	**Ht_Median** - median of altitude values in 250 m grid square (using a 50 m OS grid)
	Ht_pt - altitude of the closest 50 m grid point to the 1km grid point (it corresponds to south-east cell)
y	**MAXRai**n[3] - maximum monthly rainfall (mm x 100) from 1983 to1988 inclusive - indicator of most extreme, relatively short-term, rainfall event; 5 km point data
y	**MeanRain**[3] - mean monthly rainfall value 1983-1988 inclusive. Indicator of general long-term wetness; 5 km point data
	MinRain [3] - minimum monthly rainfall value 1983-1988 inclusive; 5 km point data
y	**STDDEVRai**n [3] - Standard deviation monthly rainfall value 1983-1988 inclusive; (might indicate if areas with large fluctuations in rainfall are more prone to erosion); 5 km point data

Notes on Table 4:

1. We are grateful to Dr. Javier Perez-Barberia of MLURI for the use of his unpublished data on deer densities. His work, involving the digitizing and analysis of DCS deer counts in terms of observer viewsheds and LCS88 vegetation classes, is an ongoing part of SERAD Work Package 302362.

2. DCS counts are subject to considerable variation, often due to the weather and distribution of deer on the day that counts were made. Most areas are counted on a 5-year cycle, although the frequency of early counts was less consistent. It was decided to take the mean count of years 1987-2002 to give a 'smoothed' assessment of deer densities relevant to the LCS88 data and the imagery of 2004-06 used for detailed examination of the three conservation study areas. These counts were considered to be the most regular and consistent counts available (counts from helicopters over much wider areas started to be introduced in 2002).

3. We gratefully acknowledge permission from the Meteorological Office to use the UKCIP Gridded Observed Climatology rainfall data. The data are from rainfall collectors throughout Scotland, extrapolated and adjusted to a 5 km grid. They therefore give much more precise estimates of local rainfall than those derived from the far more limited number of main weather stations in Scotland.

3.4.1.2. Statistical aspects

As the percentage of eroded vegetation was in most cases either 0% or 100%, this variable was treated as a pseudo-binary variable and modelled using a binomial generalized mixed model. There is a clear dependency between points on a 1 km grid, and therefore a 4 km grid was used. It should also be noted that there are high correlations between some of the potential explanatory variables. In particular, there is a correlation of 0.87 between frost number and median altitude and of 0.45 between altitude and number of deer. This multicolinearity can lead to estimated coefficients changing sign. For example, when frost number is in a model that does not include median altitude (Htmedian), the estimated coefficient is positive, but when median altitude is also included it is negative.

Of the 16 potential explanatory variables (Table 4), it was necessary to identify those that were significantly associated with eroded vegetation prior to fuller analysis. This was achieved by stepwise regression analysis, and the variables thus identified were subsequently modelled, are shown in Table 5. Note that the table does not show results for either deer or sheep densities as neither was statistically significant. Hence, there is no evidence that it is herbivore numbers - rather than another variable that is correlated with altitude (e.g. climate) - that is affecting erosion at this scale. Neither was there any evidence that any of the interactions between the parameters was significant, probably because of the high intrinsic variance of the data.

Table 5 Estimated coefficients, selected by stepwise regression, of relationship between eroded vegetation and potential drivers of erosion.

Parameter	**Estimate**	**s.e.**	**t**	**t pr.**
Constant	-10.82	1.04	-10.46	<.001
Exposure (EXPN)	0.647	0.152	4.26	<.001
Frost index (FRON)	-0.533	0.139	-3.84	<.001
Altitude standard deviation (HtSTD)	0.0277	0.0123	2.25	0.024
Mean monthly rainfall (mm) (MeanRain)	0.01763	0.00237	7.45	<.001
Percentage of area in SSSI (PC_SSSI)	-0.0066	0.00229	-2.89	0.004
Northing (Y)	0.000005766	0.000000883	6.53	<.001
Median altitude (HtMedian)	0.00827	0.00105	7.87	<.001

To examine the possible confounding effects of altitude *per se*, the full model (as for Table 5) was re-run with the parameter ‘median altitude’ excluded (note this parameter should not be confused with HtSTD shown in Table 5 which is a measure of altitudinal variation, predominantly due to slope). This exclusion made almost no difference to the other results shown in the table, except that all other parameters were now statistically significant at a probability level of 0.001 or less.

To allow for spatial autocorrelation in the residuals, a generalized linear mixed model was also fitted, in which spatial autocorrelation was modelled as an exponential function of distance. The resultant estimated coefficients for the significant terms in the model are shown in Table 6.

After allowing for spatial autocorrelation, the %SSSI, frost index and the standard deviation of altitude (an indicator of slope) were no longer significant. Thus the most important explanatory variables were rainfall, altitude, latitude and exposure. However, it should be noted that correlation does not imply causation and that there are several potential drivers (e.g. frost number, deer density and slope) that are correlated with altitude.

Table 6 Estimated coefficients for the significant terms in the peat erosion model after adjusting for spatial autocorrelation.

Parameter	Estimate	s.e.	d.f.	t	p
Intercept	-9.9938	1.2874	242	-7.76	<.001
Exposure (EXPN)	0.3942	0.1446	981	2.73	0.0065
Mean monthly rainfall (mm) (MeanRain)	0.0147	0.0032	282	4.62	<.001
Median altitude (HtMedian)	0.006920	0.000818	358	8.46	<.001
Northing (Y)	0.00000507	0.00000125	181	4.06	<.001

It is notable in all the above analyses that the relationship between erosion and the proportion of SSSI in a square was negative, although not always statistically significant. This result probably reflects conservation policy for selecting areas that are in 'good condition' for SSSI designation rather than any effect of widespread management practices to reduce erosion in these areas. Importantly, it also suggests that SSSIs are towards one end of the spectrum of erosion and therefore the results from the three study areas selected for detailed studies may not be typical of eroded blanket bogs in general.

3.4.2. *Discussion*

The first point to emphasise when interpreting these results is that they are correlations, indicating factors associated with eroded vegetation, and should not be interpreted as cause and effect (even though, for convenience and brevity, we may loosely refer to them as 'drivers').

The most important conclusions suggested by the above results are:

(i) the predominant factors associated with the erosion of blanket bog vegetation appear to be physiographic and climatic influences, over which we have no control; and

(ii) there is apparently no consistent relationship across Scotland as a whole between the area of eroded vegetation and herbivore densities.

However, the properties of the LCS88 database must be taken into account when interpreting these results. In particular, blanket bog/peatland vegetation was classified as 'eroded' if some erosion features were present, regardless of their number or extent. Hence it does not reflect the severity of erosion and this could be relevant to, for example, the lack of a relationship with maximum monthly rainfall (e.g. flash storms). In many cases, very heavy rainfall is more likely to affect areas that already have some erosion features present, so any increase in erosion features or bare ground within such an area - as a result of, say, a flash storm - would not change the area classed as 'eroded' in LCS88.

With regard to (ii), it must be stressed that the results may partly be an artefact of the scale of the data, particularly for sheep where the figures are taken from the Agricultural Parish returns. Although these data are the best available for Scotland as a whole, the parishes are quite large (as well as varying considerably in size). Consequently, a figure for sheep density can apply to a large range of physiographic situations at several sample points across a parish. Similarly, land on open moorland can have different estimates of sheep either side of a non-physical parish boundary even though the stock have free access across the whole area. While there is no detectable broad-scale relationship between sheep densities and the presence of erosion, this does not preclude the possibility of localised impacts (both spatially and temporally). These aspects are examined further in the detailed studies of the three SSSI study areas, but in the absence of higher resolution local data on sheep densities, alternative indicators have to be used as surrogates for density information.

Similar arguments also apply to deer. The DCS counts are a management tool, designed to assess changes in the numbers of deer and not densities; they were not designed for projects like this where densities are the only way that we can compare sites. Despite the fact that the DCS deer data are at a higher level of resolution than the sheep data, each location is counted on just one day at a particular time each year. For example in the Srath an Loin region, recordings were always made in February–March. They are therefore not suited to detecting other seasonal aggregations of animals that could be more likely to initiate erosion (e.g. on summits and ridges in summer). The counts are also highly susceptible to different distributions of deer on the day that they were counted (e.g. in response to adverse weather conditions). For example in Srath an Loin, counts made from similar points were commonly double or half what they were two years earlier, despite being made on similar dates. Extreme examples for counts made from similar viewpoints but in different years were 50 and 11 for one location, and 55 and 2 at another. The extent of the viewshed is also important but not quantifiable. For example, in the Ladder Hills in January 2002, a count was made from the peak of Carn na Glascaill (730 m) which gives a 360^{o} view over several square kilometres; the count recorded 222 animals – clearly not a figure applicable to a hill top in January - whereas counts at about the same time but on lower ground less than 2 km away were 38 and 18 animals.

It is notable that Pakeman (2007) reached similar conclusions to the above about deer count and density data when analysing the suitability and robustness of indices used in habitat impact assessments. In the case of both deer and sheep, field surveys (e.g. using dung counts) at several times in the year may be the only way to detect these seasonal or small-scale relationships.

3.5. **Methodology for evaluating drivers of change**

3.5.1. *Background*

The effects of drivers were likely to be evaluated most effectively by detailed assessments in a structured sample of each study area, rather than obtaining broader-scale information across the whole of each study area. Although a catchment is the process unit (and most relevant to the Water Framework Directive and wider environmental processes), there was already some information available at this level (e.g. Grieve *et al.,* 1994). Therefore detailed information at the sub-catchment level was targeted and this is the basic sample unit for this part of the project. The protocol for distributing sample units within study areas needed to incorporate existing knowledge of erosion/deposition processes, rather than some type of geographic random distribution, and preferably including both eroding and non-eroding areas, the latter acting as 'controls' for assessments of drivers.

It was decided to avoid as far as possible the subjective elements present in many assessments of peat erosion where areas of eroded *vegetation* are delimited (including LCS88). Instead, the aim was to develop an automated classification that would detect areas of *bare peat soil.* As indicated by the results of Objective 1, the scale of most satellite remote sensed data is too coarse for these assessments. Therefore, for each of the three study areas, a total of twenty 0.25 km^2 high-resolution digital colour aerial photographs (referred to as 'imagery') was acquired, distributed across selected sub-catchments within each study area. The selected imagery was GetMapping 25 cm resolution taken in 2004-2006 (http://www2.getmapping.com). This data source has the added advantage that low-resolution images can be examined free on the internet and so suitable sub-catchments for monitoring could be determined before actually ordering the high resolution data.

As discussed in Section 3.2, the quantification of changes in erosion at an adequate resolution was likely to be impractical. To confirm this, or otherwise, at least one of the recent images for a 0.25 km^2 square from each study area was compared with earlier air photos to examine the hypothesis that the rate of peat erosion is too slow to be picked up by patterns in aerial photography, as well as being limited by serious issues of rectification of old photography (e.g. Wishart & Warburton, 2003).

3.5.2. *Selection of study areas and sites within study areas*

3.5.2.1. Selection of study areas

The selection of suitable sites was crucial to the success of the project and the tender specification required three study areas - the Monadhliath SSSI and two other geographically widespread areas of high conservation value.

With the abandonment of the statistical clustering procedure for selecting sites (see Section 3.4), an alternative (but still objective) selection procedure was required and was achieved by loading the following information into a GIS and overlaying it onto a 1:50 000 OS map:

- areas of eroded peatland vegetation – as for regression analyses;
- deer densities - as for regression analyses;
- sheep densities - as for regression analyses;
- boundaries of SSSIs and SACs – SNH data;
- available recent digital airborne imagery (Section 3.5.1).

From the GIS, a .pdf file was constructed with each attribute in a different layer that could be switched on and off in any combination. This allowed visual inspection of the broad relationships between the occurrence of eroded peatland, the main potential drivers and the underlying topography (altitude and location acting as partial surrogates for climatic variables).

In conjunction with a table of associated attribute values, seven geographically widespread study areas were selected that, between them, had a range of values for the most likely drivers of erosion, thus increasing the chances of differentiating the relative effects of different drivers. The .pdf file, along with a table of broad attributes for each study area was then used by SNH staff who, in addition to the Monadhliaths (divided into 3 sub-areas), selected the Ladder Hills and Grudie Peatlands SSSIs as the other two study areas for detailed examination.

Subsequent closer examination of the Grudie SSSI imagery indicated few major areas of peat erosion that would provide useful information on processes and drivers. Although the

LCS88 data identify considerable areas of eroding peat vegetation - often as a sub-category of 'montane vegetation' at higher altitudes - these mostly appear to be mosaics of small lochans (which may or may not be flooded sites of erosion). Also some of the land where one might expect peat erosion appeared to have a mineral surface and it is not clear whether or not this was ever peat-covered. Due to these limitations, it was decided to select additional locations, and two study areas in Strath an Loin SSSI and one in Knockfin Heights SSSI were chosen after examination of the low resolution imagery available free on the Web.

3.5.2.2. Selection of sites within study areas

Sites were chosen by examining all the GetMapping[R] imagery across the whole of a study area and its immediately adjacent areas, and selecting sub-catchments that represented the different forms of erosion present, along with one or two uneroded areas where possible. Where there were several areas with the same erosion type, areas were selected that would give a range of impacts of different drivers.

3.5.3. *Classification of bare peat*

The use of the twenty sample images was optimised by distributing them between sub-catchments so that they acquired the maximum amount of information for the minimum number of images. For example, in a dendritic erosion system that had several branches with similar attributes, only enough images were acquired to cover one 'typical' branch from above its source until the branch disappeared. The images were loaded into ARC[R] GIS, and bare peat was identified by a supervised classification of the red:green spectral balance using *Definiens*[R] *Developer* software. Shadows, particularly in gullies, sometimes presented a problem but it was presumed that the sides of the gullies would usually be bare and so shadow areas were included in the 'bare peat' figure. As the area of shadows in an image was usually small, their inclusion was unlikely to have weighted the results very much anyway.

Figure 2 shows a square with the high level of coincidence usually achieved between the visual and classified areas of bare peat.

Although the accuracy of the classification was generally high, the development work carried out using the Ladder Hills imagery highlighted some problems with poor tonal and colour properties that made the automated classification of bare peat uncertain. For example, the imagery for site LH5 (see Table 8) had a green cast which gave the impression of early stages of plant regeneration on bare peat. A field visit was undertaken to validate the Ladder Hills results generally and this showed that the areas in LH5 were, in fact, just bare peat. Consequently the field results were used as a guide to adjust the spectral criteria of the image classifier before re-running it. Where these problems arose at either of the other two study areas, imagery from another source or from adjacent areas was examined and this usually provided adequate information for deciding if bare peat was being classified accurately or that the parameters of the image analysis needed adjusting.

It should be noted that the area of land on slopes will be underestimated due to the perspective of vertical imagery, the degree of underestimate being proportional to the severity of the slope. The complex procedure to correct for such factors is illustrated in a report published by the Scottish Government (2009). However this underestimate should have little, if any, effect when making comparisons between eroded and adjacent uneroded

Figure 2. An example of supervised classification of bare peat in digital imagery for a 0.25 km^2 square in the Ladder Hills SSSI.

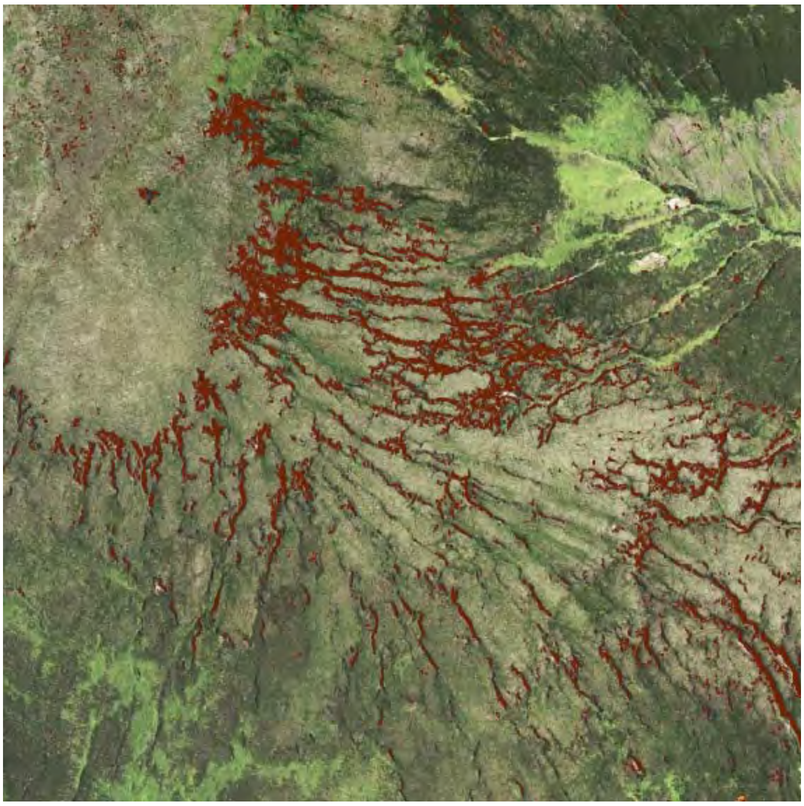
Original GetMapping digital imagery.

Areas of bare peat (coloured brown) delineated by supervised classification of red:green spectral ratio using Definiens^R Developer *software.*

Note that:

(a) the classification can identify very small patches of bare peat (e.g. in the top left corner of the image) and

(b) the classification excludes bare mineral surfaces (e.g. the white areas seen in the top right corner).



land as both tend to occur on similar slopes and will be subject to the same bias due to perspective.

The imagery of all the sites is included in a CD provided to SNH.

Having identified and quantified the areas of bare peat, it was also necessary to determine the total area of peatland, regardless of erosion, in each study area so that the amount of bare peat, identified from the imagery, could be put in context. The area of peatland was obtained from the area of appropriate vegetation types recorded in LCS88 but other data were used if they were potentially more precise. For example in the Ladder Hills study area, four of the six sites (sub-catchments) were within the boundary of the SSSI and for these SNH provided data from field-based NVC surveys in 1984. The vegetation classes that were most relevant to this study included M19A/B, M19B/C and M19/M20 (*Calluna* - *Eriophorum* blanket mires), but excluded M4, M6, M6C and M6C/M4 (predominantly *Carex* – *Juncus* - *Sphagnum* flush communities). The other two sites (L1 and L6) were outside the SSSI and the area of peatland in these sites was assessed at finer detail than in LCS88 by two experienced photo-interpreters using the current colour imagery. The agreement between LCS88 and the alternative assessments was generally close (Table 7) and therefore the readily available LCS88 data were considered to be suitable for determining the total area of peatland at the other two study areas.

Table 7 Areas of peatland in sites in the Ladder Hills SSSI recorded from different sources: LCS88 vegetation types (1988), photo-interpretation of Getmapping imagery (2004-06), and NVC ground survey (1984).

Site	**Site area** (ha)	**LCS88 classification** (ha)	**Photo-interpreter classification** (ha)	**NVC classification** (ha)
LH1	100	69.0	82.9	-
LH2 (control)	25	6.7	-	16.0
LH3	125	88.9	-	94.5
LH4	75	50.3	-	47.8
LH5	100	71.4	-	77.9
LH6	75	59.1	54.4	-

3.5.4. *Determination of slopes*

The detailed studies of sub-catchments required more localised assessments of slope than the nation-wide studies and this was achieved as follows.

The Ordnance Survey (OS) MasterMap contours were loaded into ArcMap from the Macaulay Institute's geospatial database. An area of the contours extending well beyond each site was extracted and converted to a triangulated topological network (TTN) using the ArcGIS extension 3D Analyst. This network of triangles was augmented with the OS spot heights for the area. The triangles were then converted to a regular grid of interpolated height values with a 1 m resolution. The slope in degrees for each of the 1 m grid cells was then calculated. Both of these processes were run in 3D Analyst. The statistics for the slope in the areas of bare peat and 'other' peatland were calculated using the Spatial Analyst extension in ArcGIS which calculates mean slopes for each contiguous area of bare peat or vegetated land.

3.5.5. *Localised assessments of drivers other than slope*

The same parameters used for the national regressions were also examined in each of the 0.25 km^2 images to try to identify the effects of drivers at the local level. Formal regressions within study areas were not practical because several parameters were effectively categorical with too few classes to allow the separation of different effects (e.g. having only four or five classes of animal densities with the lowest recorded densities of deer coinciding with the lowest densities of sheep). Without more variation in the dataset, it would be impossible to separate these two factors and this applies to other drivers in the datasets where similar coincidences exist. Consequently, many assessments were confined to examining the results for patterns of association.

As with the national data, the scale of the available data on animal distributions and densities was a problem but this was even more pronounced at the local level. Deer density data often cover quite large areas that include both eroded and uneroded peatlands and consequently the local effects of deer on erosion cannot be differentiated using those data. Similarly sheep data were those from agricultural parish returns and did not have the necessary level of discrimination for assessing sheep as drivers of erosion.

To try to overcome these problems, we used the following surrogate indicators of the impacts of human activity and animals that could be detected in the imagery. These were assessed in eroded and non-eroded areas within sub-catchments and so were the most localised search for relationships between drivers and erosion. Unlike other assessments where the area of bare peat present was the criterion of erosion, a slightly different approach had to be used because some of the factors could not be readily detected on bare peat as such. A particular example is where some animal paths leading into eroded areas were detectable in the fringing vegetation but not on the bare peat itself. Consequently, the areas selected for investigation comprised the bare peat in an erosion system along with a small area of surrounding vegetation to provide context. In some cases the selected area contained several erosion features where there were only narrow strips of vegetation between them (e.g. parallel gully systems).

3.5.5.1. Indicators

- *Signs of muirburn.* Hester & Sydes (1992) reported that about 50% of muirburn areas are detectable on aerial photography 11 years after burning and almost 30% are still detectable after 13 years.

- *Number of detectable animal paths*. Although many tracks are 'traditional' and numerous animals may move along the same path, often wearing them down to bare soil, experience in the field suggests that there is at least a broad positive relationship between numbers of animals and numbers of paths. Note that detecting paths was the main reason for including a fringe area with each erosion feature as animal tracks were rarely obvious on bare peat, even though there may have been several tracks leading into the eroded ground. Less heavily used sheep walks and deer paths are vegetated but can be detected - though not always easily - as thin darker green stripes on the imagery (Figure 3).

  Branches to main paths were included in the count as they indicate dispersion of animals across an area. It is possible that counts of animal paths could have included single tracks created by bikes, motorbikes and walkers (see below) but these appeared to be rare and could usually be identified by their route, location and relative lack of branching.

Figure 3   Animal paths at the edge of an area of dendritic erosion in the Ladder Hills. Paths are mostly on the left of the photo. Several paths congregate (lower left) and some paths lead into the bare peat suggesting the possibility of deer wallows or use as shelter. White areas are mineral soil or rock surfaces.

- *Number of vehicle tracks*. These were identified by parallel twin tracks associated with quadbikes and other vehicles. Constructed roads/tracks were excluded.

- *Number of paths principally for walkers*. These were confined to those marked on OS maps as walking routes or were known to be principally used by walkers. Although such paths may also be used by animals, they were very rare and so separating them from animal paths will not have any marked effect on the counts of the latter.

- *Apparent signs of recolonisation of bare ground*. Polygons were classified according to the estimated cover of recolonising plants; *viz:* 0 = none, 1 = 1-10%, 2 = 11-25%, 3 = 26-50%, 4 = 51-75%, 5 = >75% cover.

- *Fences present.* These were limited to fencelines within or across digitised polygons. They were usually identified by a narrow line of thicker, less-grazed vegetation beneath the fence or by distinct differences either side of the fence. Non-functional fences are unlikely to show these differences.

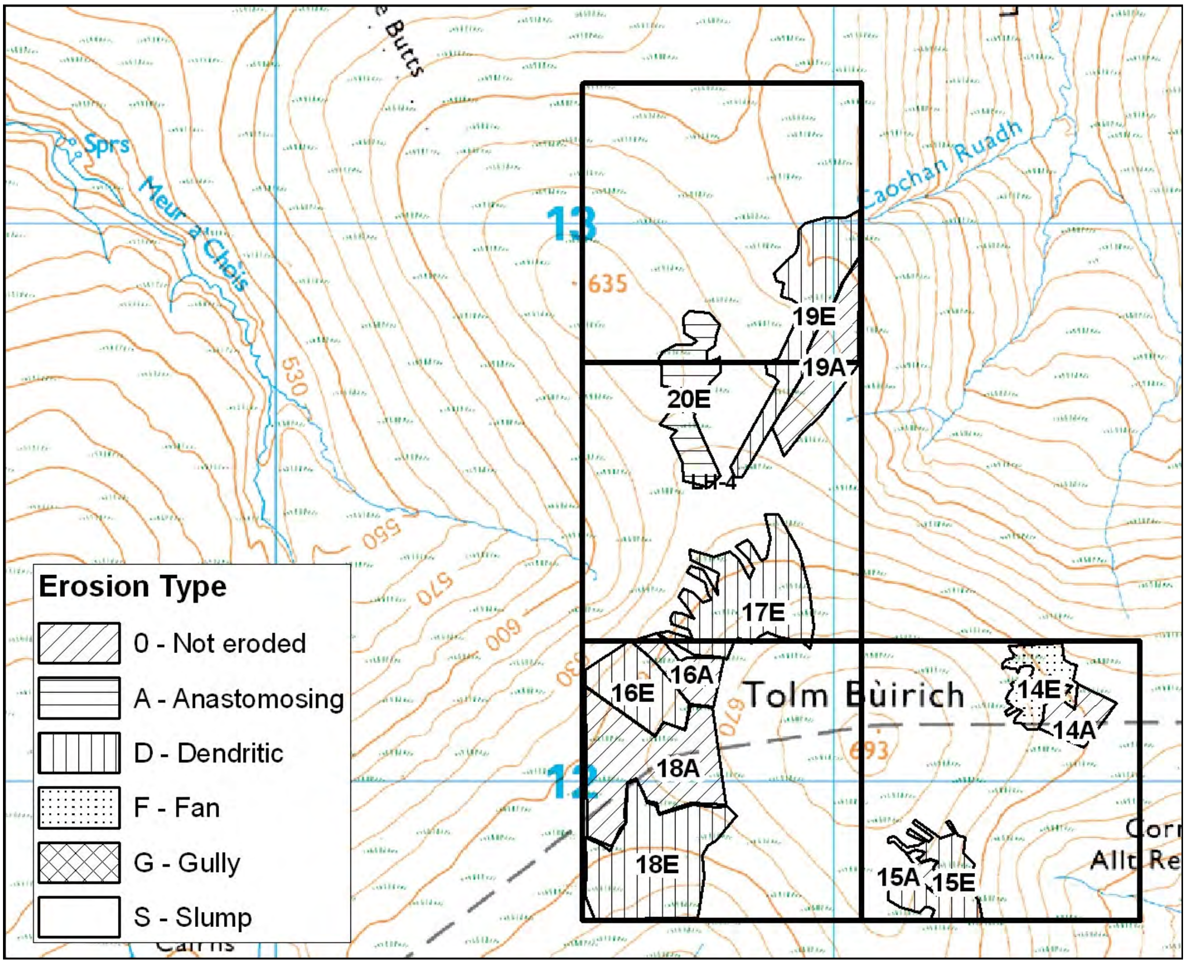
- *Mineral substrate apparent.* This was used as a broad indicator of the severity of erosion. Note, however, that the depth of overlying peat will also have an effect and that mineral substrates will be exposed more readily where the overlying peat is thin, presuming other factors are constant. The area of mineral substrate was classified using the same cover categories as for recolonisation (above).

The effects of grazing cannot be detected reliably from aerial photography, and so assessments were confined to existing reports and literature, except in the Ladder Hills where a field visit was made to several locations (see Section 5.6).

It was not possible to assess all patches of erosion in all the images due to resource constraints, but care was taken to select representative samples of the different types of erosion systems, or parts thereof, within individual sub-catchments. Characteristics of each eroded area were then compared with an area of adjacent non-eroded vegetation that was similar, as far as possible, in terms of size, topography and vegetation. This procedure helps to limit the effect of other influences that might confound the results for the factor under investigation.

Usually the equivalent eroded and non-eroded areas were outlined on hardcopy images and the areas assessed in conjunction with on-screen enlargements. However, in the Ladder Hills, the boundaries of the selected areas (referred to as polygons) were digitised in a GIS as part of the process of developing the methodology (Figure 4).

Figure 4. Example of digitised areas of eroded (E) and adjacent (A) vegetation in a Ladder Hills study area, and the associated type of erosion.



The above indices of disturbance/impacts can be localised and it was more appropriate to relate them to the presence of erosion rather than the actual amount of bare ground, which can be affected by many other factors including small-scale, undetectable variations in topography. Therefore the indices were assessed in terms of how widespread the drivers were (e.g. how many polygons have paths present), what is their potential widespread impact (e.g. the number of paths averaged over all the eroded polygons) and what their local impact might be (e.g. the number of paths averaged across only those polygons where paths occur). The numbers of polygons in any one class are variable and so some results are standardised as percentages to aid comparisons. However, care must be taken in interpreting percentages where the sample numbers are small, as a small numerical change can result in a large change in percentage terms.

All proportional (%) data were arcsin transformed before conducting statistical analyses.

4. METHODS OF MANAGING AND AMELIORATING EROSION

A section on possible methods has been included here because they are referred to in each of the following sections on individual study areas. What follows is a generalised summary, reviewed more thoroughly by Evans & Warburton (2007), but probably the most comprehensive information relevant to the current project is the work undertaken under the 'Moors for the Future' Partnership in the Peak District area of the Southern Pennines, referred to here as 'the Pennines project' (e.g. Evans *et al*., 2005). A useful brief synopsis of remediation methods and indicative costs is given in DEFRA's recent report on UK peat restoration and management projects (DEFRA, 2008).

The cost of implementing any of the following methods is likely to be considerable and site-specific depending on the materials to be used and the severity of the problem (e.g. the number of outlets to be blocked per unit area of erosion). Costs would obviously be higher for remote sites and, particularly, high-altitude sites where a helicopter might be required for transporting materials. We recommend that estimates should include not only the cost of the initial installation but also maintenance and monitoring costs, both of which could extend over very many years.

4.1. Gully blocking

On relatively flat areas, gully blocking usually aims to raise water levels and limit any directional flow, whereas in gullied areas the aim is to reduce flow rates and prevent further widening and deepening of the gullies. Such blocking can also reduce upwards expansion of erosion. If successful, there should be a concomitant reduction in the loss of particulate material and, hopefully, the process of re-vegetation would be initiated and encouraged. Gully blocking, in particular, has been used with some success in the Pennines project where trials have included dams made of peat, stone, plastic, bales (heather and straw), wool, plastic, and in lowland sites, concrete and timber. Semi-porous stone and wood dams were found to be effective for trapping sediments, while plastic piling was the best method for raising water levels. Wooden dams, possibly accompanied by planting *Eriophorum,* were recommended for heavily degraded moorlands (DEFRA, 2008).

Tiered successions of weirs have been used on steeper sites but, logically, there must be a limit on the severity of slope to which blockage can be successfully applied, although there is no published information to indicate that this has been fully researched. The DEFRA report recommends that action should generally be concentrated on slopes less than 0.01 m/m (i.e. slopes of 10% or 6^o).

An important aspect of effective gully blocking on fairly level ground is achieving a level such that blocking in one location does not cause overflows in vulnerable places elsewhere. Evans *et al.* (2005) have reported on the development of an effective GIS tool which uses a topographic wetness index and LiDAR DEM data to efficiently plan the most effective location of gully blocking. Without such a tool, skilful decisions are required as to which outlets to block and to what level; in most cases there will still be an excess of water during rapid snow melt or heavy rain, and consideration must be given as to where the excess will go so that it does not cause new erosion or exacerbate erosion in other existing gullies.

It is also important to be clear about the targets and what the surrounding vegetation is as a seed source. Blanket bog with moderate cover of heather will require a lower water table than a community dominated by *Eriophorum* – a key species in peat stabilisation – while relatively high dams would be required in areas where it might be possible to recreate pool systems with standing water.

The cost of this work will clearly vary depending on how many blockages are needed per unit area of erosion, the materials to be used and the costs of installation and subsequent maintenance. These methods have only been in use for a few years and so little is known about their long-term effectiveness or for how long they need to be maintained.

4.2. **Gully widening**

It may seem contradictory that one aim of gully blocking (above) is to prevent them becoming wider and here we consider deliberate widening of gullies to limit erosion. However, gully blocking basically aims to control the inputs of water into systems, whereas the aim of gully widening is to disperse the existing water flow over a wider area, thus reducing its energy and erosive force. Gully widening is also used to reprofile overhanging blocks of undercut peat so that they form sloping vegetated banks to the gully. The method as a whole is particularly disruptive on the site itself and additional damage is possible when accessing areas, even with low-pressure footprint machinery (although small sites may be tackled by hand). Consideration also needs to be given to any archaeological features both on-site and along the access route. Of the methods discussed here, it is probably the least acceptable for use in designated areas.

4.3. **Drain cutting**

Extensive drainage of blanket mires in Scotland for agricultural or forestry purposes has been linked to a decrease in runoff response time following rainfall and snow melt (Bragg, 2002). Blocking of such drainage systems has been undertaken for conservation purposes and can significantly reduce rates of sediment output, although drains tend to revegetate and infill naturally on slopes of less than around 4°.

Conversely, a radical possibility for controlling water flows would be to cut header drains (e.g. across the top of a dendritic system) that would intercept surplus water and lead it into a preferred route away from more damaging locations. Cutting drains above footpaths to prevent them eroding is quite common but it does not appear to have been used for conservation management of erosion in blanket bogs. Such drainage may not be considered acceptable if heavy machinery was required in, for example, SSSIs.

4.4. **Controlling animal numbers**

The major difficulty in linking erosion of blanket peat to contemporary grazing pressures lies in the fact that erosion systems can be many hundreds of years old, predating the relatively intensive use of the hills for grazing (Rhodes & Stevenson 1997; Tallis, 1998). Sheep grazing has a long history in the UK uplands, with increases in sheep numbers in Scotland from the 1800s associated with the Highland clearances and change of land tenure. Increases during the 1950s and 1960s have been linked to subsidies for improvement of hill grazing through drainage, and during the 1970s and 1980s to subsidies under the CAP (Holden *et al*., 2007a). Impacts of red deer on blanket bog are largely expressed through trampling damage (MacDonald *et al*., 1998), and while deer numbers across Scotland have been steadily increasing since the 1960s, recent research indicates that heavier impacts of grazing and trampling in general were predominantly due to sheep (Albon *et al.*, 2007).

Animals have several impacts that can variously initiate or increase erosion. Excessive grazing will result in reduced vegetation cover or, in severe case, total loss of vegetation. Reductions in the above-ground plant mass usually result in increased surface wind-speed, drying out the peat more quickly and increasing the loss of particulate matter. This is exacerbated when vegetation dies and consequently plant roots are lost which help to bind the soil. In addition, trampling by sheep and deer can be expected to have an impact along paths or adjacent to them, while the congregation of deer on bare peat wallows in the summer must increase trampling impacts there several-fold. Importantly, large and small herbivores can prevent recolonisation of bare peat by selectively grazing young plants. This is an active process whereby animals seek out such areas (as is often seen on young muirburn sites) and so the critical density of animals that would allow recolonisation may be even lower than those given below. This could prevent the establishment and growth of seedlings on bare peat, whether from natural regeneration or deliberate attempts to revegetate areas by planting or mulching (see below).

The critical density of sheep on blanket bog is commonly quoted as ~0.5 sheep/ha - more than this is not biologically sustainable in the long term. Deer densities are considered to be high if they exceed a density of ~15 deer/km^2. However, these are generalised figures and, despite being within these overall limits, local concentrations of animals commonly occur that can far exceed these densities. Therefore reducing sheep stocking densities or culling of deer may not produce the desired result if the remaining animals still congregate on sensitive areas. The impact of sheep can be reduced by careful shepherding and by not allowing sheep onto the hill during winter, when the vegetation and ground surface are most prone to being damaged. Congregations of animals tend to be greater on low ground in winter and on high ground in summer. High ground is usually far more sensitive to animal impacts and the precautionary approach when making plans for animal management should be to adopt figures suited to high-altitude areas. This requires detailed local knowledge. There is a clear conservation conflict in localised areas where the control of mountain hares might be necessary to maintain vegetation cover.

Fencing animals out of susceptible areas, or redirecting them to other areas, could be an expensive option and might only serve to shift the problem elsewhere. Erosion is more readily created than recovered, so this might actually increase the overall amount of erosion. Conversely, there may be 'hot-spots' where fencing could be considered. As the intention would be to severely reduce impacts and not necessarily to exclude animals completely, occasional breakthroughs would be acceptable. In this case, wind-powered multi-strand electric fences ('New Zealand' style) would be a cheaper option and probably more acceptable in conservation terms than the standard netting deer-fences.

4.5. **Reducing muirburn**

If the Muirburn Code (Scottish Government, 2008) is followed, there should be no intentional burning of blanket bog vegetation. It is recommended that such best practice is encouraged and that landowners continue to protect areas from damage due to fire, notably fires during the summer months, either unintentional or deliberate, as such fires are regarded as being potentially altogether more damaging to peatlands (Tallis *et al*., 1997). The Muirburn Code should be strictly followed and areas of blanket mire avoided, especially where there are nearby patterns of erosion.

4.6. **Revegetating bare peat**

4.6.1. *Application of brash*

There are several methods for promoting regeneration, depending on the site and the scope and extent of the problem. Where heather is a common species, chopped heather brash can be used to help stabilise the surface and provide additional seed sources for regeneration. This has been used in the Pennines project, applying 18 tonnes of brash per ha at a cost of around £1700 per ha (although considerably more costly elsewhere when a helicopter was used to transport and help spread the brash). It is unlikely that this method could be used successfully on steep slopes due to the possibility of slippage and/or downwash, which would not only lose the benefit of the brash on-site but it could also bury viable existing vegetation below the site. No reference has been found as to what the cut-off point for the gradient might be.

4.6.2. *Reseeding using nurse crop*

Reseeding with a nurse crop has been used over quite large areas - and can be applied efficiently by helicopter - but it is usually targeted at drier sites because there are few, if any, 'nurse' species that are tolerant of blanket bog conditions and for which suitable amounts of seed are available. The nurse crop is usually a rapidly growing species that is not well suited to the site (e.g. a variety of *Lolium*) and therefore requires help to establish by the application of fertilizer and lime, possibly over two or three years and serves to stabilize the peat. Adjacent native species can then seed in naturally or be sown artificially. The nurse crop eventually dies once the application of fertilizer ceases, leaving a more natural and stable sward. For this method to be successful, it is crucial that there are few, if any, herbivores present - especially sheep – because they are attracted to the nutritious young grass and can graze it out before it has any effect. Therefore this method might be appropriate to the areas where sheep have been, or are going to be, removed but even then additional local control of deer might be required. The alternative is to fence off the reseeded areas but this is impractical in many situations and would add considerably to the cost, even with relatively cheap electric fencing to control just sheep, and may cause conservation conflicts.

4.6.3. *Planting*

Plug plants of *Eriophorum* have been used to try to recover areas but this and other appropriate species are not available commercially and it is prohibitively expensive to raise the numbers of plants required for planting at meaningful densities. Even if this were done, personal experience of conducting experiments on the open hill shows that the plants would be vulnerable to being uprooted by herbivores and would need similar protection to those required for reseeded areas. Overall, the use of plug plants is not considered to be a viable option for many sites.

4.6.4. *Surface stabilisation*

A radical approach is the use of geo-textiles to actively stabilize peat surfaces, combined with measures to revegetate areas of bare peat. Again, this has been used within the Pennines project where geo-textiles, fertilizer, grass seed and heather brash have been shipped - and sometimes spread - by helicopter. Even then, this process still requires large amounts of manpower. Of all the potential management strategies, this is probably the most expensive.

4.7. **Atmospheric pollution**

Acid deposition has been implicated as one of the causal factors of peatland erosion, in particular in the Southern Pennines and might be one explanation for the severity of the problem in that area. Indeed, some management methods to revegetate blanket bogs in the Pennines benefited from the use of lime to reduce acidity. However, the UK's emissions of SO_2 peaked in 1970 and have declined by almost 70% since 1990 (Fowler *et al*., 2005). Nitrogen is also a potential source of perturbation of peatland ecosystems. Although N deposition has only yet shown small reductions, these may reduce further as car engine technology improves and the use of N fertilisers decreases. It is likely that the influence of acid and nitrogen deposition on peat erosion processes in Scotland was much less than in northern England, and these factors are likely to be of minimum effect in the future. Governments should be encouraged to follow international agreements on controlling atmospheric pollutants, such that the potentially deleterious effects are carefully managed.

5. RESULTS FROM EVALUATION OF DRIVERS: LADDER HILLS STUDY AREA

5.1. Background information

This section summarises data available from SNH in relation to local land management trends, the existence of any management agreements, any information on major fire events, activities related to domestic herbivores, and notes from field visits connected with habitat condition monitoring.

Resources allowed twenty sample squares per study area and in the Ladder Hills these were distributed across six sites, ranging in size from one to five squares (Appendix 1 Table A1.1). The sites are dispersed on a south-west – north-east axis over a distance of approximately 15 km from Tom Buirich (692 m) over the main ridge of the Ladder Hills (Carn Mor, 804 m) and down towards the Kymah Burn (550 m). The majority of the sites are within the Ladder Hills SSSI, apart from two outlying clusters – one in the south-west and one in the north-east.

5.1.1. *Designated features*

The Ladder Hills SSSI, extending to 4 240 ha, encompasses extensive areas of, and wide variation in, Callunetum types typical of the Scottish Highlands. These range from sub-montane, tall heather-dominated communities to lichen-rich prostrate montane heaths (NVC H12 – *Calluna vulgaris-Vaccinium myrtillus* heath, H13 – *Calluna vulgaris-Cladonia arbuscula* heath, H18 – *Vaccinium myrtillus-Deschampsia flexuosa* heath, H21 – *Calluna vulgaris-Vaccinium myrtillus-Sphagnum capillifolium* heath, and H22 – *Vaccinium myrtillus-Rubus chamaemorus* heath). However, the area is especially noted for the extensive occurrence of blanket bog habitat (NVC M19 – *Calluna vulgaris-Eriophorum vaginatum* mire, and notably the lichen-rich sub-community M19c). Cloudberry (*Rubus chamaemorus*), a plant species of restricted mountain distribution characteristically associated with mountain bogs, is described as being unusually abundant in this general area. Blanket bog is a habitat of great international importance in Great Britain as a globally rare formation and there are very fine examples of large areas of intact and relatively undisturbed habitat of this type in the Ladder Hills. Areas of drained bog are restricted to the south-eastern parts of the general area and mostly date from decades ago.

5.1.2. *Ownership and management*

The sites lie on three estates: Allargue Estate (to the south-west), Edinglassie/Dunecht Estates (to the north-east of the watershed) and Glenlivet/Crown Estates (to the north-west of the watershed). There are no specific management agreements in place covering any of the estates that extend over the designated area, apart from the standard list of 'Operations Requiring Consent' (as defined by SNH; formerly 'Operations Likely to Damage the Features of Special Interest') which include changes in the grazing regime, burning, drainage and changes in game management and hunting practices. The overall area is defined as being managed as "grouse estates and rough grazing".

Across the selected Ladder Hills study areas, deer numbers between 1987 and 2002 were relatively low, averaging 10 animals per km^2 both within and outside the SSSI boundary. The Parish returns indicate overall densities of 0.75 sheep per ha in the sites inside the SSSI in both 1986 and 2006, which is around 25% lower than outside the SSSI where densities were also unchanged at about 1.1 sheep per ha. The shortcomings of these data have already been discussed but, despite the data for both sets of areas indicating some redistribution of animals within the overall figures, there is little evidence to support the suggestion that a decline in shepherding across some parts of the area may have resulted in localized overgrazing.

Appropriate management is encouraged by SNH in liaison with landowners. Some blocking of moorland drainage grips in blanket bog took place in 1998 on Edinglassie Estate, but it is likely that the areas concerned were at relatively low altitudes below the major areas of concern.

In the 1992 site management brief and review of the SSSI, the only domestic livestock were sheep, run by agricultural tenants, not the estates. Although stocking levels had not been satisfactorily defined, grazing was considered to be high but within acceptable limits. The site was important for grouse shooting and was described as having a very high quality of muirburn with small patches of different ages, localised in appropriate communities. There are populations of both red and roe deer (*Cervus elaphus* and *Capreolus capreolus*) on the SSSI. The local view in 1992 was that red deer grazing was limited, with animals not hefted to the hill but just passing through. Mountain hare (*Lepus timidus*) populations are notably large on the hill and are exploited for sport.

5.1.3. *Site condition monitoring*

Site condition monitoring was carried out in 1999 and 2007. In 1999, grazing by mountain hares appeared to be relatively high on the sub-alpine and alpine heaths but in most instances there was little indication that this was damaging the habitats. Grazing on blanket bog was recorded as universally low. This was the first monitoring episode using the standard site condition monitoring procedures and all the targets for each feature were met, so the overall condition of the site was favourable. No changes in management were suggested, but it was stated that reconsideration of muirburn in areas of blanket bog susceptible to erosion may be advisable.

The monitoring in 2007 reported that blanket bog suffered from locally severe gullying and hagging, mainly in saddle and spur geographic locations. Mountain hares were recorded as abundant and it was stated that they probably make some contribution to the erosion. However, no measurable decline in the condition of blanket bog was noted.

5.2. **Evaluation of role of drivers in sites in the Ladder Hills study area**

The areas of peat vegetation and bare peat in each of the six sites in the Ladder Hills study area are given below (Table 8). The locations of sites are given in Appendix 1 Table A1.1.

The following broad descriptions provide some context for the subsequent detailed assessments of drivers of erosion and are presented in order of increasing erosion, expressed by the area of bare peat as a percentage of the area of all peatland. More detailed descriptions of some areas are given in Section 5.6 (field validation).

LH2 was a single square at lower altitude than the other five sites and was chosen as an almost intact ‘control’ study area with no erosion.

LH1 lies just outside the SSSI boundary and, with 2.5% of all peatland covered by bare peat, was the site with the lowest proportion of bare peat except for the control square. Most of the site was dominated in the south by a clearly defined uneroded summit bog. Drainage gullies emerged some way downslope of the bog and were predominantly dendritic systems with narrow channels. Some drier heaths to the north-west and south-east of the summit had been burnt but the burning did not appear to have extended onto the peatlands.

Table 8 Areas and proportions (%) of (a) peatland estimated from vegetation records, and (b) bare peat determined by supervised classification of digital imagery in sites in the Ladder Hills study area.

	(a) Peatland vegetation					**(b) Bare peat**		
Site	Area of site (ha) *(A)*	LCS88 classification (ha)	Photo-interpreter classification [1] (ha) *(V)*	SNH classification (ha) *(S)*	Percent of site area that is peat vegetation *(S/A or V)*	Area of bare peat soil (ha) classified in Definiens *(B)*	Bare peat as % of site area *(B/A)*	Bare peat as % of peat vegetation *(B/V or S)*
LH1	100	69.0	82.9	-	82.9	2.10	2.1	2.5
LH2 (control)	25	6.7	-	16.0	64.2	0.00	0.0	0.0
LH3	125	88.9	-	94.5	75.6	10.91	8.7	11.5
LH4	75	50.3	-	47.8	63.7	3.75	5.0	7.9
LH5 (modified after field checks)	100	71.4	-	77.9	77.9	10.3	10.3	13.2
LH6	75	59.1	54.4	-	72.6	5.81	7.7	10.7

[1] *Classified from imagery by A Nolan & R Cummins*

LH4 was intermediate in its cover of bare peat (almost 8%) and here much of the peatland lay on slopes below ridges or plateaus that were dominated by montane vegetation on predominantly mineral substrates. There are three main areas of erosion: (a) to the west, an area of anastomosing erosion with a very high proportion of bare peat; (b) centrally, an example of peat slippage with bare mineral rock visible; (c) to the east, a complex area of dendritic, anastomosing, fan and gully systems, some of the gullies being quite broad. This study area included some locations targeted for field validation and further descriptions are given in Section 5.6.2.3.

LH6 also lay outside the SSSI boundary and had a series of dendritic systems below a relatively intact area of peatland on a fairly level broad spur. Erosion systems to the north-west had noticeably broader channels than the much finer systems to the south-east, all contributing to a total of almost 11% bare peat.

LH3 had slightly more bare peat (11.5%) than LH6 and was dominated by a highly eroded anastomosing system on the crest of a ridge. This fed into complex gully and dendritic systems to the west and east. In the north east of the study area, an area of slippage showed the mineral substrate in some places, whereas other parts of the slippage had revegetated. For field observations of part of this study area, see Sections 5.6.2.1 – 0.

LH5 had over 13% of peatland eroded to bare peat, the highest amount of all the sites, and a considerable part of it was surveyed in the field. The highest proportions of bare peat in this study area were in two anastomosing systems on almost level ground on the summit of Broom Knowe (see Section 5.6.2.4 for detailed description) and in two fan systems on fairly gentle slopes further north (see Section 5.6.2.5). In the north-west was an area of large haggs on a north-west facing slope, with a system of much smaller haggs and fan erosion on the opposite south-east slope (see Section 5.6.2.6).

5.3. Relationships between bare peat and drivers at the 0.25 km^2 scale

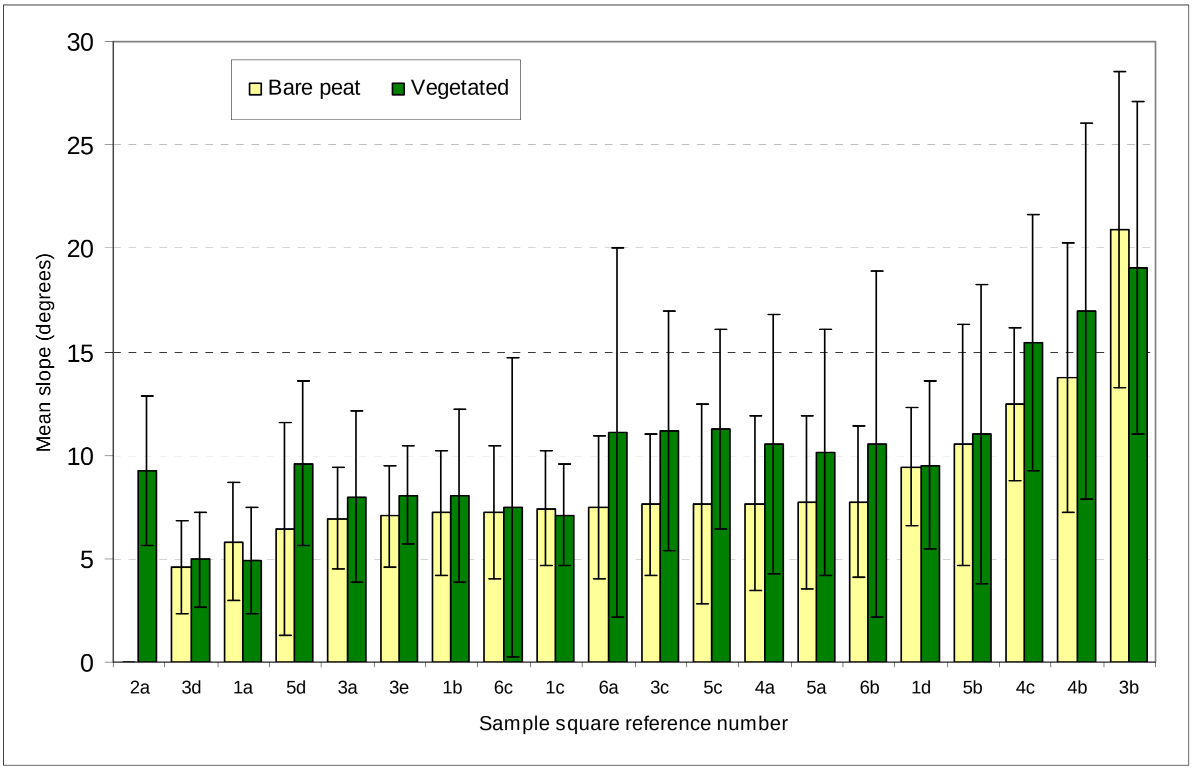
The indicator of erosion used in the following assessment is the area of bare peat, as determined from the imagery, because this provides a much more precise estimate of the actual area of actively eroding land than the more generalised LCS88 area of eroded peatland *vegetation* which was used in analyses of slopes for the national data.

5.3.1. *Slopes: analyses of 1m resolution data for individual squares*

The slopes where bare peat occurred were compared with those for vegetated peatland in each square, using the TTN slope data. It must be remembered when interpreting these results that the sites are not a random selection of peatlands in the SSSI. Indeed, in order to provide information appropriate to the aims of the project, most of the selected sites had to have some erosion present. Therefore, the results should not be extrapolated to the SSSI as a whole and conclusions must be taken to apply only to *areas susceptible to erosion* at the 0.25 km^2 scale in the Ladder Hills.

The results for individual squares, arranged in order of increasing amounts of bare peat, are shown in Figure 5. The 'control' square (2a) had no bare peat and consequently cannot have a score for that factor. Therefore, the data from square 2a were excluded from the following statistical analyses.

Figure 5 The mean slopes of bare peat and vegetated ground in individual 0.25 km^2 sample squares in the Ladder Hills study area calculated from TTN models. Vertical lines indicate +/- 1 standard deviation.

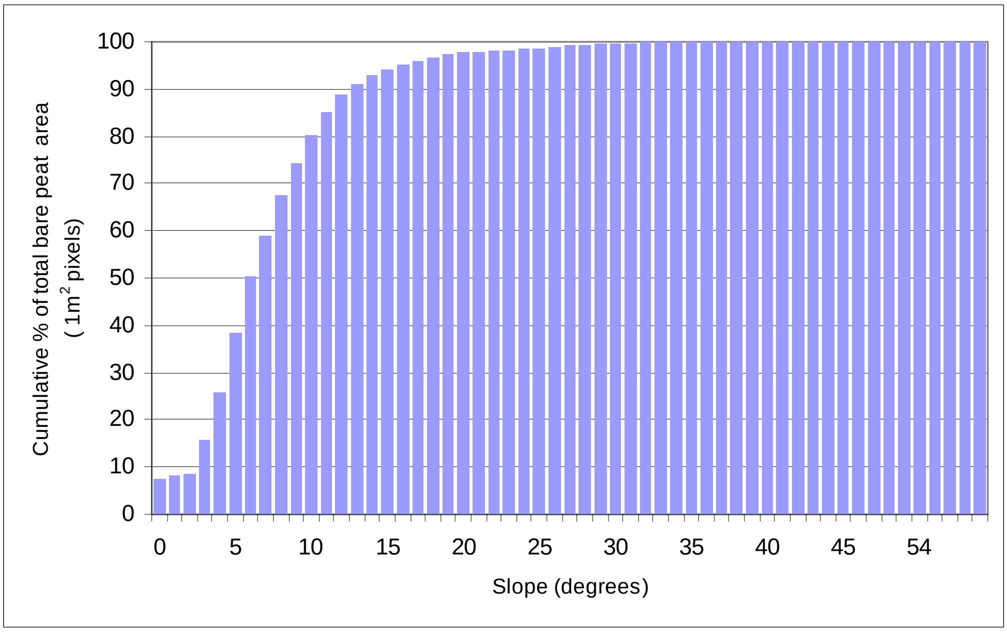


Note: the 'control' square (2a) had no bare peat

The difference between the mean slope of vegetated peatland and bare peat within each square was small, exceeding +/-3^o in only five of the twenty sites. In 16 of the 20 sites, the vegetated slopes were steeper than those with bare peat and these results were reflected in the overall mean slopes of 10^o and 9^o respectively. Although the data were very variable (Figure 5, vertical lines), the difference between the mean slopes of vegetated and bare peat areas within squares was statistically significant (paired two-tailed t-test: $p<0.001$ at the 5% level of significance). This small difference might be explained, at least partly, by the type and distribution of erosion features, although this will clearly vary from square to square. Basically, the mean slope of bare peat areas is weighted by the larger areas of erosion that commonly (but not exclusively) are present on more level ground, for example anastomosing systems on ridges and summits. The remaining (vegetated) ground in a square therefore tends to have a relatively higher proportion of the steeper slopes falling away from ridges. Where bare peat occurs on steeper slopes, it is commonly in gullies that have a relatively small plan area in the imagery, and consequently these areas have relatively less weighting on the mean slopes of bare peat.

A second aspect of erosion obtained from the slope data was to examine the occurrence of bare peat in terms of slopes for all twenty squares together. Figure 6 shows the cumulative amount of bare peat in 1^o slope classes as a percentage of the total area of bare peat. Note that these results are for all bare peat present when the imagery was taken and therefore include the small patches that occur across upland landscapes but do not form part of what would normally be considered as an erosion system (e.g. seasonally dry pools).

Figure 6 The area of bare peat on different slopes shown as a cumulative percentage of all bare peat in sample squares in the Ladder Hills study area



The graph shows that 50% of bare peat was on slopes of 6^o or less, and 80% on slopes of 10^o or less. As mentioned previously, the results for erosion on steeper slopes will be an underestimate of the actual area on the ground because of the perspective of the imagery. Nevertheless, bare peat on steeper slopes represents only a relatively small proportion of the total area of bare peat in the sample squares. The equivalent figures for vegetated ground were 8^o and 13^o, respectively, suggesting that bare peat occupies somewhat shallower slopes than are present elsewhere in the square.

Conclusion: Eighty percent of bare peat occurred in the sample squares on slopes of 10 ^{o} or less and, on average, was on marginally gentler slopes than vegetated ground. Although the latter result was statistically significant, the mean difference of one degree is clearly too small to be of practical value to conservation practitioners for trying to identify 0.25 km squares that are susceptible to erosion.

5.3.2. *Relationship between bare peat and local drivers other than slope*

The same parameters used for the national regressions were also examined in each of the 0.25 km^2 images to try to identify the effects of drivers at the local level. Table 9 shows the results for a selection of the more likely drivers of erosion, as informed by the national analyses. The full set of results, in site order, is given in Appendix 1, Table A1.2.

To make consistent comparisons it was necessary to standardise the data to take account of differences in the area of peat vegetation (i.e. the potential area for erosion) in each square. Consequently, the measure of erosion used is the area of bare peat expressed as a percentage of all peatland in a square. To facilitate assessments of relationships, the results below are shown in ascending order of % bare peat.

As noted in Section 3.5.5, formal statistical analyses were not practical because several parameters are effectively categorical with too few classes to allow the separation of different effects. Here, for example, the lowest density of deer occurs in four squares and all but one of these also coincides with the lowest densities of sheep. Similarly, the 'control' square was at the bottom end of the range for most of the potential drivers, but without more variation in the dataset (i.e. more detailed local information), it is impossible to separate the effects of the various factors.

The problem of the scale of the available data on animal distributions and densities has also been mentioned previously. Deer density data covered quite large areas that included both eroded and uneroded peatlands. Consequently, the effects of deer on erosion would not be differentiated in such areas. Similarly, sheep data were those from agricultural parish returns and did not have the necessary level of discrimination for assessing sheep as drivers. A good example of the problem in the Ladder Hills is seen near Carn Liath where the agricultural parish boundary runs along an old fenceline. To the west of the fence, in Kirkmichael parish, the sheep density was 0.34 per ha in 1986 and 0.21 in 2006. In the adjacent parish, east of the fence, the equivalent figures were much higher at 0.49 and 0.48, respectively. However, the fence has apparently been derelict for many years and sheep from both parishes have free access to the same plateau area.

For the above reasons, assessments were therefore limited to close inspection of the data and this revealed no clear patterns or relationships between the proportion of bare peat and single variables or combinations of variables.

Conclusion: At the 0.25 km^2 scale, there is no clear evidence of single or multiple relationships between the amount of bare peat and potential drivers of erosion, including large herbivore densities, altitude and climatic variables.

Table 9 Ladder Hills study area - the proportions (%) of peat vegetation (LCS88) in 0.25 km² sample squares that were classified as bare peat and the associated published data for potential drivers of erosion. Results are arranged in ascending order of bare peat. (Note red deer density per km²).

Sample square	**Bare peat as % of total peat vegetation**	Red deer density 1987-02 (mean no. per km²)	Sheep density 1986 (no. per ha)	Sheep density 2006 (no. per ha)	% change in sheep density	Altitude (m) Mean	Altitude (m) Min	Altitude (m) Max	Monthly rainfall (mm) Mean	Monthly rainfall (mm) Max	Exposure index	Frost index
LH-2 (control)	**0**	8.23	0.36	0.39	8	554	522	590	94	231	3	5
LH-1a	**1**	8.23	0.36	0.39	8	611	592	634	94	231	3	5
LH-1c	**2**	8.23	0.61	0.59	-3	657	629	687	94	231	4	5
LH-3e	**3**	10.30	0.61	0.59	-3	737	695	769	103	253	4	5
LH-1b	**5**	8.23	0.36	0.39	8	630	593	669	94	231	4	5
LH-6c	**5**	10.30	1.81	1.84	2	637	599	656	101	266	4	5
LH-1d	**7**	13.08	0.61	0.59	-3	657	597	692	94	231	4	5
LH-4b	**7**	10.30	0.61	0.59	-3	732	634	787	103	253	5	5
LH-4c	**7**	10.30	0.61	0.59	-3	726	666	789	103	253	5	5
LH-4a	**9**	10.30	1.81	1.84	2	745	705	771	103	253	5	5
LH-3a	**10**	10.30	0.36	0.39	8	722	670	761	85	198	4	5
LH-3b	**10**	10.30	0.61	0.59	-3	700	607	759	103	253	5	5
LH-5c	**11**	10.30	0.61	0.59	-3	689	626	738	103	253	5	5
LH-5b	**11**	10.30	0.61	0.59	-3	731	688	752	103	253	5	5
LH-6a	**12**	10.30	1.81	1.84	2	624	561	655	88	214	3	5
LH-6b	**12**	10.30	1.81	1.84	2	616	545	645	101	266	3	5
LH-5d	**12**	10.30	0.61	0.59	-3	666	615	691	103	253	4	5
LH-3c	**16**	10.30	0.61	0.59	-3	730	658	765	103	253	5	5
LH-5a	**21**	10.30	1.81	1.84	2	742	700	772	103	253	5	5
LH-3d	**23**	10.30	0.36	0.39	8	769	746	791	103	253	5	5

5.4. Relationships between erosion systems and drivers within sub-catchments

5.4.1. *Comparisons of eroded and non-eroded areas within individual sub-catchments using 1 m resolution slope data*

This section examines the relationship between erosion and slopes at the finest, most local level of discrimination used within the project, complementing assessments at the coarsest scale (national occurrence of eroded vegetation) and the medium scale results for the amount of bare peat in 0.25 km² images. Because the areas in the Ladder Hills had been digitised, it was possible here to use the TTN data to make some statistical comparisons of the slopes associated with different types of erosion system and also to make some paired comparisons between eroded ground and the immediately adjacent non-eroded area (Table

10). However, anastomosing, dendritic and gully erosion were the only types where sample sizes were large enough for analyses.

The sample sizes vary not only between erosion types but also between eroded and non-eroded areas within those types. This was because several of the areas of erosion that were digitised did not have comparable areas adjacent to them (e.g. where the adjacent area was also eroded but of a different type, or was not peatland - commonly montane vegetation). Hence the numbers of paired data available for analysis are limited by the sample sizes of uneroded adjacent vegetation.

5.4.2. *Comparisons between types of erosion*

The aim here is to investigate if different types of erosion are associated with differences in slope at the local level. Comparisons are made for the whole sample of each erosion type using the results shown in the 'eroded' column in Table 10.

The mean slopes of anastomosing and dendritic systems were very similar and both were almost twice that for gully erosion. Analysis of variance showed that there was a highly significant overall difference between these three types of erosion ($F=16.3$, $p<0.001$), and subsequent t-tests showed that differences between individual types were also significant ($p<0.05$ in all cases). That overall difference would probably have been larger but the major channels below dendritic systems, often present on the steeper slopes, were not digitised because some of them continued off the imagery and it was necessary to try to maintain a degree of consistency when defining the systems.

No conclusions can be reached for slippage and fan systems due to their small sample sizes. However, the occurrence of slippage on steep slopes and similarities between the slopes of fan and dendritic systems are reported in the literature. Indeed, the relationships between the slopes of all these systems are in line with other studies (reviewed in Evans & Warburton, 2007), although actual slope values for each type would be expected to vary depending on geography, topography and the characteristics of the peat itself.

Comparing these results with those shown in Figure 6, we can infer that anastomosing and dendritic erosion systems are probably the source of the largest total area of the bare peat in the Ladder Hills study area because they tend to occupy the shallower slopes.

5.4.3. *Comparing slopes of eroded and uneroded vegetation for different types of erosion*

To make paired comparisons of eroded and uneroded categories within different erosion types, the unpaired data – all from eroded areas – were excluded. This results in some generally small shifts in mean slopes (Table 10: c.f. 'eroded whole' and 'paired' columns). These shifts have little effect on the results because none of the results for the three major types of erosion was statistically significant ($p >0.4$ in all cases). In other words, based on slope alone, erosion was just as likely to have taken place on an adjacent, currently vegetated, patch of land.

Table 10 Mean slopes of different types of erosion systems in the Ladder Hills study area and differences from adjacent non-eroded areas. Data from TTN models of digitised systems.

Type of erosion		Eroded - whole sample	Eroded-paired sample	Non-eroded	Mean difference (eroded minus non-eroded)
Anastomosing	Mean	6	5	5	-1
	s.d.	3	2	2	1
	Max	12	7	8	1
	Min	2	2	1	-2
	No. sites	16		8	
Dendritic	Mean	7	8	8	0
	s.d.	2	2	2	1
	Max	12	12	13	2
	Min	5	5	5	-2
	No. sites	22		12	
Gully	Mean	12	13	11	1
	s.d.	5	5	4	3
	Max	20	20	16	6
	Min	5	5	4	-3
	No. sites	8		7	
Fan	Mean	9	10	9	1
	s.d.	1			
	Max	10		NA	
	Min	9			
	No. sites	2		1	
Slippage	Mean	17	28	18	10
	s.d.	12	NA	NA	NA
	Max	32	32	30	2
	Min	6	18	10	8
	No. sites	4		2	

Note: Mean differences were calculated on raw data before rounding of results for the table. Hence the result in the last column does not necessarily equal the difference between the preceding two columns.

Conclusion: Anastomosing and dendritic erosion systems occur on generally shallower slopes than most other types of erosion and are apparently the predominant sources of bare peat in the Ladder Hills study areas. Therefore, these gentler slopes are likely targets for prevention or remediation of erosion. In contrast, the results indicate that slopes do not have a significant influence on the precise location of an eroded area within any particular type of erosion (i.e. erosion is just as likely to have occurred on an adjacent piece of ground, based on slope alone). Therefore, if there is any physiographic effect it has to be assumed that it is not expressed by slope alone and is at a more local scale than can be determined from the imagery used in this project.

5.5. **Visual assessments from the imagery of local drivers due to human activity and animals**

5.5.1. *Muirburn*

There was no evidence of burning that was associated with erosion in any of the twenty sample squares in the Ladder Hills, at least within the 11-13 year detectability timescale reported by Hester & Sydes (1992). Of course this result does not preclude the possibility that historical muirburn could have initiated or accelerated erosion but if it had, cause and effect could only be reasonably inferred from remotely sensed data if, for example, the whole of a burnt area became eroded or there was other supporting evidence. Otherwise, the occurrence of small patches of erosion within a burnt area might have occurred regardless of burning.

5.5.2. *Animal paths*

This indicator of animal presence is examined in two ways:

1. The number of polygons with animal paths present is used to assess the overall dispersion of animals.
2. The number of animal paths within polygons is used as an indicator of local density/impacts and is assessed:
   (a) for different types of erosion, by the mean numbers of animal tracks (Figure 7 and Table 11); and
   (b) for paired comparisons between impacts on eroded and adjacent non-eroded areas (Table 12).

Statistical analyses were again limited to the top three types in Table 10 due to small sample sizes for the other types.

Figure 7 The mean number of animal paths in different types of erosion in the Ladder Hills study area. Vertical bars indicate one standard deviation. No paths were present in areas of fan erosion.

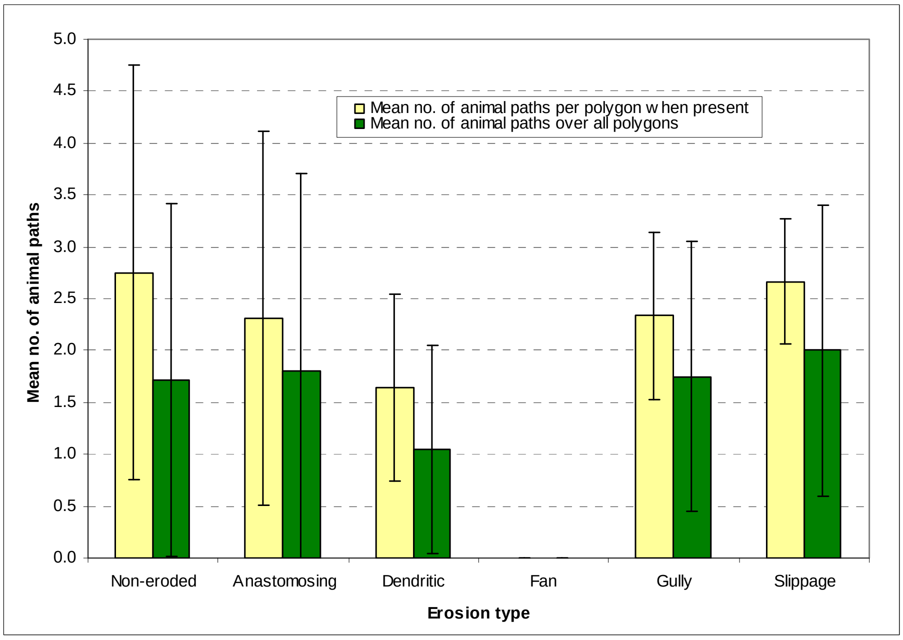


Table 11 The occurrence of potential drivers of erosion due to animals and human activity in different types of erosion and in adjacent non-eroded land in selected polygons in the Ladder Hills study area.

	Number of polygons recorded	Detectable muirburn (no. of polygons)	Number of polygons with animal paths	Proportion (%) of polygons with animal paths	Mean no. of animal paths per polygon **when present**	Mean no. of animal paths over all polygons	No.of polygons with vehicle tracks	Mean no. of vehicle tracks per polygon **when present**	No. of polygons with recolonisation	Proportion (%) of polygons with recolonisation	No. of polygons with detectable mineral soil/rock	Proportion (%) of polygons with mineral soil/rock	Mean index of mineral cover **when present**
Non-eroded	32	0	20	63	2.8	1.7	0	0	0	0	0	0	0.0
Anastomosing	17	0	13	76	2.3	1.8	0	0	1	6	10	59	1.5
Dendritic	22	0	14	64	1.6	1.0	1	1	0	0	6	27	1.7
Fan	2	0	0	0	0.0	0.0	0	0	0	0	0	0	0.0
Gully	8	0	6	75	2.3	1.8	0	0	2	25	3	38	1.3
Slippage	4	0	3	75	2.7	2.0	0	0	2	50	3	75	3.5
OVERALL	84	0	56	67	2.3	1.5	1	1	5	6	21	25	1.9

It must be emphasised that these assessments seek to identify if animals aggregate more in localised erosion systems than in immediately adjacent uneroded vegetation. The results do not provide information about uneroded land that occupies large areas elsewhere in the squares.

At the broadest scale, animal paths were common, being present in two-thirds to three-quarters of the selected areas (Table 11). However, in terms of impact, the actual numbers of paths per polygon vary considerably, and an analysis of variance showed no statistically significant effect to suggest that animal tracks are particularly associated with any one type of erosion, either on an overall basis (green columns: F=1.05, p= 0.37) or when limited to just those areas where paths are present (yellow columns: F=0.77 p=0.47).

Similarly, there is no evidence that the mean numbers of animal tracks in eroded areas of anastomosing, dendritic and gully systems are significantly different from those in adjacent non-eroded areas (Table 12. Two-tailed t-test, p>0.5 in all cases).

Table 12 Paired comparisons of the mean number of animal paths over all digitised polygons of eroding and non-eroding vegetation in the Ladder Hills study area.

Type of erosion		Eroding	Non-eroding
Anastomosing	Mean	2.0	2.2
(9 paired polygons)	s.d.	2.4	3.1
Dendritic	Mean	1.2	0.8
(16 paired polygons)	s.d.	1.2	1.2
Gully	Mean	1.6	3.0
(9 paired polygons)	s.d.	1.3	3.1
Slump	Mean	2.0	2.8
(4 paired polygons)	s.d.	0.4	2.1
Fan	Mean	0.0	0.0
(1 paired polygon)	s.d.	-	-
Overall	Mean	1.5	1.8
(39 paired polygons)	s.d.	1.6	2.4

Conclusion: None of the results showed a statistically significant association between the occurrence or type of erosion and disturbance by large herbivores, as indicated by the numbers of animal paths.

5.5.3. *Vehicle tracks*

The only vehicle track present crossed an area of dendritic erosion but in a location that would not have caused or accelerated erosion itself.

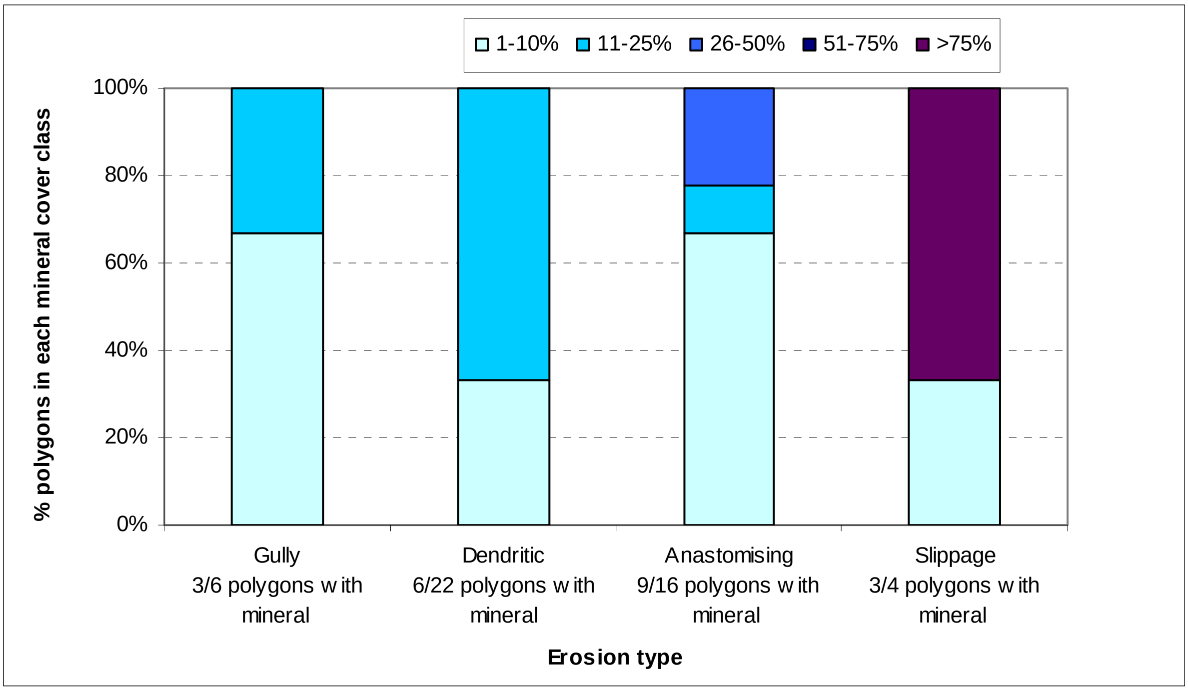
5.5.4. *Recolonisation*

Revegetation was apparent in only five polygons (two in gully erosion, one in anastomosing and two in slippage areas) and in four cases was estimated to have less than 10% plant cover. The exception was an area of old slippage that appeared to have almost complete vegetation cover, in contrast to an immediately adjacent section of the same slippage where there was a high proportion of bare mineral ground, probably rock.

5.5.5. *Mineral soils/rock*

Severe erosion down to the mineral substrate occurred fairly frequently, being present in between 25% and 75% of polygons, depending on the type of erosion (Table 11). The highest percentage of polygons with bare mineral material was in areas of slippage, although there were only 4 polygons with slippage in total, so this percentage is somewhat misleading. Nevertheless, mass slippage of peat, by its nature, is probably the most likely type of erosion to reveal bare mineral substrates, especially on steep slopes. Therefore it is not surprising that this type of erosion also had the largest proportions of mineral surfaces present (Figure 8).

Figure 8. The proportion (%) of eroded polygons with mineral substrate in each cover class in the Ladder Hills study area. Erosion types are arranged from left to right in increasing total cover of mineral substrate. Column labels show the number of polygons with mineral substrates present out of the total number of polygons recorded of each erosion type.



Erosion in anastomosing systems was also fairly severe in places, with more than half of the polygons having some bare mineral surfaces (Table 11). Moreover, the amount of bare mineral surface exceeded 25% in at least one-fifth of the polygons where it was present (Figure 8). This fairly high degree of erosion is probably due in part to anastomosing systems being frequent on exposed summits where the peat is relatively shallow.

Mineral substrates were also fairly common in dendritic drainage systems but without the more severe erosion of anastomosing systems. The nature of dendritic systems is such that runoff is focussed relatively rapidly into fewer and fewer narrow channels. Consequently much of the energy of the system is expended in the lower parts of the system and this is where mineral surfaces were commonly concentrated. Also the base of some of the deeper channels was hidden by shadow, as discussed for gully systems, below.

The amount of detectable mineral surfaces in gully systems was the smallest of the four types of system discussed here. This is not unexpected because the majority of gully systems in the Ladder Hills study area are not particularly wide and so do not occupy a large area. However, it is almost certain that the low recorded amount of mineral surface is partly an artefact of the imagery because many gullies are deep, as well as narrow, with their bases in deep shadow, thus potentially obscuring mineral surfaces. In addition, the base of some of the narrowest gullies can sometimes be obscured by overhanging vegetation.

Conclusion: Many systems were eroded to a depth where at least a small amount of mineral surface was apparent in the imagery but it should be noted that the initial depth of peat prior to erosion can vary considerably. Consequently, the same level of impact can have widely differing results in terms of erosion down to the mineral substrate. Slippage and anastomosing systems were the most severely affected. However, there were no consistent relationships with the various indices of anthropogenic and animal disturbance.

5.6. **Field validation of results in the Ladder Hills study area**

5.6.1. *Background to methodology*

It was not possible to visit all of the study areas in this project within the resources available, and so field assessments and validation were confined to selected sites within the Ladder Hills study area. The aims of the fieldwork were to:

a. supplement information already obtained from SNH for the desk-based study;

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

c. assess the relative impacts of wild and domestic herbivores and whether or not grazing was apparently limiting recovery;

d. assess if the current activity of erosion appeared to be balanced, increasing or decreasing;

e. evaluate the potential for restoration and likely methods to promote this.

The field visit was carried out on 11 August 2008 and included three of the six Ladder Hills sites (Areas LH3, 4 and 5 – A1 Table 1.1). The three sites were selected as broadly representative of the topography and patterns of peat erosion across the study area in general. A data recording form was designed to capture information in as systematic and objective a manner as possible and included the following information:

1. a record of the sample point and 12-figure O.S. Grid Reference (Garmin-12 GPS);
2. site photograph with signboard identification;
3. ground truth information related to the image classification (bare mineral, bare peat, colour and shadow tones, depth of eroded peat, width of banks, etc);
4. vegetation type (NVC type, dominant species);
5. topography (slopes, patterns of erosion related to ground features, break points, etc);
6. impacts (after MacDonald et al., 1998), including animal presence, tracks, dung, wallows, sheep/deer scrapes, human impacts, burning, ditching, overall impact assessment;
7. apparent state of erosion (active, increasing or decreasing, also whether grazing appeared to be limiting recolonisation and recovery);
8. summary notes related to restoration potential and methods to promote this.

An example of the field recording sheet is included in Appendix 1 Table A1.3. Copies of all sheets were provided to SNH on CD.

The field visit focussed on six of the most distinct sub-areas of peat erosion; two within site 3, one within site 4 and three within site 5. Detailed aerial photograph images, enlarged to approximately 1:500 scale and an overlay of the areas classified as eroded peat, were studied prior to the field visit. This enabled a number of suitable points to be selected to provide ground truth information related to the presence/absence of peat erosion, the nature of colour and tonal patterns, and the relationships between topography and patterns of peat erosion. A total of 25 sample points were visited and 56 photographs were taken, illustrating the different patterns and extent of erosion, the nature of ground surfaces, and the types of re-vegetation present.

An index to the locations and photograph references used below is in Appendix 1 Table A1.4 and the photographs are included in Table A1.5.

5.6.2. *Results*

5.6.2.1. Site 3 – sub-area 1

This area is approximately 0.5 km to the south of Carn Liath (792 m altitude), towards the southern part of the main Ladder Hills ridge, and data were recorded at three locations (LH020-LH022). The area is gently sloping and broadly convex and 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 (Photos 31-34). Tonal patterns of the eroded areas on the aerial photographs included darker brown colours, related to the darker more humified (presumably) lower peat layers, and lighter pinkish-brown tones, related to eroded and exposed upper layers of less well humified and more *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 was very striking. The image classification of eroded peat areas was generally very accurate. 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* were expanding out from remnant peat banks. However, grazing was not considered to be limiting recovery from erosion.

The overall impact class 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.

***Conclusion*:** Peatland erosion was considered to be active and in a relatively advanced stage and it was concluded that this was 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 evidence observable in the field, such processes were considered to have been operating over an extended period of time, possibly hundreds of years.

5.6.2.2. Site 3 – sub-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 (Photo 46). 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, not classified as peatland, 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.

Conclusion: 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 a long timescale.

5.6.2.3. Site 4

This area straddles the ridge between Carn Liath (792 m altitude) and Carn Mor (804 m altitude and 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 (sample points LH017-LH019). 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 (Photos 24-30). 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 misclassified 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* spp. colonising both bare mineral and peaty areas.

The overall impact was Light, with very few signs of large herbivore or human impact evident. There were a few, very localised areas where the grazing impact was Moderate, partly due to mountain hares whose signs were encountered relatively frequently. 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.

Conclusion: Erosion was considered to be active and in a relatively advanced stage; it 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 partly counter-balanced by revegetation of mineral and peaty/mineral areas post-erosion.

5.6.2.4. Site 5 – sub-area 1

This area is located on Broom Knowe (691 m altitude), a broad spur extending southwards from the main Ladder Hills ridge and data were recorded at eight specific locations (sample points LH001-LH008). The area is fairly level, occupying a saddle on the broadly convex ridge and is 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. (Photos 1-12). Tonal patterns on the aerial photograph were relatively clear, including light grey exposed mineral areas and light yellowish green areas of lichen-rich blanket mire. A range of darker brown tones represented eroded peat areas, and lighter greenish-brown tones appeared to be possibly re-vegetated areas. In the field, the image classification of eroded peat areas was found to be generally good but a proportion of the total actual eroded area (approximately 25%), and specifically the lighter brown and greenish-brown areas, was found to correspond to areas of bare peat. While the latter had been interpreted as 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 (notably Photo 6). In fact 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. These 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.

The overall impact class 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.

***Conclusion*:** Erosion was considered to be active and in a very advanced stage. As with the above areas, the main drivers of erosion were considered to be largely climatic acting over very long periods. Following the field visit, the spectral balance of the imagery was adjusted to correct the poor tonal separation prior to reclassifying areas of bare peat.

5.6.2.5. Site 5 – sub-area 2

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 (Photo 11). The more gently sloping summit of the broad ridge is characterised by fairly 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 recognisable, 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.

***Conclusion*:** Peat erosion was considered to be active and in an advanced stage, and largely due to the interaction of slope and climatic factors, operating over an extended period of time. As with sub-area 1, the spectral balance of the imagery was adjusted and then reclassified following the field visit.

5.6.2.6. Site 5 – sub-area 3

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 locations (sample points LH009-LH016 and LH023-LH025). 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 (Photos 13-23). Again, the contrast of tonal patterns on the aerial photograph was poor. The image had an overall greenish-brown appearance, and while the peat banks and relatively more intact areas of blanket mire were generally recognisable, 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 that the pattern on the ground was very clear and striking, almost exclusively consisting of widespread bare eroded peat surfaces and remnant peat banks (notably Photos 16 and 21). 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, and 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. Occasional mountain hares were encountered and there were only very localised areas of grazing. Signs of sheep occupancy or grazing were minimal and there was no evidence of grazing or disturbance that could be attributable to deer. Very few animal or human tracks were evident and there were no signs of burning.

Conclusion: Peatland erosion was considered to be active and very advanced. The principal drivers were again considered to be long-term climatic effects, resulting in extensive areas with between 75% and 90% bare peat. Imagery quality was again not adequate for accurate detection of bare peat and required adjustment before reclassification.

5.6.3. *Additional observations*

The aim of the field visits was to validate the detection of bare peat, and so the six areas in the Ladder hills that were selected for field visits were those showing the most active erosion from the aerial photography. However, some non-study areas seen during the field visits, showed greater evidence of past erosion surfaces becoming gradually revegetated (Photos 51-54). This varied from a fair cover of vegetation in the gully bottoms through to almost complete re-vegetation of even vertical faces and a cessation of active erosion. In one case where there was complete vegetation cover, it was unclear - apart from clues in the surface topology - whether the area had undergone erosion or not.

5.7. Summary of field validation in the Ladder Hills study area

- The peatland areas visited 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 with, in some places, up to 2 m of peat having eroded over time and thus exposing the underlying mineral substrate.

- The effects of rainfall, wind, frost and alternate cycles of drying and wetting of the surface were clearly evident. Surface flow in channels and gullies appeared to be the most erosive agent, but there was also some 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.

- There was very little revegetation or colonisation by algae or mosses on the areas visited but some was seen elsewhere.

- Grazing or disturbance was not considered to be limiting recovery on any of the sites investigated, with only light impacts attributable to human and animal influences.

- Burning was rare in the immediate vicinity of eroded peat areas, although some muirburn of adjacent heather-dominant vegetation on steeper slopes lower down had burned out upslope in the transition from heath to blanket mire.

- The procedure for classifying bare peat in the imagery was estimated to be 75-95% accurate in four of the areas visited but only 25% or less in the other two areas. After adjusting the spectral properties of, and reclassifying, the imagery of those two sites, the field surveyors considered the accuracy to be equivalent to that for the other sites.

A summary of the data for all six sites is presented in Table 13.

5.8. Summary of results from the Ladder Hills study area

- **General**

Most of the sites were selected because they had some erosion present. Therefore the results should not be taken as a representative sample of the SSSI and nearby land as a whole.

- **Accuracy of semi-automated detection of bare peat**

  - The information from the field validation was used to assess the accuracy with which the semi-automated system had detected bare peat in the imagery of areas that had not been visited. These visual assessments indicated that detection rates were generally extremely good with accuracies of up to about 95%.

  - Colour correction of the imagery as supplied was not totally consistent and a green cast on some images reduced initial accuracy to 10-25%, as estimated during field visits. Accuracy was improved to similar levels to the other sites by using the field results to guide re-classification.

- **Historical evidence of changes in extent of erosion**

  - Earlier monochromatic aerial photographs were examined and compared with the current imagery. Many similar patterns of erosion were evident but it was not possible to determine if the dimensions of those patterns had changed without spatially rectifying the two sets of imagery to make them comparable. Indeed, adequate rectification may not possible due to the limited numbers of unchanging features that could be used as registration points.

Table 13 Summary of the field validation data and peat erosion characteristics of six sample locations in the Ladder Hills study area.

Sample location	**Image quality and accuracy of classification of bare peat**	**Nature of eroded surface and any re-vegetation**	**Topography**	**Impacts of grazing and trampling**	**State of erosion**	**Probable factors in on-going erosion**
1. Site 3 sub-area 1	Very good tonal contrast, accuracy of classification very high (95%)	Extensive areas of bare eroded peat, some re-distributed peat and mineral substrate, very localised re-vegetation	Broadly convex, gently sloping	Light	Active and advanced	Climate
2. Site 3 sub-area 2	Very good tonal contrast, accuracy of classification very high (95%)	Extensive areas of bare eroded peat, some mineral substrate, very localised re-vegetation	Gently to very steeply sloping	Light (some burning of heath on lower slope)	Active and advanced	Climate, topography
3. Site 4 sub-area 1	Good tonal contrast, accuracy of classification high (90%)	Moderately extensive areas of bare eroded peat, some mineral substrate, localised re-vegetation	Broadly convex, gently to moderately sloping and undulating	Light (very locally Moderate)	Active and advanced, locally some re-vegetation	Climate
4. Site 5 sub-area 1	Good tonal contrast, accuracy of classification moderately high (75%)	Extensive areas of bare eroded peat, re-distributed peat and mineral substrate, very localised re-vegetation	Broadly convex ridge, mostly level, some gently sloping	Light	Active and very advanced	Climate
5. Site 5 sub-area 2	Relatively poor tonal contrast, accuracy of classification poor (25%)	Moderately extensive areas of bare eroded peat, very localised re-vegetation	Gently to moderately sloping	Light	Active and advanced	Climate, topography
6. Site 5 sub-area 3	Relatively poor tonal contrast, accuracy of classification very poor (10%)	Very extensive areas of bare eroded peat, virtually no re-vegetation	Broadly convex and undulating, with gentle to moderate slopes	Light	Active and very advanced	Climate, topography

- **Slopes**
  - Analyses of 1m resolution slope data for the twenty squares showed that 80% of bare peat occurs on slopes of 10^{o} or less. The predominant types of erosion on such slopes in the sites were dendritic and anastomosing systems.

  - The mean slopes of anastomosing (6^{o}), dendritic (7^{o}) and gully (12^{o}) systems were statistically significantly different from one another. Even so, the data were quite variable and it is unlikely that this information is of much practical use in identifying local areas at risk of erosion. Fan and slippage systems could not be analysed statistically due to small sample sizes, but the mean slope of the four slippage sites was notably high at 17^{o}.

- There were statistically significant differences between the mean slopes of vegetated ground and bare peat at the 0.25 km^2 scale. However, the mean difference of 1^o is too small to be of much practical value at this scale. Local topographic characteristics are probably more important than the broad-scale slope in determining the precise location of where erosion occurs.

- **Climate**
  - There was insufficient variation within the data to formally assess the relationship between climatic effects and the occurrence and extent of erosion in the Ladder Hills study area.
  - Field observations indicate that climatic effects are the principal driver of on-going erosion and could have been the main driver over many years, perhaps centuries. However there is no way of confirming this or of assessing whether it was climate or other factors that initiated the erosion process.

- **Animals and human activity as drivers**
  - No consistent single or multivariate relationships with erosion were identified within the data already available on animal densities and human activities. If these factors are drivers, the spatial and/or temporal scale of the data were too coarse to identify them, suggesting that they have their effect at a relatively local level.
  - Similarly, there were no consistent relationships between erosion and various parameters of disturbance assessed directly from the current imagery (muirburn, animal and human paths, vehicle tracks, fences, mineral substrates, recolonisation). Using earlier photography to assess changes and the long-term effects of these parameters is not practical, principally for reasons discussed in Section 1.2.1.

- **Recolonisation**
  - Evidence of apparent recovery of eroded areas was sparse both on the imagery and in the field. No evidence was found in the field to suggest that regeneration is being limited by current densities of deer or sheep. Assessing changes in recolonisation is not possible due to the lack of earlier colour photography.

5.9. **Evidence-based management recommendations: Ladder Hills study area**

5.9.1. *Background*

Overall, the peatland areas studied in the Ladder Hills were considered to be actively eroding with extensive areas of bare peat exposed to the on-going effects of a harsh climate. Much of the erosion is very advanced and, based on published data of erosion rates (see Section 2.2), the process is likely to have been occurring over hundreds of years (see Section 2.4). Analysis of past and current imagery for the Ladder Hills study area indicates that anastomosing and dendritic systems are the predominant erosion feature. The potential current drivers of erosion are examined below, followed by possible management methods to ameliorate their impacts.

5.9.2. *Climate*

Although the results for blanket bogs in Scotland as a whole clearly show the importance of rainfall and exposure, no correlation was found between the extent of erosion and any of the climatic variables in these study areas, probably because of the relatively broad scale of the climatic data. Nevertheless, climate is implicated as perhaps the strongest driver of current erosion. Areas of eroded peat mostly occurred on the broadly convex and undulating, gently sloping, 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 in the field, with the predominant driver apparently being excessive water flow, presumably generated during periods of heavy to extreme rainfall or rapid snow melt. In some areas, up to 2 m of peat had eroded over time and the underlying bare mineral substrate was exposed at the surface. Conversely, there were areas of peat deposition, downslope of eroded peat, characterised by a flat, reworked and less stable surface.

Based on scenarios of future climate change (Hulme *et al.*, 2002), erosion may be exacerbated, particularly as a result of increased intensity of winter rainfall and the likelihood of severe flash storms. Conversely, a milder climate could help to counterbalance these effects by enhancing the growth and recovery of vegetation, particularly at higher altitudes. The resultant root systems would help to bind and stabilise the peat, and the increased areal growth would act as a better buffer against temperature fluctuations and the mechanical impact of rain and wind. But wherever the balance lies between these effects, there is realistically little that can be done about climate change apart from encouraging governments to comply with global treaties on the control of atmospheric pollutants.

The main target must therefore be to mitigate the effects of climate by: (a) managing erosive water flows; and (b) managing the blanket bog vegetation so that it is in favourable condition with bare peat revegetated if possible.

5.9.3. *Grazing and trampling*

There is little or no evidence, either in the field or in the imagery, that recent human or animal influences are a major factor in relation to the extent and intensity of the erosion in the areas studied in this project (Tables 9 and 11). The most obvious animal paths on the imagery were predominantly on the plateau areas, possibly because the vegetation is particularly sensitive to trampling in these exposed sites. Paths were less obvious elsewhere but nevertheless were generally infrequent apart from a few local concentrations or aggregations. Combined with relatively low overall sheep and deer densities (Table 9), this indicates that large herbivores are not a significant driver in this part of the Ladder Hills - an observation that was verified by the field validation of current impacts. This does not preclude a role in the past when animals may have been more numerous, although the parish data for sheep numbers suggest almost no change in the past 20 years. Neither does it preclude impacts due to highly localised concentrations of animals that could be several times the overall densities but this was considered unlikely given the nature of the terrain and localities studied. Human tracks were negligible, being limited to a patchy footpath linking some of the main hill tops outside the main sites.

5.9.4. *Burning*

There is no evidence from the imagery or on the ground that recent wildfires or prescribed burning have played a significant role in driving erosion.

5.9.5. *Management recommendations*

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. There is some scope for gully blocking to reduce flow rates but, considering the expense of such operations, these would have to be carefully targeted, not necessarily at the most eroded areas but at those which are considered to have the best potential for recovery. Anastomosing systems and the upper part of dendritic systems would be the most likely candidates for this, but, again, this would require local assessments in the field.

If heather is fairly common in the nearby vegetation, some areas might be appropriate for treating with heather mulch; alternatively, a nurse crop might be considered to allow blanket bog graminoids to encroach and reseed. It would be advisable to limit such treatments to slopes of less than about 5^o, if only because little is known about their success rate on steeper slopes. However, it has to be accepted that the nurse crop in an upland situation is usually visually intrusive for several years. In all cases, current and potential local animal densities should be assessed first to ensure that grazing would not be a problem. These management strategies are still in their early stages (though first signs are encouraging) and so some pilot trials would be advisable, especially as these methods are very expensive.

Areas of re-deposited peat were rare and currently are probably too unstable for natural recolonisation, although they may respond to mulching or stabilisation with geo-textiles.

Cutting header drains might be considered (e.g. across the top of a dendritic system) to intercept surplus water and lead it into a preferred route away from more damaging locations, but this is an untried method and pilot trials would be essential.

Given the information obtained in relation to herbivore impacts and sheep and deer numbers, it would appear that there is little or no scope for reducing erosion by changing grazing regimes other than to beware of red deer numbers increasing. Any change in the management of animals would therefore be precautionary but may be necessary if any attempts were undertaken to recolonise areas with vegetation.

There is a clear conservation conflict in localised areas where the control of mountain hares might be necessary to maintain vegetation cover. In relation to burning management, the Muirburn Code should be strictly followed and areas of blanket mire avoided, especially where there are nearby patterns of erosion.

6. RESULTS FROM EVALUATION OF DRIVERS: MONADHLIATH STUDY AREA

6.1. Background information

This summary of background information is largely based on published literature relating to the conservation status of designated sites in this general area (SNH, 2002, 2006, 2008a), and management and herbivore impacts (notably Dayton, 2006). Within the study area there are three separate groups of sites (Figure 9):

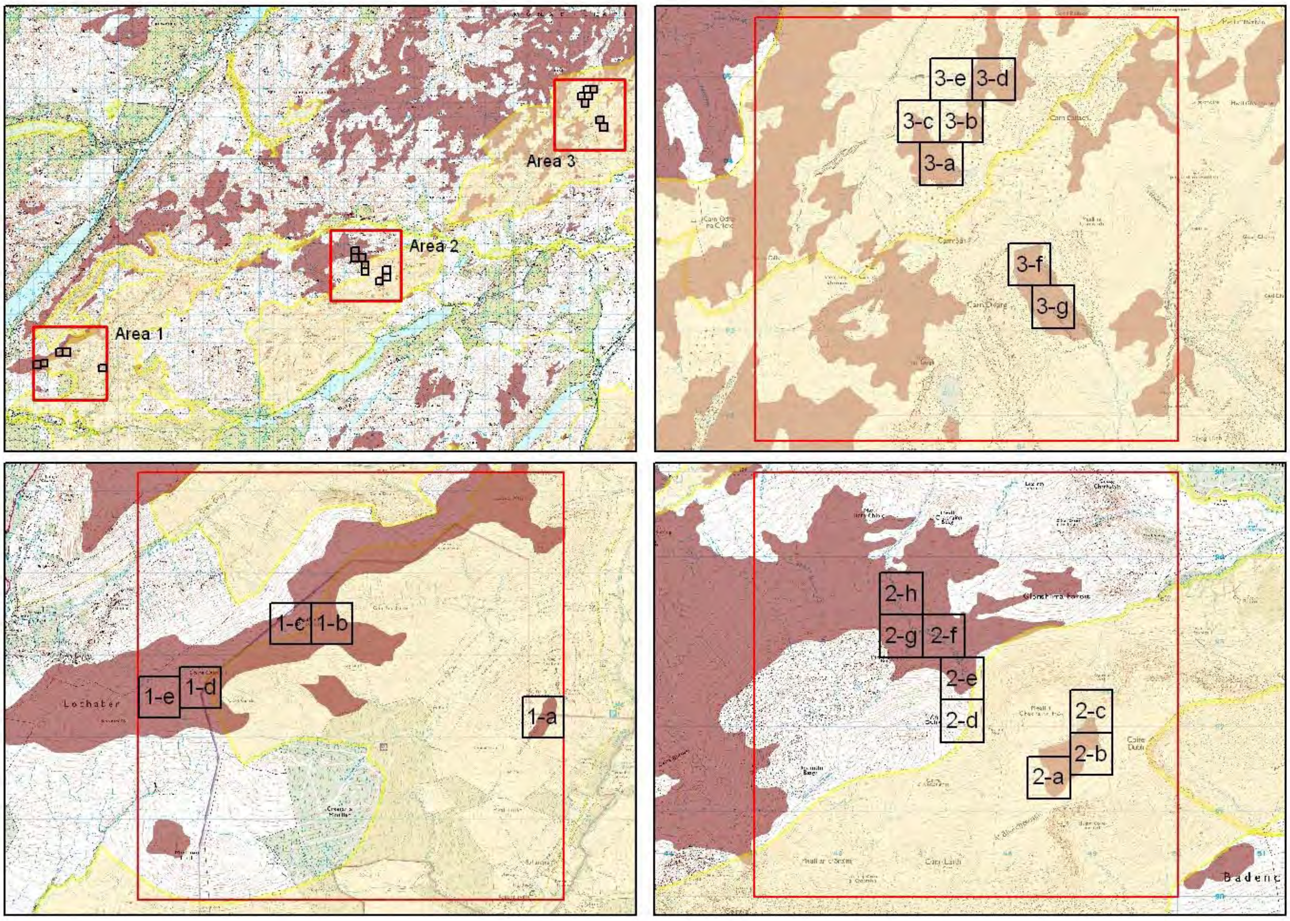
(i) a south-west group (M1) located between Glen Gloy and Glen Roy (three sites totalling five 0.25 km^2 sample squares);

(ii) a central group (M2) located on Glenshirra Forest (two sites totalling eight 0.25 km^2 squares); and

(iii) a north-east group (M3) located around Carn Ban and Carn Dearg (two sites totalling seven 0.25 km^2 squares).

Figure 9. Locations of sites in the Monadhliath study area.

Brown – eroded blanket bog (LCS88) outside designated SSSI/SAC/National Park areas
Tan – eroded blanket bog (LCS88) within designated SSSI/SAC/National Park areas
Yellow – designated areas without eroded blanket bog



Within these three groups, the majority of the sites are in designated conservation areas (Appendix 2, Table A2.2), notably the Parallel Roads of Lochaber SSSI (south-west), the Creag Meagaidh SSSI/SAC (central), and the Monadhliaths SAC (north-east).

6.1.1. *South-west group*

This group comprises three sites (Appendix 2, Table A2.2). The first (M1a) is a single sample square on the summit of Beinn a' Mhonicag (567 m), abutting dwarf shrub heath on adjacent lower slopes in places. Some of that heathland appears to have been burnt but it is unclear if the fires extended into the blanket bog vegetation. The other two sites each consist of a pair of squares (M1b-c and M1d-e, respectively) on the summit ridge and gently sloping montane plateau of Coire Ceirsle Hill (654 m) and Meall an Driuchain (619 m), located between the lower parts of Glen Gloy and Glen Roy, approximately 5 km north-east of Spean Bridge. These sites are all well above the Parallel Roads, which occur up to 350 m altitude in the surrounding glens, but are mostly included within the Parallel Roads of Lochaber SSSI (SNH, 2002). The SSSI was designated primarily for the striking terrace-like geomorphological features on the slopes of Glen Roy and the surrounding smaller glens. These features are the former shorelines of ice-dammed lakes formed towards the end of the last glaciation.

The vegetation of the sites consists primarily of high-altitude blanket bog (NVC M19 – *Calluna vulgaris-Eriophorum vaginatum* mire) with *Cladonia* spp. and *Racomitrium lanuginosum*, along with some sub-montane heather-dominated communities, lichen-rich prostrate montane heaths and grass-sedge-moss heaths. The blanket bog is extensively eroded in places with areas of deep hagging, and occasionally the drainage and erosion patterns run across the hillslope, perhaps reflecting underlying small-scale topography that mirrors the more pronounced parallel terraces at lower altitudes.

Present land use includes grazing by domestic livestock and deer. In many parts of the SSSI, a key requirement of management is to have grazing levels that ensure the visibility and accessibility of the geomorphological features. Agricultural parish register data indicate a reduction in sheep densities of approximately 15% from almost 0.5 per ha in 1986 to 0.4 per ha in 2006 (c.f. unchanged densities of around 0.85 in the Ladder Hills study area). The Deer Commission for Scotland (DCS) counts of red deer in this area from 1987 to 2002 gave an average density of 16 deer per km^2 - just within the moderate-high category of 15-20 deer per km^2 (c.f. 10 per km^2 in the Ladder Hills) – and indicated that there has been no marked change over recent times. Habitats are generally considered to be in a reasonable condition although there is little information available on current impacts.

6.1.2. *Central group*

This group of eight sample squares is split across two sites (Appendix 2, Table A2.2). The first comprises three squares (M2a-c) that are totally within the northern boundary of the Creag Meagaidh SSSI/SAC on the gently sloping summit ridge of A' Bhuidheanach (967 m). The other five squares (M2d-h) are on An Doire (779 m) and along the Allt a' Chaorainn stream that flows north towards Drummin. Two of these squares (M2d-e) are partially within the boundary of the designated area, while the other three are completely on non-designated land (Appendix 2, Table A2.2). The SSSI/SAC is designated for the ecological importance and exceptional nature of the natural heritage interests of the area.

The SSSI represents an unbroken succession of semi-natural vegetation from the shores of Loch Laggan to the summit of Creag Meagaidh (1130 m). Features of interest include eleven habitats of European conservation importance, notably sub-Arctic willow scrub, siliceous alpine and boreal grasslands and tall herb communities, but also blanket bog and montane heath. The extensive montane plateau above 750 metres altitude is an important area of Dotterel breeding habitat. The sites chosen as part of this study are dominated by extensive areas of high-altitude blanket bog (NVC M19 – *Calluna vulgaris-Eriophorum vaginatum* mire, sub-communities b and c). This vegetation is characteristically lichen-rich, with *Cladonia* spp. and woolly-fringe moss (*Racomitrium lanuginosum*) present, and the terrain is often gullied and extensively eroded, with associated areas of sub-montane and montane heath on drier knolls and ridges.

The SSSI is managed by SNH and the features of interest are assessed through a national programme of 'Site Condition Monitoring'. Between 1999 and 2005, seven of the 16 features of interest at Creag Meagaidh were recorded as being in favourable condition and nine in unfavourable condition, according to standard criteria (SNH, 2008a). Blanket bog was one of the features assessed as in unfavourable condition, along with alpine and subalpine heaths, wet heath and dry heath (2002-05). The initial focus of reserve management (1985-present) has been on creating appropriate conditions for the natural regeneration of trees in the woodland zone to increase the area of native woodland. The management objectives and vision for Creag Meagaidh in 2025 (SNH, 2008a) also aim to improve the condition of upland, heathland and blanket bog communities by reducing grazing and trampling pressure where necessary.

The DCS data indicate that densities of red deer in this general area are similar to the south-east group of sites (i.e. averaging about 16 deer per km^2 overall from 1987 to 2002, although this figure will currently be much lower on Creag Meagaidh SSSI itself). Agricultural parish data indicate historically lower densities of sheep than in the south-east group (c. 0.35 per ha in 1986) and a considerably higher reduction of 28% to about 0.25 per ha in 2006. In 2002, the Creag Meagaidh SAC became a DCS 'Site for Assessment' because of concerns about the impacts of deer on blanket bog habitats (DCS, 2005). However, in 2005, impacts on blanket bog habitat overall, based on a total of 96 sample points, were assessed as predominantly Low (65% of sample points), with the remainder of random points assessed as Moderate (35%), and none as High impact (Morris, 2006). Thus, it would appear that measures taken to reduce numbers of herbivores have been effective in achieving their objectives.

6.1.3. *North-east group*

This group of seven squares constitute two sites (Appendix 2, Table A2.2). The first comprises five squares (M2, M3a-e) on the gently to moderately sloping dissected montane plateau to the north of Carn Ban (942m); and the second comprises two squares (M3f-g), ranging from 600-700 metres altitude, in Gleann Ballach to the east of Carn Dearg (945 m).
The sites are totally within the Monadhliaths SAC, located approximately 10 km north-west of Newtonmore. This SAC includes a range of high and remote mountains and upland plateaux, supporting one of the largest expanses of blanket bog in the UK, which was the primary reason for the conservation designation of the area.

The sites selected for this study are dominated by extensive areas of high-altitude blanket bog (NVC M19 – *Calluna vulgaris-Eriophorum vaginatum* mire, sub-communities b and c, and with some affinities towards M20 – *Eriophorum vaginatum* blanket and raised mire). This vegetation is characteristically lichen-rich, with *Cladonia* spp. and woolly-fringe moss (*Racomitrium lanuginosum*) abundant in places. The terrain is often gullied and extensively eroded, with associated areas of sub-montane and montane heath vegetation on drier knolls and ridges.

The Monadhliath SAC became a DCS 'Site for Assessment' in 2002 because of concerns expressed by SNH about the impacts of deer on blanket bog habitats, although the average

DCS count from 1987 to 2002 of nearly 15 deer per km^2 is marginally lower than the other two groups. As a result of joint working between landowners and agencies, a baseline survey of blanket bog habitats was carried out in 2005 (Dayton, 2006). This study aimed to assess the impacts on blanket bog due to trampling and grazing across the SAC, to draw conclusions as to the nature and source of impacts observed and to provide a prognosis for the vegetation. The assessment was based on 197 plots, randomly located across seven land ownership units, and three plots (CF13, 23 and 25) coincide with sites in the current project (M3a-c). The 2005 study recorded a strong association between Heavy trampling and the high altitude plateau. Likewise, these areas were also recorded as subject to chronic Heavy grazing. Areas of blanket bog habitat on hillslopes and valley bottoms were almost all assessed as being subject to Light or Moderate trampling and grazing impacts.

Most of the SAC has been managed historically for sheep, deer stalking and grouse. In 1986, agricultural parish records indicate densities of 0.45 to 0.53 sheep per ha but in the last five years or so, many estates have greatly reduced the numbers of sheep on the hills to levels of about 0.23 to 0.33 sheep per ha, a reduction of 38% to 49% - a much bigger reduction than in the other two groups of sites. Therefore, when the survey work of Dayton was carried out in 2005, the density of sheep was relatively low (as it was for other herbivores such as mountain hares and grouse). Based on this evidence, and the direct and indirect observations of deer trampling, it was concluded that deer were largely responsible for the current trampling and grazing impacts. They were also considered to be exacerbating erosion and preventing the re-vegetation of bare peat. However, it was acknowledged that the role of trampling in initiating the loss of vegetation cover was yet to be established. (It should also be noted that whether or not re-vegetation would actually occur in the absence of herbivores is also open to question, as there is incomplete understanding of many of the processes involved in peatland erosion). It was considered possible that changes in deer distribution and behaviour, rather than just density, may be exacerbating erosion (e.g. due to reduced food supply following extensive defoliation and death of heather by heather beetle, biting insects moving higher up the hillside due to climate change, and increased recreational disturbance).

A point that should be borne in mind in relation to the assessments carried out by Dayton (2006) is that in the overall assessment of trampling, the weighting system of indicators relies heavily on the indicator for damage to *Sphagnum*. However, in areas of bare peat, it is stated that a score of High was given for this indicator even where there was no *Sphagnum* moss to assess, on the assumption that its total loss was considered an extreme impact of trampling (although this could be due to many other factors besides herbivore impact, operating over much longer timescales than would qualify as ‘current trampling’). So, while it is clearly stated that it was current trampling and grazing impact that were being assessed, some of the indicators have an in-built bias due to inherent assumptions which may be erroneous. Overall, while the impact on the blanket bog on the hill-slopes and valley areas was assessed as Light or Moderate, the blanket bog on the plateau was considered to be severely impacted, with large areas of bare peat. From current trends it was suggested that, if anything, impacts will increase on those areas already most impacted, leading to further deterioration of the blanket bog habitat.

Although current densities of red deer in this general area appear to be relatively moderate, it is acknowledged that locally higher densities and concentrations of deer on the higher plateau may be having adverse effects on the already highly eroded and susceptible peatland terrain. A related SNH study is under way to investigate the effects of excluding herbivores on peatland erosion and the potential for re-vegetation, using exclosure cages. Three of those sites (C13a, C13b, C14b) occur in sites (M3a-c) used in this study. The results of such work will be useful in guiding policy with regard to longer-term future management of wider areas of eroded terrain but may need to be extended to cover a wider range of estates, habitat types, altitude, terrain and different degrees of erosion.

Agencies met with owners in May 2006 to discuss the way forward in relation to the current levels of grazing and trampling impact in the Monadhliath SAC and to encourage landowners to manage blanket bog habitats with the aim of moving these areas towards, or into favourable condition. Repeat monitoring is scheduled for 2010-2012.

6.1.4. *Summary*

Peat erosion results from the complex interaction of climatic and anthropogenic influences acting over a long period of time. Presently, much of the eroded peat is at high altitude, suggesting that climate, past and present, is a major factor. In relation to future climate change scenarios, it is difficult to predict the likely effects with any certainty because the Monadhliaths are in an area that can be influenced by contrasting predictions for both the east and west of Scotland. However, it is likely that there will be an overall increase in the frequency of extreme events such as the intensity of rainfall, increased wind speed, and more unseasonal variations in weather patterns, due to the greater amount of energy being transferred from the tropics to the polar regions. This may exacerbate erosion.

In relation to grazing impact, the major difficulty in linking peat erosion to contemporary grazing pressures is that gully systems can be several centuries old and the original trigger for initiation probably predates any relatively intensive use of the hills for grazing in recent decades. Once initiated, grazing animals may have accelerated the erosion but any suggestions of cause and effect must be speculative as there is a dearth of adequate information for suitable time periods or at suitable spatial scales that take account of local concentrations of animals.

Acid deposition has been implicated as one of the causal factors of peatland erosion, in particular in the Southern Pennines, and might be one explanation for the severity of the problem in that area. In addition, nitrogen deposition onto organic soils can be harmful in terms of altering species composition 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 Northern Pennines, thus providing a stabilizing influence (Evans & Warburton, 2007). The UK's emissions of SO_2 peaked in 1970 and have declined by almost 70% since 1990 (Fowler *et al.,* 2005). Although there have only been small reductions in N deposition, these may reduce further as vehicle engine technology improves and the use of N fertilisers decreases (Fowler *et al*., 2005). The influence of acid deposition on peat erosion processes is likely to have been much less in the past in Scotland and is likely to have little effect in the future.

The drivers of change in relation to this particular study area are complex and difficult to separate. The wider peatland ecosystem of the Monadhliath Mountains, notably that of the dissected upland plateau, will have been subject over time to many of the natural and anthropogenic influences that have affected peatlands across the rest of the country. Such is the extent of the high-altitude blanket bog in the Monadhliaths that this area is regarded as one of the pre-eminent areas of peatlands, and also one of the most notable areas of peatland erosion, much of it in a very advanced state with extensive areas of bare peat, often with little of the former vegetated surface remaining. This has probably come about over millennia, with the conditions for peat formation varying according to shifts in climate since the last ice age. The resulting accumulation of organic material has led to increased instability and likelihood of erosion (Evans & Warburton, 2007), most likely triggered by a combination of climate, natural processes and anthropogenic influences. Much of the eroded peatland occurs at an altitude of over 600 metres and is subject to seriously adverse climatic conditions. Indeed, Dayton (2006) notably draws attention to the contrast between the largely un-eroded blanket bog at lower altitudes where grazing and trampling impacts are predominantly Light to Moderate, and the predominantly eroded blanket bog at higher altitude with heavier impacts (though not necessarily higher densities of herbivores). Thus, while the effects of human activity in terms of grazing and burning may have had a role in exacerbating erosion, it is considered more likely that natural drivers predominate in relation to the initiation and on-going momentum of peat erosion. In terms of very recent influences, sheep densities have been reduced markedly in the past 10 years and efforts are on-going to find a balance between numbers of red deer and their impacts on sensitive habitats, such that the population is sustainable in the longer term.

6.2. Evaluation of role of drivers in sites in the Monadhliath study area

The areas of peat vegetation and bare peat in each of the three sites in the Monadhliath study area are summarised below (Table 14). The locations of sites are given in Appendix 2, Table A2.1.

Table 14 Areas and proportions (%) of (a) peatland estimated from vegetation records, and (b) bare peat determined by supervised classification of digital imagery in sites in the Monadhliath study area.

Group	Area of group (ha)	LCS88 area of peat vegetation (ha)	Percent of group area that is peat vegetation	Area of bare peat soil (ha) classified in Definiens	Bare peat as % of group area	Bare peat as % of peat vegetation
M1	125	99.8	80	2.52	2.0	2.5
M2	200	93.5	47	8.66	4.3	9.3
M3	175	81.9	47	8.06	4.6	9.8

The following broad descriptions of these results provide context for the later detailed examination of individual squares.

The three sites constituting group M1 had the smallest overall proportion of bare peat, although the patterns of erosion varied widely between the groups of squares: in M1a the bare peat is mostly in a small dendritic system, with the remainder in apparently deep but not extensive gullies. In contrast, M1b-c has extensive dendritic systems of haggs often eroded to the mineral substrate; consequently, the area of bare peat *per se* is less than it has been historically and this tends to mask the extent and severity of erosion here. There was relatively little bare peat in M1d-e, mostly confined to some small anastomosing systems and occasional very narrow gullies.

In group M2, the site with three squares that are totally within the designated area (M2a-c) has relatively little bare peat which is mostly in a very diffuse series of small anastomosing systems and narrow gullies at higher altitudes, feeding into the main dendritic system lower down. In contrast, the larger site of five squares (M2d-h) lies predominantly outside the designated area and has a complex of fan, dendritic and gully systems with particularly severe and extensive erosion in anastomosing and dendritic systems to the north-west (squares M2g-h).

Of all three groups, M3 has the largest contiguous areas of bare peat, mostly in highly complicated anastomosing systems with relatively large areas of uneroded vegetation in between. In the larger site of this group (M3a-e), many of these systems lie markedly across the hill slope, suggesting that small-scale terracing in the topography limits their downslope extent. In comparison, the other site (M3f-g) has more gully erosion, much of which is down to the mineral substrate; consequently, as with group M1, the results tend to underestimate the overall area that has been affected by erosion in the past, although still giving a good estimate of the area of current bare peat.

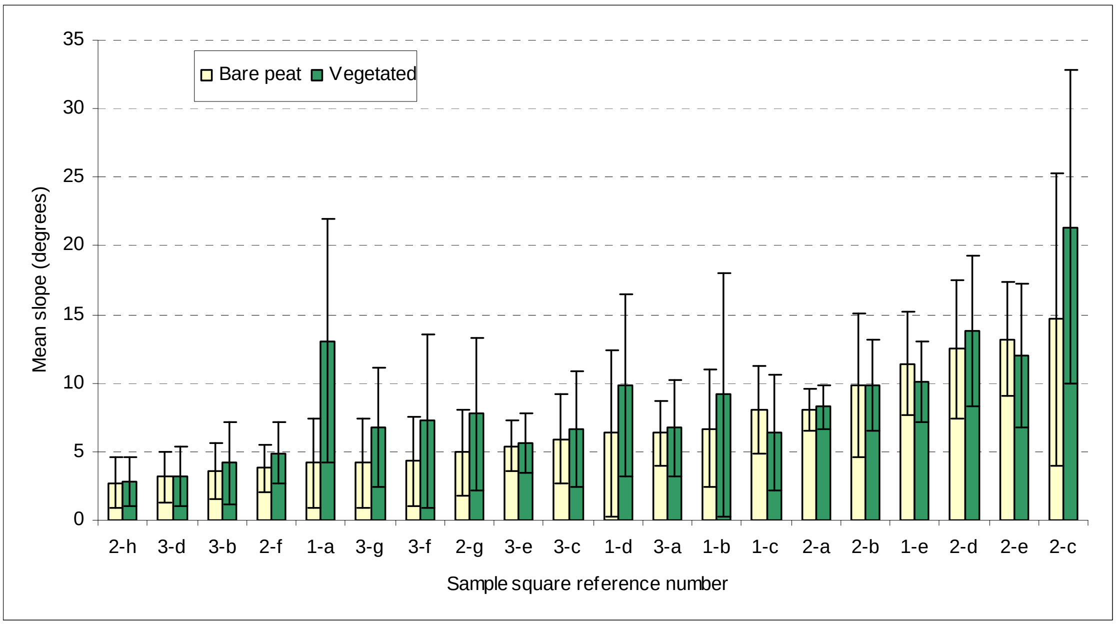
6.3. Relationships between bare peat and drivers at the 0.25 km^2 scale

6.3.1. *Slopes: analyses of 1m resolution data for individual squares*

As with the Ladder Hills, the slopes where bare peat occurred were compared with those for vegetated peatland in each square, using the TTN 1 m slope data. It must be reiterated that the sites were selected to provide information on erosion systems and are not a random selection of peatlands in the region. Any generalising to the area as a whole must therefore be done with care.

The results for individual squares, arranged in order of increasing amounts of bare peat, are shown in Figure 10.

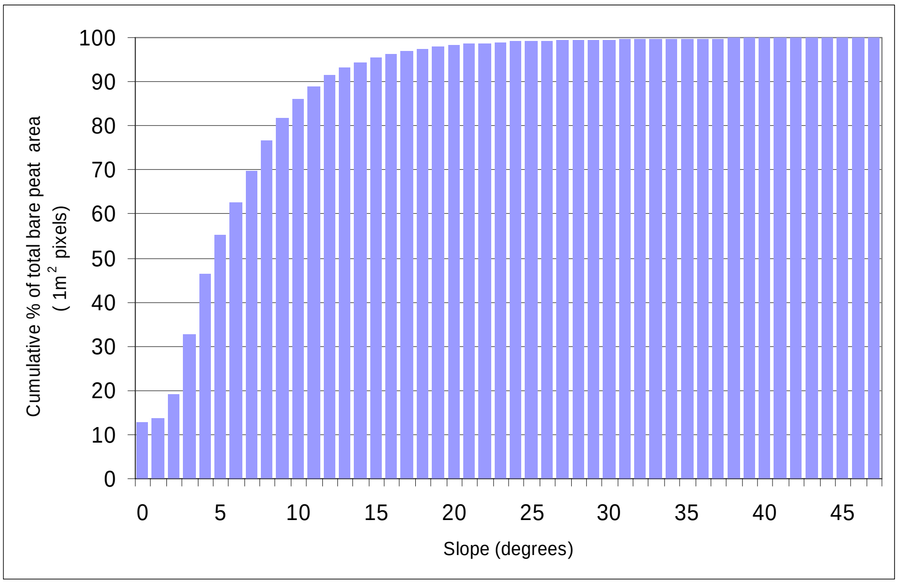
Figure 10 The mean slopes of bare peat and vegetated ground in individual 0.25 km^2 sample squares in the Monadhliaths study area. Results were calculated using 1m resolution TTN models. Vertical lines indicate +/- 1 standard deviation.



The difference between the mean slope of vegetated peatland and bare peat within each square was small, exceeding +/-3^o in only three of the twenty sites, and in all three cases the slope of bare peat areas was less than that of the vegetated land. The overall mean slopes for vegetated land (8^o) and bare peat (7^o) were slightly less than the equivalent figures for the Ladder Hills (10^o and 9^o). The data were similarly variable (Figure 10, vertical lines) and, again, the difference between the mean slopes of bare peat and vegetated areas within squares was statistically significant (paired two-tailed t-test: $p<0.05$ at the 5% level of significance). The areas - hence slope values - of bare peat are weighted by some larger areas of anastomosing erosion but, unlike the Ladder Hills, such systems seemed to be less concentrated on the more level ground on summits and ridges.

Another aspect of the overall distribution of bare peat on different slopes is shown in Figure 11, where the area of bare peat in each 1^{o} slope class is expressed as a cumulative percentage of the total area of bare peat. Hence, the graph shows that 50% of bare peat was on slopes of 5^{o} or less and 80% on slopes of 9^{o} or less. The graph for vegetated ground (not shown) had a very similarly shaped distribution but with equivalent figures of 7^{o} and 11^{o}, respectively. Hence, the occurrence of bare peat tends to occupy somewhat gentler slopes than those present elsewhere.

Figure 11 The area of bare peat on different slopes shown as a cumulative percentage of all bare peat in the Monadhliath study area.



Conclusion: Eighty percent of bare peat occurred on slopes of 9^{o} or less. Analyses of paired data showed that the mean slope of bare peat in the sample squares was significantly less than vegetated ground. However, the overall difference was only 1.5^{o} and so is of no practical value to conservation practitioners when trying to identify 0.25 km^2 squares that are susceptible to erosion.

6.3.2. *Relationship between bare peat and local drivers other than slope*

The same parameters used for the national regressions were examined in each of the 0.25 km^2 images to try to identify the effects of drivers at the local level. Results shown below (Table 15) are for the most likely drivers of erosion, informed by the national analyses. As before, the results are shown in ascending order of percentage bare peat to facilitate assessments of relationships. For results ordered by sites, the full set of data is given in Appendix 2, Table A2.2.

Note that the highest percentage of bare peat was recorded in square M3e which also had the smallest area in any square for eroded vegetation from the LCS88 database (1.4 ha); this reinforces previous caveats about percentages being possibly misleading. As this figure could have a high leverage on any statistical analyses, analyses were conducted both with and without that sample square. This made a small difference to the levels of probability but did not materially affect the conclusions, and none of the results changed from being significant to non-significant or *vice versa*. Results given below include the data for that square.

Table 15 Monadhliaths study area - the proportions (%) of peat vegetation (LCS88) in 0.25 km² sample squares that were classified as bare peat and the associated published data for potential drivers of erosion. Results are arranged in ascending order of bare peat %. (Note red deer density per km²).

Sample square	**Bare peat as % of total peat vegetation**	Red deer density 1987-02 (mean no. per km²)	Sheep density 1986 (no. per ha)	Sheep density 2006 (no. per ha)	% change in sheep density	Altitude (m) Mean	Altitude (m) Min	Altitude (m) Max	Monthly rainfall (mm) Mean	Monthly rainfall (mm) Max	Exposure index	Frost index
M1e	**1**	16.0	0.5	0.4	-15	562	511	610	152	292	3	4
M3g	**2**	14.6	0.4	0.2	-49	633	610	676	124	204	5	5
M2e	**2**	16.0	0.3	0.2	-28	596	549	672	150	280	4	5
M1d	**2**	16.0	0.5	0.4	-15	627	574	652	152	292	4	4
M1a	**2**	16.0	0.5	0.4	-15	539	468	566	149	289	3	4
M1c	**4**	16.0	0.5	0.4	-15	595	538	618	149	289	4	4
M2f	**4**	16.0	0.3	0.2	-28	523	501	551	150	280	4	5
M1b	**4**	16.0	0.5	0.4	-15	593	530	616	149	289	4	4
M2g	**5**	16.0	0.3	0.2	-28	514	488	578	150	280	4	5
M3f	**6**	14.6	0.4	0.2	-49	661	640	698	124	204	5	6
M3a	**6**	14.6	0.4	0.2	-49	848	820	887	124	204	4	5
M2h	**10**	16.0	0.3	0.2	-28	478	465	495	150	280	3	5
M2b	**11**	16.0	0.3	0.2	-28	873	827	910	150	280	5	6
M2a	**11**	16.0	0.3	0.2	-28	899	865	938	150	280	5	6
M3d	**15**	14.6	0.5	0.3	-38	831	819	850	124	204	4	5
M3c	**18**	14.6	0.5	0.3	-38	800	768	822	124	204	4	5
M2c	**27**	16.0	0.3	0.2	-28	788	670	850	150	280	4	5
M3b	**27**	14.6	0.4	0.2	-49	833	807	854	124	204	5	5
M2d	**30**[a]	16.0	0.3	0.2	-28	671	620	721	150	280	4	5
M3e	**96**	14.6	0.5	0.3	-38	805	781	829	124	204	4	5

[a] *Peatland vegetation in M2d was recorded as 'sub-montane' in LCS88, with eroded blanket bog as a sub-class. The 'bare peat %' figure shown is based on visual estimates of the blanket bog component using the original LCS88 imagery.*

Regression analyses showed a statistically significant positive relationship between the % cover of bare peat and altitude when calculated for the 20 individual sample squares ($F=5.395$, $p=0.033$) and at the broader scale of the seven sites comprising those squares ($F=11.84$, $p=0.018$). However, there were no significant relationships between the area of bare peat and any of the other individual factors that might affect erosion ($p>0.18$ in all cases). As noted in section 3.4.1, there is a lot of auto-correlation between altitude and the other potential drivers of erosion and there are also problems with the broad scale of climatic and herbivore density data. Nevertheless, it is likely that various drivers contribute to the increase in bare peat as altitude increases, but the relevant data are too coarse for this to be detectable. In contrast, altitude can be determined for relatively small areas and it may be that the variable 'altitude' integrates the effects of some of those other correlated factors but at the very local scale.

Conclusion: Altitude was the only variable that was significantly correlated with the amount (%) of bare peat at the 0.25 km^2 scale in the Monadhliaths study area. However, it is possible that this result also reflects localised influences of other altitude-related drivers that are not apparent at the broader scale of those data.

6.4. Visual assessments from the imagery of local effects of human activity and animals within sub-catchments

The same list of anthropogenic drivers examined in the Ladder Hills study area was assessed in a total of 50 eroded and 44 uneroded polygons (giving 44 sets of paired data) in the Monadhliath study areas (Table 16).

6.4.1. *Muirburn*

There were some signs of fire in two sample squares (M1a and M1e), mainly on heathland at lower altitude than the peatlands themselves, but there was no obvious patterning to indicate that this was done for management purposes. It was not clear from the imagery if the fires had encroached on the blanket bog areas but, regardless, there was no apparent association between burning and eroded areas in either square.

There were no detectable signs of burning in or near any of the other sub-catchments examined in detail in the twenty sample squares. Hence there is no evidence that relatively recent burning might be associated with erosion. However, as with the Ladder Hills, this does not preclude the possibility that historical burning might have had an impact.

6.4.2. *Animal paths*

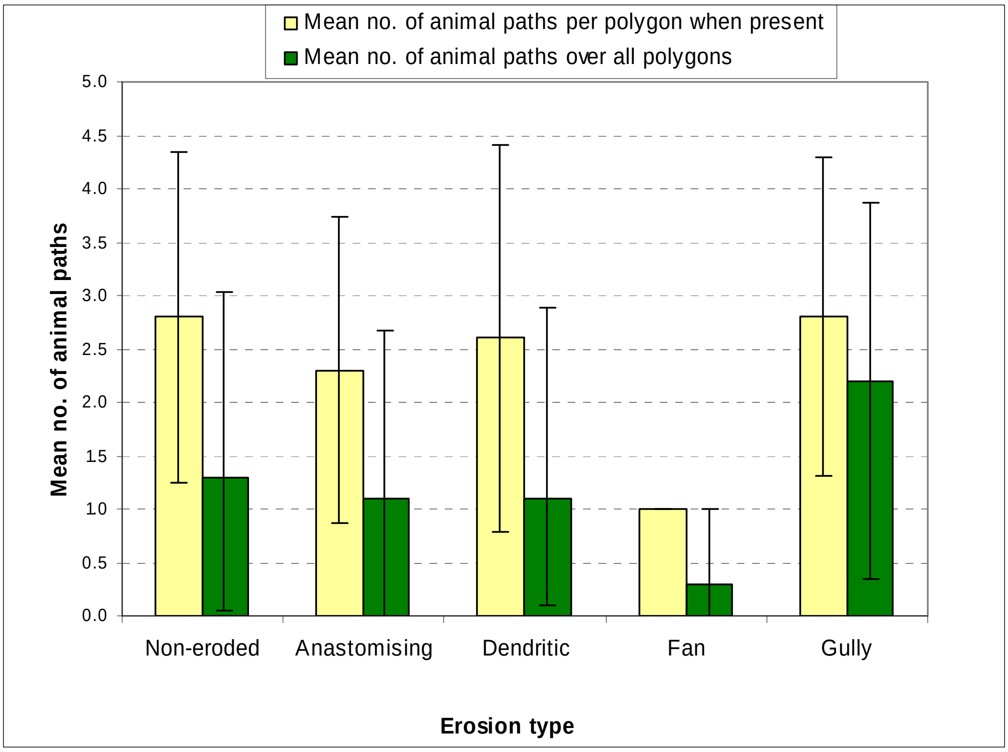
Across the sample as a whole (i.e. regardless of whether or not the land was eroded), animal paths were present in 48% of the selected polygons in the Monadhliaths (Table 16). This was roughly one-third less than in the Ladder Hills (67% with paths) and broadly reflects the published estimates of the combined densities of sheep and deer in the two study areas - approximately 95 animals per km^2 in the Ladder Hills compared to about 50 animals per km^2 in the Monadhliath study areas. There were similar differences when comparisons were made of the individual types of erosion in the two study areas. The exception was gully erosion where the figures for the two study areas were almost identical, paths being present in 75% and 80% of polygons, respectively (albeit with relatively small samples). One possible reason for this similarity, suggested by the evidence on the imagery, is that animals seem to avoid passing through deeply gullied areas and, as a result, diffuse paths often coalesce as they pass very close to gullies but without entering them. This concentration of paths means that one or more paths are commonly present in the fringe vegetation which is included as part of the 'eroded' system, thus maintaining relatively high proportions of gully systems with paths. None of these 'fringe' paths appeared to be a current source of erosion but that does not mean that they would not become so in the future, perhaps by creating weaknesses that could contribute to the upward creep of erosion.

Table 16 The occurrence of potential drivers of erosion due to animals and human activities in different types of erosion and in adjacent non-eroded land in selected polygons in the Monadhliath study area.

	Number of polygons recorded	Detectable muirburn (no. of polygons)	Number of polygons with animal paths	Proportion (%) of polygons with animal paths	Mean no. of animal paths per polygon **when present**	Mean no. of animal paths over all polygons	No.of polygons with vehicle tracks	No. of polygons with recolonisation	Proportion (%) of polygons with recolonisation	Mean index of recolonisation **when present**	No. of polygons with detectable mineral soil/rock	Proportion (%) of polygons with mineral soil/rock	Mean index of mineral cover **when present**
Non-eroded	44	0	20	45	2.8	1.3	0	0	0	-	3	7	1.0
Anastomosing	25	0	11	44	2.3	1.1	0	1	4	3.0	16	64	1.5
Dendritic	12	0	5	42	2.6	1.1	0	1	8	4.0	5	42	1.2
Fan	3	0	1	33	1.0	0.3	0	0	0	-	2	67	0.7
Gully	10	1	8	80	2.8	2.2	0	3	30	3.0	7	70	1.6
OVERALL	94	1	45	48	2.6	1.3	0	5	5	3.2	33	35	1.4

The overall mean numbers of animal tracks in different types of erosion are compared graphically in Figure 1, and the results of the paired eroded/non-eroded comparisons within erosion types, in Table 17.

Figure 12 The mean number of animal paths in different types of erosion in the Monadhliath study area. Vertical bars indicate one standard deviation.



[Note: only one of the three polygons of fan erosion had animal paths present, hence no standard deviation for 'when present' column].

As with the Ladder Hills, the counts of numbers of paths vary considerably (vertical bars in Figure 12) and an analysis of variance showed no statistically significant indication that animal tracks in the Monadhliath study area are particularly associated with any one type of erosion either on an overall basis (green columns: $F=1.76$, $p= 0.18$) or when limited to just those areas where paths are present (yellow columns: $F=0.28$, $p=0.84$).

Similarly, there is no evidence that the mean number of animal tracks in any particular type of erosion system is significantly different from those in the adjacent non-eroded area (Table 17) (two-tailed t-test, $p>0.2$ in all cases).

Table 17 Paired comparisons of the mean number of animal paths in selected polygons of eroding and adjacent non-eroding vegetation in the Monadhliath study area.

Type of erosion		**Eroding**	**Non-eroding**
Anastomosing	Mean	1.1	1.2
(25 paired polygons)	s.d.	1.6	1.7
Dendritic	Mean	1.0	1.1
(7 paired polygons)	s.d.	1.8	1.8
Fan	Mean	0.5	0.5
(2 paired polygons)	s.d.	0.7	0.7
Gully	Mean	1.9	1.9
(10 paired polygons)	s.d.	1.7	2.0
Overall	Mean	1.9	1.9
(44 paired polygons)	s.d.	1.7	2.0

Conclusion: There is no clear evidence to indicate that recent local densities of deer and/or sheep (as indicated by the numbers of animal paths) are associated with the incidence or the severity of erosion, either overall or within different types of systems.

6.4.3. *Vehicle tracks*

No vehicle tracks were recorded within erosion systems or in the immediately adjacent land.

6.4.4. *Recolonisation*

Recolonisation of eroded ground was detected in a total of only five (10%) of the polygons in erosion systems (Table 16). Three of these were in old deep gully systems between haggs on land that had probably eroded down to the mineral substrate but now appeared to be stable. There was only one polygon with recolonisation in each of anastomosing and dendritic systems. Although the frequency of revegetation was fairly low, the degree of new plant cover was relatively high, estimated at more than 25% in four of the five cases.

There were too few instances of recolonisation to allow formal statistical analyses but it is notable that recolonisation was never recorded in polygons that did not have some mineral surfaces present. Such surfaces were most frequent and extensive in gully systems and it is here that recolonisation appeared to be most frequent, occurring in 43% of gully polygons that had mineral surfaces present. The equivalent figures were 20% for dendritic systems and 6% for anastomosing systems. It is possible that this was not a direct association of recolonisation with bare mineral surfaces but was actually due to some extrinsic factor – for example, mineral surfaces were more prevalent in gully systems (see Section 6.4.5). It could be that the topography of the latter made them less accessible to herbivores, thus affording some protection to seedlings and young plants. However, there was no evidence from the numbers of paths or the features of recolonising areas on the imagery to suggest that this was the case. Conversely, there was no clear evidence to suggest that herbivores were congregating more on bare peat surfaces and preventing recolonisation there. These differences in the occurrence of regeneration are therefore most probably attributable to site factors. Generally, exposed bare peat is a poorer medium for seed germination and seedling establishment than mineral surfaces whose granular composition and greater density provide a more stable surface and better microclimate.

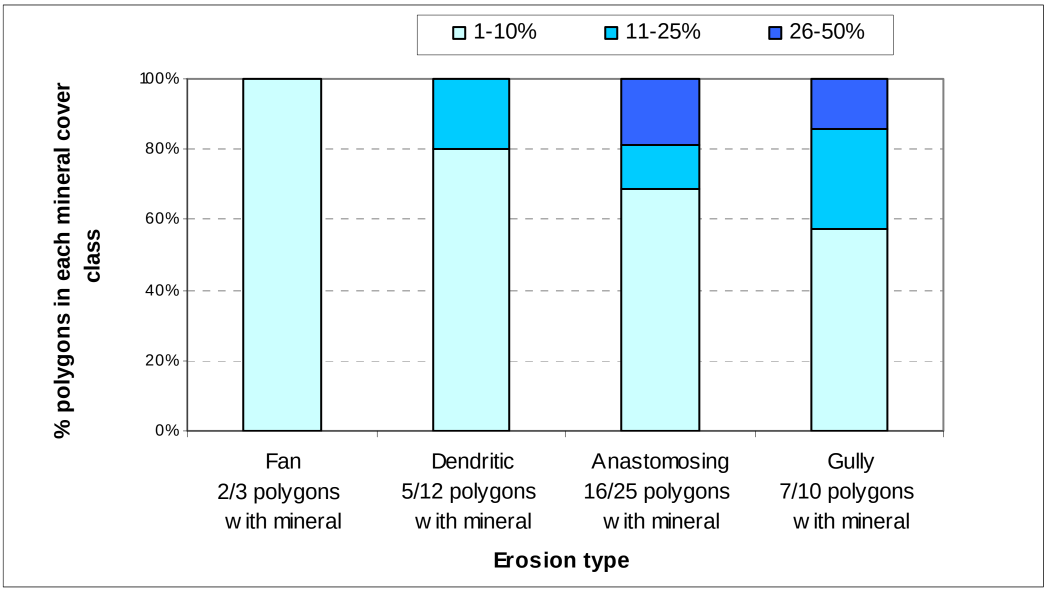
Conclusion: Recolonisation was rare and apparently associated with areas where severe erosion had exposed mineral surfaces, suggesting that most bare peat is currently unsuitable for recolonising seedlings. This could be for a wide range of reasons but the relative instability of bare peat surfaces is likely to have a strong influence.

6.4.5. *Mineral soils/rock*

The presence of mineral substrates is used as a broad indicator of the severity of erosion in terms of how common it is (i.e. how many polygons have mineral surfaces present) and how severe it is when present (using the index of how much of a polygon is mineral – see Section 3.5.5.1).

Little importance can be attached to the information about fan erosion systems due to the small sample size. Elsewhere, severe erosion was most common in anastomosing and gully systems with mineral surfaces being present in about two-thirds of the selected patches of erosion (Table 16). The actual severity of erosion was also greatest in these systems as mineral substrates occupied more than a quarter of the surface area in 14% and 19% of patches in the two systems, respectively (Figure 13). Severe erosion was considerably less in dendritic systems, both in terms of its frequency and degree of severity - mineral surfaces were present in less than half of the patches of erosion, and 80% of polygons had 10% or less bare mineral surfaces present. In comparison, mineral surfaces were present in only 7% of the patches of non-eroded adjacent land and it never exceeded 10% of the surface area.

Figure 13 The proportion (%) of eroded polygons with mineral substrate in each cover class. in the Monadhliath study area. Erosion types are arranged from left to right in increasing total cover of mineral substrate. Column labels show the number of polygons with mineral substrates present out of the total number of polygons recorded of each erosion type.



The general principles behind the above differences, in terms of the energy flows in systems, were outlined in the discussions of the Ladder Hills results (Section 5.5.5) and it is interesting to note the similarity of the results for anastomosing systems in the two study areas. However, it is also notable that the severity of gully erosion in the Monadhliath study area was considerably greater than in the Ladder Hills. There are many possible reasons for this, including peat depth and differences in slope, but to investigate the latter would require digitising the systems and GIS analyses, which is beyond the current project resources. Nevertheless, the effects of shadow in the imagery are also a likely factor. Subjectively, the bottom of the gully systems examined in the Monadhliath study area appeared to be less masked by shadows than in the Ladder Hills, thus resulting in a higher proportion of mineral surfaces being detectable, but this cannot be firmly established without field visits.

Conclusion: Erosion was most severe in gully systems (usually ascribed to localised, high energy waterflows) and anastomosing systems, where exposure is commonly a strong influence. The severity of erosion in both of these systems was considerably greater than in the dendritic systems and the small sample of fan systems studied. It is beyond the scope of this project to undertake the detailed examinations required to assign causes, but there were no clear associations between the severity of erosion and any of the anthropogenic impacts recorded here.

6.5. **Summary of results from the Monadhliath study area**

- **Historical evidence of changes in extent of erosion**
  - Comparisons of earlier monochromatic aerial photographs and current imagery showed similar patterns of erosion but the work required to try to quantify the extent of these patterns was beyond the scope of this project.

- **Slope**
  - Analyses of 1m resolution slope data for the twenty squares showed that 50% of bare peat was on slopes of 5^o or less and 80% on slopes of 9^o or less. For vegetated ground, the equivalent figures were 7^o and 11^o, respectively. Hence bare peat tends to occur on slightly less steep ground than elsewhere in the study area.
  - More detailed analyses using the paired data for each sample square showed that the mean slope of bare peat in the sample squares (7^o) was significantly less than vegetated ground. However, the overall difference was only 1.5^o and so is of no practical value to conservation practitioners when trying to identify 0.25 km^2 squares that are susceptible to erosion. At this scale, slope alone is apparently not a good predictor of where erosion is likely to occur, and local topographic characteristics are more likely determinants of the precise location of where erosion might occur.

- **Climate**
  - There was insufficient variation within the climatic factors (frost, exposure, rainfall) to statistically analyse their relationship with the occurrence and extent of erosion but informal inspection of the data revealed no clear trends.
  - However, there was a statistically significant positive relationship between altitude and the amount (%) of bare peat at the 0.25 km^2 scale. It is likely that this result is, to some degree, influenced by localised influences of other altitude-related drivers such as climate.

- **Animals and human activity as drivers**
  - No consistent single- or multivariate relationships with bare peat were identified using the published data on animal densities. If animals are currently acting as drivers, it is likely that their impacts are at relatively local level and the spatial or temporal scale of the published data is too coarse to identify them. Similarly, no relationships were identified between the occurrence of bare peat and alternative indicators of anthropogenic impacts derived from the current imagery (e.g. counts of animal and vehicle tracks).

- **Recolonisation**

  Recolonisation was rare and apparently associated with areas where severe erosion had exposed mineral surfaces, suggesting that most bare peat is currently unsuitable for recolonising seedlings. This could be for a wide range of reasons but the relative instability of bare peat surfaces and their susceptibility to frost heave and rapid desiccation in summer are all likely to have a strong influence. No evidence was apparent to suggest that regeneration was being limited by current densities of deer or sheep.

6.6. Evidence-based management recommendations: Monadhliath study area

6.6.1. *Background*

Like the Ladder Hills, much of the erosion in the Monadhliaths is in such an advanced state that it has probably been occurring over hundreds of years. From the evidence obtained in this study, the likely drivers of more recent change are complex and interrelated and individual effects could not be differentiated, although there is little doubt that climate is still the predominant force. The likely influence of the different drivers will be explored in turn to determine what potential there is for management action.

6.6.2. *Climate*

Our analyses of the data for blanket bogs in Scotland as a whole clearly show the importance of rainfall and exposure and even though the data were inadequate for pinpointing climatic effects in the Monadhliath study areas, there was a reasonable correlation between altitude and erosion. Indeed, the cover of bare peat exceeded 10% of the total peatland area in eight of the 20 Monadhliath sample squares, and all but two of those squares had a mean altitude in excess of 750 m. The effects of rainfall, wind, frost and alternate cycles of drying and wetting of the surface are severe at such altitudes and help to make bare peat surfaces unstable and subject to erosion. In several places in the Monadhliath sites, 2 m or more of peat have been eroded over time, sometimes down to the underlying mineral substrate, and this is most probably due to excessive water flow, generated during periods of heavy to extreme rainfall and under conditions of rapid snow-melt. At the same time, there are a few areas of peat deposition downslope of eroded areas, characterised by flat, reworked surfaces, but where the peat has very little structural integrity to resist further erosion.

As in the Ladder Hills, climate change scenarios indicate that there is likely to be increased perturbation and potential for exacerbated erosion in the Monadhliaths, driven particularly by an increase in extreme rainfall events. At higher altitudes this might be partly counterbalanced by a generally milder climate increasing plant growth and opportunities for more rapid recolonisation of bare peat.

We cannot manage the effects of climate *per se* and so any management effort needs to be targeted at mitigating its effects, for example by aiming to have the blanket bog vegetation in favourable condition and encouraging revegetation of bare peat. The main problem in achieving this in the Monadhliaths is the sheer extent of the current situation where there are tens of square kilometres of degraded peatland on the upland plateau. Current research and monitoring, commissioned by SNH, is examining the effects of grazing and trampling on bare peat in the area and whether removal of herbivores leads to revegetation of bare peat surfaces. This should provide some indication of whether practical measures can be undertaken to halt or even reverse the decline in peat erosion on such terrain (see Section 6.6.4 'grazing and trampling').

6.6.3. *Topography/geomorphology*

The actual location and severity of erosion is influenced by topography and the wider geomorphological processes acting upon the landscape. While these factors may not be considered to be drivers of erosion *per se*, they are nevertheless continuous underlying controls on how the effects of other drivers are expressed. For example, studies in the Southern Pennines indicated that slope strongly affects patterns of incision and that significant drainage patterns do not develop on gradients of less than 2-3^o. Almost 20% of the bare peat in the Monadhliath study areas occurred on gradients of 3^o or less and so there are potential opportunities for managing any outflow from these sites that might cause downslope channel incision and erosion. Commonly, gully-blocking has been used to raise water tables but this is unlikely to be effective on some sites in the Monadhliaths where erosion has been so severe that the peat is now very shallow – often with the mineral substrate showing – and so has very limited capacity for holding more water.

6.6.4. *Grazing and trampling*

In some of the sites in the Monadhliaths, there has been a marked decline in recent years in sheep numbers (Table 15) and efforts are on-going to find a balance between numbers of red deer and their impacts on sensitive habitats, such that the population is sustainable in the longer term. The effects of herbivores, revealed by this project and SNH's assessments of grazing and trampling impacts in the Monadhliaths, show a variable pattern which is often very localised. While these impacts are predominantly light in some areas, they are a cause for concern where there are local congregations of animals; these can be due to a wide range of site-specific factors in the short term (e.g. weather), medium term (e.g. seasonal behaviour) or long term (e.g. the hefting behaviour of sheep). Along with the information revealed by the examination of erosion from aerial photographs over a time period of 42 years, this suggests that large herbivores are not a significant widespread driver of erosion, although it is recognised that they may sometimes initiate erosion (e.g. through the creation of sheep scrapes and deer wallows) or, when locally present at higher densities, they may exacerbate the on-going erosion caused by other agents.

The central study area of the Monadhliaths is largely managed by SNH and concerns were expressed in 2002 about the impacts of deer on blanket bog habitats. However, in 2005, impacts on blanket bog habitat were assessed as predominantly Low, with the remainder of random points assessed as Moderate and none as High impact. Thus, it would appear that measures taken to reduce numbers of herbivores had been broadly effective in achieving their original objectives. In view of the deer numbers reported in Section 6.3.2, there is likely to be little further scope for reducing grazing impacts, other than complete removal of all larger herbivores. The latter course of action is something that is unlikely to be feasible under the current pattern of estate ownership. It is also far from clear if removal of herbivores would have the desired effect of preventing an increase in peatland erosion or even reverse it, especially in exposed areas where climatic effects may maintain unstable surfaces and conditions otherwise unsuited to plant establishment. Current studies are using cages to investigate the effects of excluding herbivores from eroded peatland and the results of such work will be useful in guiding policy with regard to longer term future management of herbivores. This work may need to be extended to cover a wider range of estates, habitat types, terrain and different degrees of erosion. In addition, it must be reiterated that the density of animals that is acceptable for preventing damage to existing vegetation may be considerably higher than that which allows recolonisation. Hence the aim of managing animal numbers will have to be clear about its targets. Nevertheless, the experiments have the potential to provide powerful and convincing evidence to guide and support management action in relation to such sensitive areas.

Until other information becomes available, the scope for making any further management recommendations is limited to supporting the measures already underway for controlling grazing by domestic stock and red deer. With regard to mountain hares, the overall numbers are relatively low and should be readily controllable if required, particularly as their impact is usually quite localised. However the mountain hare is a listed UK BAP species and proposals to cull it could cause a conflict of conservation interests.

6.6.5. *Artificial drainage*

Drainage is not viewed as a major factor in stimulating or exacerbating peat erosion in Scotland and most if not all of the extensively eroded bogs in the Monadhliaths have no artificial drainage channels. Likewise, areas that have been drained show no evidence of recent erosion features. Thus, artificial drainage is not regarded as a driver of erosion in the Monadhliaths.

6.6.6. *Burning*

There were signs of fire in 10% of the sample squares but it was not clear if this was intentional muirburn and whether or not it had extended into the blanket bog. In summary, there was no evidence that suggested burning or wildfires had played a significant role in driving erosion in the Monadhliaths.

6.6.7. *Recreation*

While there has been an increase in recreational hill-walking in recent decades, human tracks were negligible, being limited to footpaths linking the main hill tops and none were apparent in the sample squares. Increased recreational use of the Monadhliaths in recent decades has been reported (SNH, 2008a) but this is mainly associated with the mountain ridges and summits and there is very little sign from the imagery of paths developing on peatland areas. Thus, it is concluded that recreational pressure in the Monadhliaths is not an issue or a driver of peatland erosion.

6.6.8. *Atmospheric pollution*

Atmospheric pollution is not considered to have been a major driver of peat erosion in the Monadhliaths because of their remoteness from major sources of inputs.

6.6.9. *Management recommendations*

From the assessments of drivers of erosion, there appears to be a complex of factors that, separately or in combination, might initiate or exacerbate erosion. The components of that complex and their relative impact vary between sub-catchments - probably even at the level of individual patches of erosion – and includes not only the drivers of erosion but also the local integrity of the peat and any vegetation cover. The results also indicate that appropriate management techniques cannot be determined remotely but must be made in the field on a site by site basis. Therefore it is extremely difficult to make specific management recommendations that would be applicable to the Monadhliath region as a whole. Instead, we present a generic range of possible options that should be considered separately or in combination for individual sites.

Gully blocking has some potential for reducing erosion by decreasing flow rates but it is important to bear in mind the factors to be considered given in Section 4.1 and the need to assess sites individually. Potential targets include sites on more level ground, particularly anastomosing systems and the heads of dendritic systems that are feeding water into eroding systems downhill. Here the aim would be to reduce erosion directly, whereas the alternative use of gully blocking aims to promote the natural recolonisation of bare peat by vegetation. For example, some of the gently sloping gully systems that have good potential for recolonisation would benefit from redirected water flows. Gullies at higher altitude could be particularly suited to this approach as the banks of the gullies would provide some shelter from the most severe effects of exposure. There were few locations in the study areas where there would be clear benefits from raising the actual water levels substantially but this may be considered if there are degraded pool systems. Due to the altitude of most erosion, the development of *Sphagnum*-dominated communities is likely to take a long time, if indeed they developed at all under present (or future) climatic conditions.

Artificial revegetation of erosion also has potential in several areas, especially in areas of erosion in the NVC M19 – *Calluna vulgaris-Eriophorum vaginatum* community, where heather mulch could be used with a reasonable chance of success and would be appropriate to the surrounding vegetation. The slope of potential sites is likely to be a limiting factor for this technique. The use of nurse crops has very limited potential and may not be acceptable anyway in designated sites due to the use of fertilisers (which could leach out into other vegetation), the introduction of species ‘alien’ to that environment and its visual intrusion in the earlier years.

Regardless of which method might be chosen for artificial or natural colonisation (see below), assessments of grazing and trampling impacts indicate that control of animal densities would probably be required, especially on plateau sites. The method would be most appropriate to the areas in the Monadhliaths where sheep have been removed in the past five years or so but, even then, additional localised control of deer numbers might be required. The alternative is to fence off the reseeded areas but this is impractically expensive in many situations and could cause conservation conflicts.

Although rare, natural recolonisation was present in the study areas, particularly in gully systems so these are potential targets using techniques outlined in Section 4.6. Existing natural colonisation appeared to be associated with areas where mineral substrates were present, indicating that nearby peat may already be very thin, at least. It is impossible to tell from the imagery which species are establishing on these sites but on drier sites it is quite likely to be a species such as wavy hair-grass (*Deschampsia flexuosa*). Considering that mineral substrate is likely to be gravel or rock and less prone to erosion than peat, it would be a matter of conservation priorities whether or not such sites warrant any expenditure.

From the information obtained in relation to herbivores, there is only limited scope for further reduction in sheep numbers in the Monadhliath sites as there has already been quite extensive removal of sheep in recent years. The situation with red deer numbers is also in a state of transition. In relation to the south-west study area, a key requirement of the management of the Parallel Roads of Lochaber SSSI is that current levels of grazing by domestic livestock and deer should be maintained to ensure the visibility and accessibility of the geomorphological features. In terms of deer, this would only become an issue if deer densities in the SSSI dropped to 5 per km^2 or less (the density at which woodlands would probably be able to regenerate naturally and start to obscure the relevant SSSI features). However maintaining at least minimum levels for grazing has implications for other features that may be accessible to those deer and sheep populations, especially if it was desired, for example, to have zero grazing at severely eroded sites.

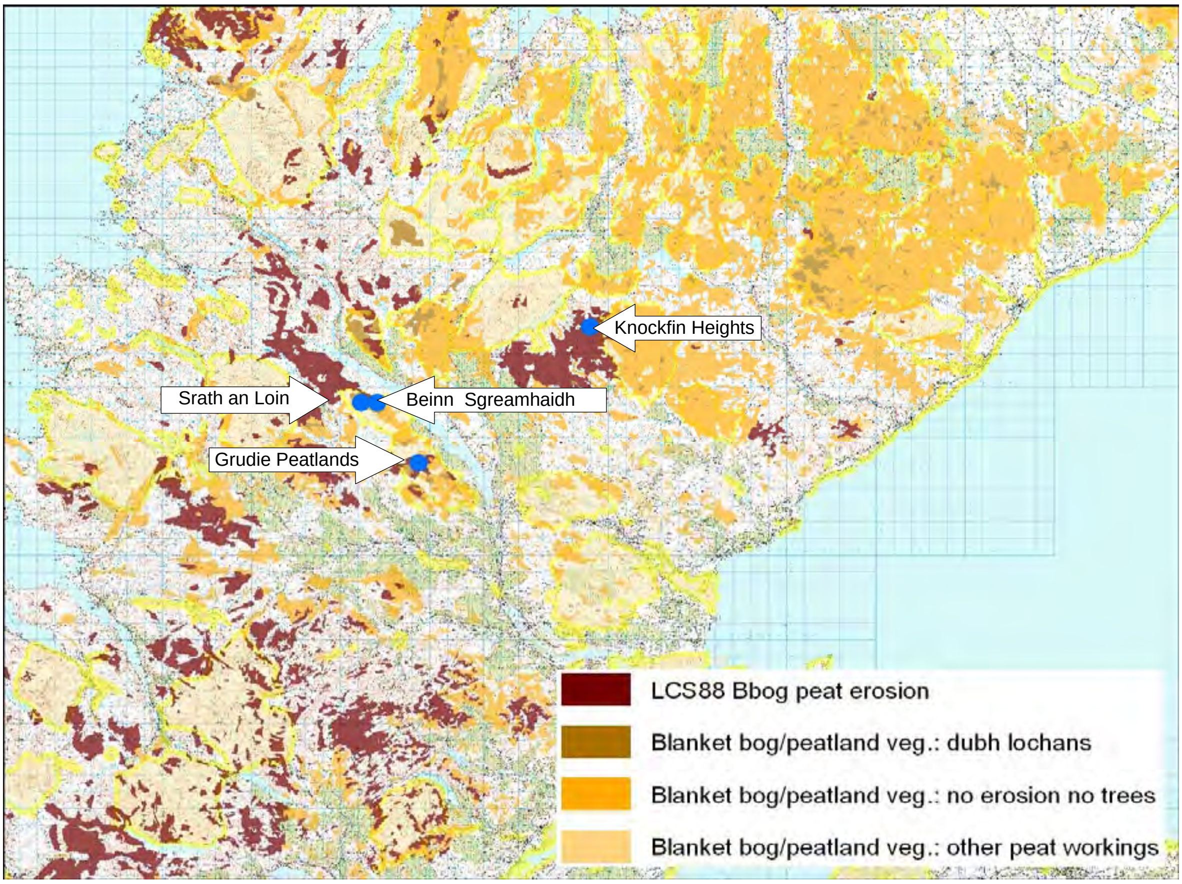
While the effects of human activity in terms of sheep grazing, burning and the more recent increase in deer numbers may have had a role in exacerbating erosion, it is considered more likely that natural drivers predominate in relation to the initiation and on-going momentum of peat erosion. To what extent this can be halted or even reversed remains open to question but it is considered unlikely that even the total removal of herbivores from an area with such extensive and advanced erosion would result in a major reduction in erosion over time. The evidence indicates that peat erosion in the Monadhliaths is largely a natural phenomenon, driven by factors outwith human control. At the same time, there is some evidence that under certain conditions a limited amount of 'self-healing' can occur. The exact conditions that lead to this are unknown, which reinforces one conclusion of the DEFRA (2008) report – "*very little is known about peat erosion processes and impacts in the UK scientific literatur*e."

7. RESULTS FROM EVALUATION OF DRIVERS: GRUDIE REGION AND KNOCKFIN HEIGHTS STUDY AREA

7.1. Background information

The original intention was to focus the sites within the Grudie Peatlands SSSI but, for reasons given in Section 3.5.2.1, three additional sites were selected, two within the Srath an Loin SSSI (referred to as Beinn Sgreamhaidh and Srath an Loin) and one in the Knockfin Heights SSSI (Figure 14). For convenience, the first three sites will be referred to collectively as the Grudie Region, although individual references will be used when appropriate.

Figure 14 Location of sites in the Caithness-Sutherland district and their associated cover of peatland vegetation types, as recorded in LCS88.



All four sites are completely within SSSIs lying in the Caithness and Sutherland Peatlands Natura 2000 site, designated a Special Area of Conservation (SAC) and Special Protection Area (SPA). The OS grid references of the areas are given in Appendix 3, Table A3.1.

The SAC contains a large proportion of the Caithness and Sutherland peatlands which form the largest and most intact area of blanket bog in Britain (SNH, 2005). These peatlands, and the surrounding moorland and open water, are of international importance for conservation because they form the largest peat mass in the UK with extensive areas of *Sphagnum* carpets and numerous intact pool systems. These habitats also support a diverse range of rare and unusual breeding birds. The Caithness and Sutherland Peatlands is cited as a potential RAMSAR site supporting one of the largest and most intact known areas of blanket bog in the world. It encompasses an exceptionally wide range of vegetation and surface pattern types, some of which are unknown elsewhere (SNH, 2008b).

7.1.1. *Grudie Region*

The Grudie SSSI, near Sallachy to the west of Loch Shin in Sutherland, extends to 4786 ha stretching from Lochan a' Choire in the north to Loch na Fuaralaich in the south, and from Ben Sgeireach and Loch Sgeireach in the north-west to Cnoc Riabhaich in the south-east. Included are a range of watershed, valleyside, saddle and other hydromorphological forms of blanket mire (SNH, 1993). Abutting this to the north is the smaller Srath an Loin SSSI (2344 ha) which includes the Allt Cer burn and its catchment, and Beinn Sgreamhaidh.

The vegetation of the region consists primarily of communities of blanket bog (NVC M19 – *Calluna vulgaris-Eriophorum vaginatum* mire), some with *Cladonia* spp. and *Racomitrium lanuginosum*. The blanket bog terrain is extensively eroded in places and there are intervening drier mounds and ridges of sub-montane heather-dominated communities, lichen-rich prostrate montane heaths and grass-sedge-moss heaths.

Present land use includes grazing by domestic livestock and deer. Agricultural parish register data indicate a reduction in sheep densities (number per ha) of approximately 16% from 0.42 in 1986 to 0.35 in 2006. Densities of red deer in this Deer Management Group (DMG) area, based on 2003 Deer Commission for Scotland figures, are within the low to moderate range of about 8 -11 per km^2. A rapid assessment of grazing and trampling impacts was carried out in this area in 2000 as part of a survey of the West Sutherland Deer Management Group area. The area covered the estate management unit, extending from Sallachy northwards up Loch Shin and occupying almost all the ground between the watershed with Glen Cassley and the loch. The vegetation categories of 'blanket bog with erosion' and 'blanket bog with dubh lochans' were both assessed as having Light impacts, while 'blanket bog without erosion' was assessed as having Light-Moderate impacts overall (Henderson *et al*., 2000). Surrounding areas of undifferentiated heath and wet heath vegetation categories were also assessed as having Light-Moderate impacts. Red deer were regarded as the main herbivore but, at the time of the survey, deer numbers were recorded as low and sheep numbers on the open hill were negligible.

7.1.2. *Knockfin Heights*

This SSSI of 5205 ha, lies to the east of the Strath of Kildonan and occupies the plateau watershed that forms part of the Caithness-Sutherland boundary. The area is largely around 400 m altitude and is dominated by watershed blanket mire, supporting the most extensive area of bog pool development on upland blanket peat in Scotland. Many of the pools have coalesced to form dubh lochans up to a few hundred metres in length. Subsequent peripheral erosion has caused many of these pools and lochans to drain, with some revegetation of the peaty/mineral substrate (SNH, 1993).

The vegetation consists primarily of blanket bog (NVC M19 – *Calluna vulgaris-Eriophorum vaginatum* mire), montane in character, with *Cladonia* spp. and *Racomitrium lanuginosum*, along with the extensive development of bog pools and dubh lochans.

Present land use includes grazing by domestic livestock and red deer. Agricultural parish register data indicate a reduction in sheep densities (number per ha) of approximately 27% from 0.39 in 1986 to 0.28 in 2006. Densities of red deer in this Deer Management Group area, based on Deer Commission for Scotland figures, are within the low to moderate range of 8 -11 per km^2.

A rapid assessment of grazing and trampling impacts was carried out in this area in 1999 as part of a survey of the Northern Deer Management Group area. Impacts on blanket bog and blanket bog with dubh lochans were assessed as Light and Light-Moderate, respectively

(Stolte *et al*., 2000). More recently, a survey of the current levels and patterns of herbivore grazing and trampling impacts was carried out in 2006 across a large proportion of the Caithness and Sutherland peatlands SAC (Headley, 2006). Only a very small proportion of the northern part of the Knockfin Heights SSSI was covered in this survey and consequently, few if any conclusions can be drawn about the grazing and trampling impacts in that area. Only two systematic points were assessed (one Low, one High). Headley (2006) noted that this SSSI had the most extensive areas of peat erosion observed in the overall survey and that, because of the drainage of lochans, deer hoof prints were much more evident in the bare peat surfaces than in areas of blanket bog with intact vegetation and un-drained bog pools. Consequently, this may exaggerate the trampling impacts in this part of the survey area. Importantly, the presence of shoots of *Eriophorum angustifolium* and *E. vaginatum* within eroded areas suggested that some re-vegetation of the bare peat was taking place.

In 2005, a survey and baseline monitoring programme was initiated by the Royal Society for the Protection of Birds in response to concern about the condition of the Knockfin Heights SSSI (RSPB, 2005). The baseline survey revealed that Knockfin Heights has higher levels of bare peat and lower levels of *Sphagnum* cover than should be expected in active, healthy blanket bog. Bare peat was shown to be more common in parts of the plateau dominated by pool systems where, in addition to empty pools, there are large numbers of drainage channels as well as reticulate networks of bare peat and micro-haggs. In 2005, 41% of all pools were empty and their bases were covered by bare peat that was frequently observed to be drying, cracking and eroding. In many parts of the plateau there were empty pools, connected by channels arranged downslope from one another.

Many of these channels were clearly used by deer as routes through pool systems (Figure 15). There was plenty of evidence to suggest that deer also use the narrow strips of land between pools for the same purpose and it was considered that trampling may well be a significant factor in contributing to the erosion and breakdown of connections between pools.

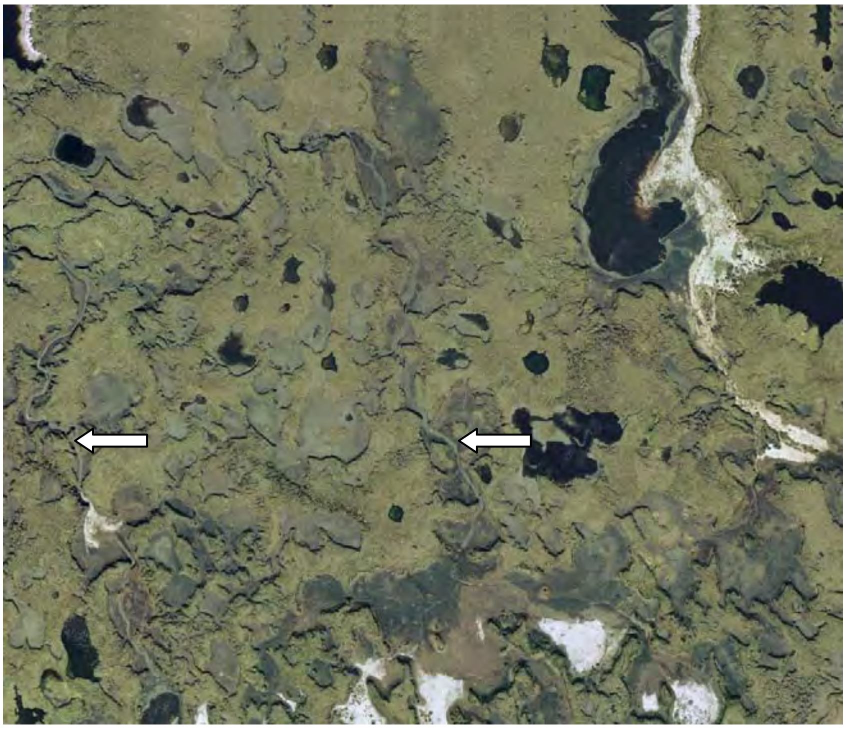


Figure 15 Sample square G4 on Knockfin plateau showing animal paths (arrowed) on peat.

A retrospective study, based on aerial photographs, showed that the number of empty pools in 1946 was far lower than in any other year analysed. However, there were more empty pools in 2001 than in 2005, indicating that change was not entirely in one direction. It is thought that changes in water levels are a result of two main processes: the level of recent rainfall and the number and size of channels connecting pools to one another. The former may cause short-term fluctuations, while the latter is likely to result in progressive and irreversible damage to pool systems.

The conclusion drawn by the RSPB was that the condition of the Knockfin Heights SSSI was below that of a healthy blanket bog. One long-term concern was that the continuing emptying of pools could result in very large areas of bare peat being exposed. Not only would that reduce pool habitats for breeding birds but it could result in erosion and large-scale loss of carbon from the site. Repeat monitoring was recommended and it was suggested that further survey work be carried out to characterise existing channels in terms of size, determine rates of erosion and assess what proportion of ongoing erosion might be attributable to the effects of climate or deer impacts.

Counts were carried out by the RSPB on their Knockfin Heights Reserve where the mean number of deer (1995-2005) was estimated to be 4.4 per km^2, with the overall trend being a slight decline from 5.2 per km^2 (1995-2000) to 3.4 per km^2 (2001-2005) (i.e. about half the DCS density estimates). Despite this discrepancy, deer numbers on the Reserve are nevertheless relatively very low, on a declining trend, and within the target range set by the RSPB. However, concern was still expressed about deer using narrowly defined routes, particularly through pool systems where evidence of damage by deer to narrow zones of vegetation separating pools was frequently observed in the field.

In the wider context of the Caithness and Sutherland peatlands SAC, surveyed by Headley (2006), of the 90 systematic sample points recorded, 38 (42%) were assessed as Light impact, 43 (48%) as Moderate and 9 (10%) as High. A total of 511 target notes of trampling events were taken along approximately 112 km of blanket bog habitat. There were on average three tracks per km of blanket bog traversed and they were typically between 20cm and 30cm wide. Trampling by deer tended to be concentrated at the margins of the blanket bog either on ridges or along stream valleys, where the ground was generally firmer, but did not appear to be coincident with forestry blocks. The higher impacts were concentrated in flushes and the better drained areas of mires where there was a predominance of graminoids. Grazing impacts were generally not regarded as having an adverse effect on the nature conservation value of the overall blanket bog habitat. Grazing pressure appeared to be stable and in some areas may be declining, but firm conclusions could not be reached with respect to trends because of the ambiguity of the trend indicators (Pakeman, 2007). In summary, it was concluded that current levels of grazing were unlikely to lead to a significant loss of vegetation structure or loss of blanket bog habitat. Also, current levels of trampling did not generally appear to be leading to a significant loss of blanket bog vegetation. However, there was a suggestion that localised areas of High impact may be subject to some deterioration, and that there may be consequences of Moderate impacts over a longer timescale.

7.1.3. *Summary*

Much of the eroded peat on the Grudie and Knockfin sites is on relatively exposed sites, suggesting that climate, past and present, is a principal factor in peat erosion. The processes involved in the formation of dubh lochans, though not fully understood, are also more likely to be determined by climate and topography. In terms of very recent influences, sheep densities have been reduced markedly in the past 10 years and red deer densities are relatively low. Overall grazing pressure is therefore generally light, and while trampling is concentrated in some places, its contribution to erosion rates is not known due to the absence of suitable historical data. It is difficult to predict the likely effects of climate change, as this general region is likely to be influenced by contrasting predictions for both the east and west of Scotland. However, overall, it is likely that there will be an increase in the frequency of extreme events such as the intensity of rainfall, increased wind speed, and more unseasonal variations in weather patterns, due to the greater amount of energy being transferred from the tropics to the polar regions. This may exacerbate erosion.

7.2. Evaluation of role of drivers in the Grudie Region and Knockfin Heights study area

The areas of peat vegetation and bare peat in each of the four sites are summarised below (Table 18). Information on the OS gridlocations of sites and imagery are given in Appendix 3, Table A3.1.

Table 18 Areas and proportions (%) of (a) blanket bog indicated by LCS88 vegetation classification, and (b) bare peat determined by supervised classification of digital imagery in sites in the Grudie Region and Knockfin Heights SSSIs.

G= Grudie Peatlands, BS= Beinn Sgreamhaidh, SaL= Srath an Loin, K= Knockfin Heights.

Site	Area of site (ha)	LCS88 area of peat vegetation (ha)	Percent of site area that is peat vegetation	Area of bare peat soil (ha) classified in Definiens	Bare peat as % of site area	Bare peat as % of peat vegetation
G	75	71.4	95	6.02	8.0	8.4
BS	125	117.0	94	5.30	4.2	4.5
SaL	200	157.0	79[1]	13.06	6.5	8.3
K	100	100.0	100	24.74	24.7	24.7

[1] *Includes visual estimates, made using original imagery, of peat vegetation in two squares where blanket bog was a sub-class of 'undifferentiated dwarf shrub heath' in LCS88*

It is important to remember that the study areas are deliberately selected individual sub-catchments and are not representative of any SSSI as a whole. The data above are given only as contextual information for the broad descriptions of the study areas.

Grudie Peatlands SSSI study area

The study area in this SSSI (referenced as G in tables) is an L-shaped group of three 0.25 km^2 sample squares at 300 m to 350 m altitude on the gently sloping ridge to the south-east of Cnoc nan Imrichean and at the upper limit of the Allt a Bhurn Beag catchment. Most of the ground classified by the image analysis process as bare peat (Table 18) is in fact standing water in pool complexes, although bare peat and mineral surfaces are occasionally apparent where the water has receded. Subjectively, these pools appear to be determined principally by topography/geomorphology. There is no information about the time of year when the imagery was obtained so it is not apparent to what extent these systems might dry out thus exposing bare peat (or mineral) surfaces to erosional influences. For this project, a 'worst case' scenario is adopted and it is presumed that any such pool systems overlie peat which can be exposed if the pool dries out. Consequently, they will be treated as 'bare peat' in the assessments.

Beinn Sgreamhaidh study area

This block of five squares (referenced as BS) runs upwards from the banks of the Allt Cer burn onto the north–facing foothill of Beinn Sgreamhaidh in the Srath an Loin SSSI. The squares are at altitudes from 220 m to 320 m and erosion is mostly in diffuse anastomosing systems or obscure dendritic complexes. These often appear to be overgrown to the extent that the substrate is not visible and so the area of bare peat given in Table 18 is almost certainly an underestimate. There are some areas with linked pool systems which constitute the majority of the 'bare peat' in one sample square but, overall, these are far less frequent than in the Grudie study area (above).

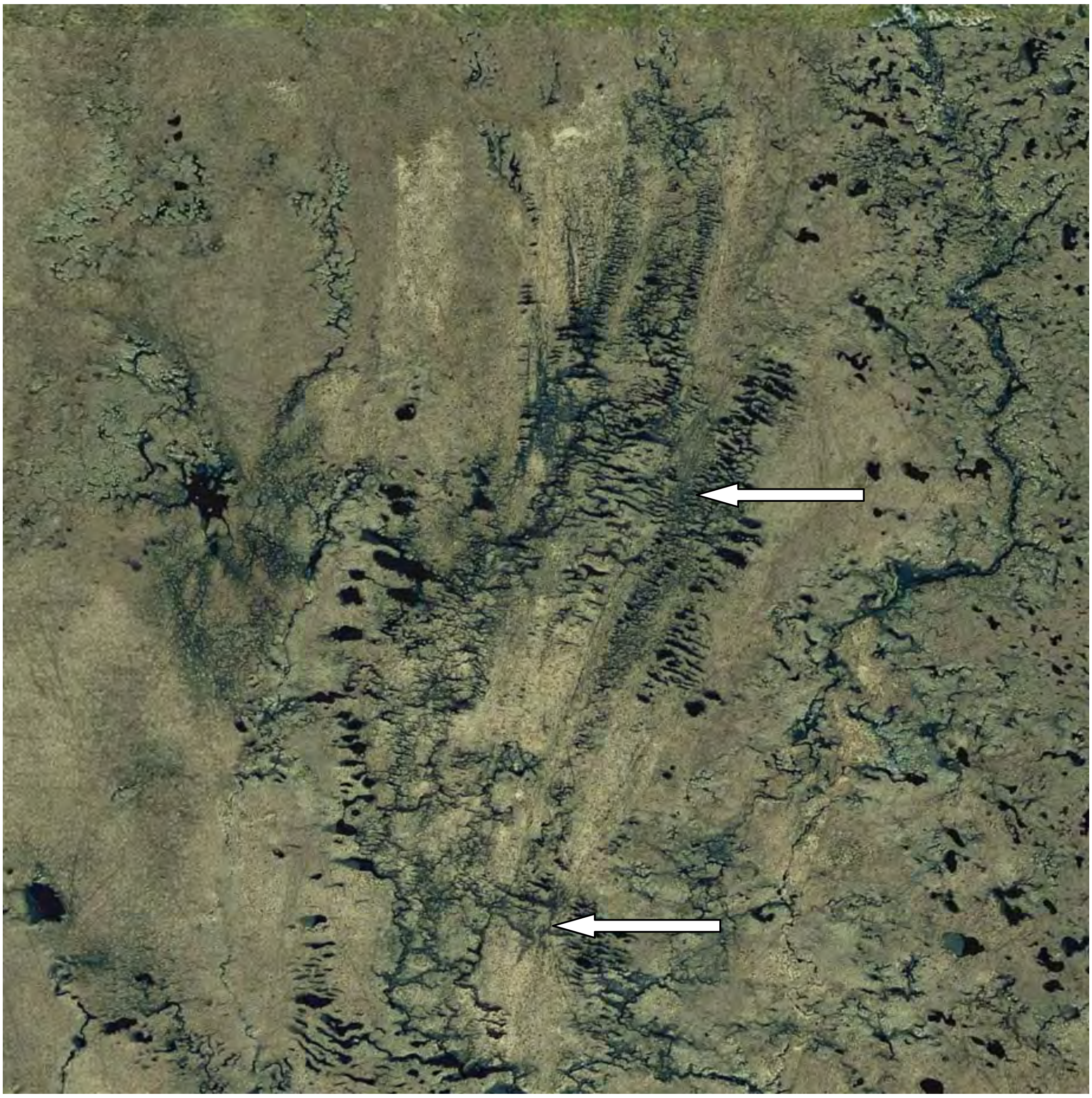
Srath an Loin study area

This block of eight squares (referenced as SaL) in the Srath an Loin SSSI constitute the largest study area in the project. They cover some of the upper reaches of the Allt Cer catchment at about 250 m altitude, ascending onto a gentle south-facing slope almost to the summit of Cnoc a Bhaid Bhain (367 m). This slope forms the major part of the study area and has a wide range of erosion patterns, mostly poorly defined gullies and sparse dendritic systems with few upper branches. Some of these are isolated and deep with no obvious inlet or outlet, and there are signs that some may have become overgrown.

There are also occasional anastomosing systems and pool complexes and one almost unique area of terraced cross-slope tears or slumps (Figure 16).

Figure 16 Example of erosion patterns in Srath an Loin - sample square SaL 7.

Note the two arrowed examples where animal paths converge and run uphill through strips of terraced erosion before fanning out. This square has a high number of paths (see also lower left corner).



Knockfin study area

This study area comprises a group of four sample squares located on the Knockfin Heights summit plateau at 400 m to 430 m altitude. Because there is very little slope, the pattern of bare peat is unusual amongst the study areas and has its origins in interconnected pool systems. It is difficult to define the status of these systems without knowing exactly when the imagery was taken. Some had standing water present, commonly with a fringe of what is probably bare peat, while others were apparently dry either because the pools were shallow and the imagery was taken during a very dry period or because the pools had become drained. Some sites that were formerly pools appear to have revegetated but it is difficult to be certain due to an overall greenish tone to the imagery. The exception to this overall picture is a sample square (K3), adjacent to one of the outlets from the plateau, that has a confused mixture of gullies - a few of which are eroded to the mineral substrate - along with some pools and anastomosing systems.

In this study area as a whole, the proportion of the blanket bog vegetation that had eroded to bare peat is about three to six times that of the three study areas in the Knockfin region, mainly due to the relatively large areas of the (former) pool systems.

7.3. Relationships between bare peat and drivers at the 0.25 km^2 scale

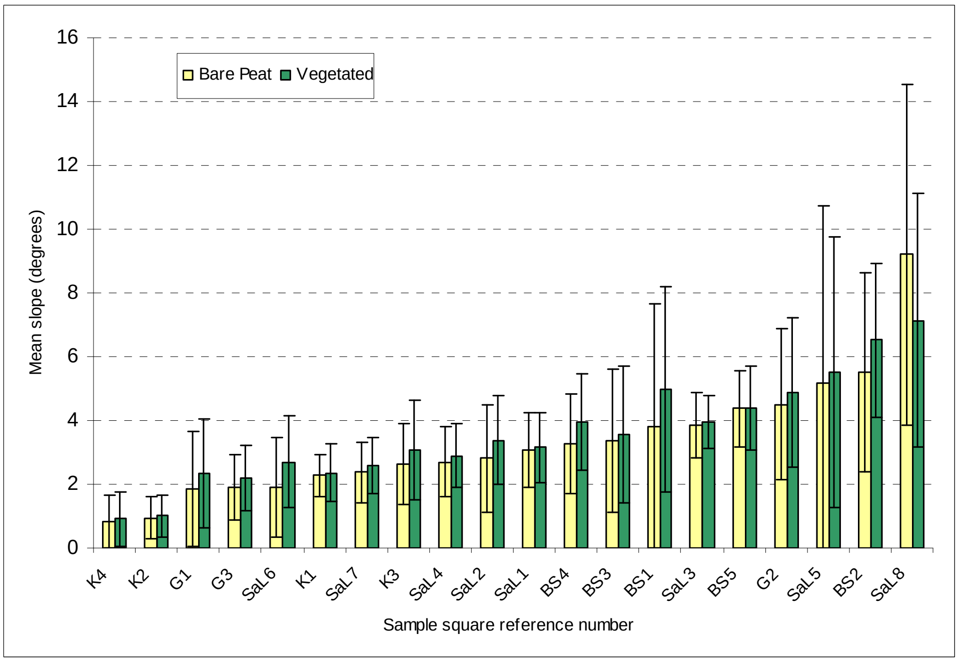
7.3.1. *Slopes: analyses of 1 m resolution data for individual squares*

The TTN 1m slope data were used to compare the mean slopes of bare peat areas with those of vegetated peatland in each square as a whole and the results, arranged in order of increasing amounts of bare peat, are shown in Figure 17. As might be expected from the general descriptions, the mean gradients in these selected sample squares were relatively gentle and only two exceeded 6^o (which was considerably less than the equivalent figures for the Ladder Hills and the Monadhliath study areas, where means ranged from 3^o to 21^o and 5^o to 21^o, respectively).

Beinn Sgreamhaidh was the only study area where there was a difference between the overall mean slope of bare peat (4^o) and vegetated ground (5^o). The two means were effectively identical in the Knockfin (2^o), Grudie (3^o) and Srath an Loin (4^o) study areas. The sample squares on the almost flat ground of the plateaux in Knockfin and Grudie are noticeably clustered towards the lower end of the scale in Figure 17. Within this limited range of mean slope values, the component 1 m^2 data were quite variable with standard deviations similar in magnitude to the means (Figure 17).

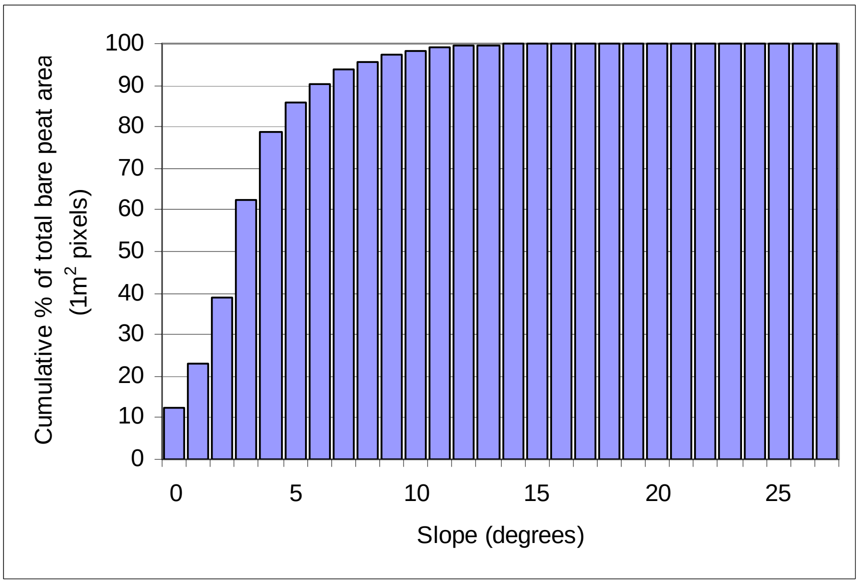
The difference between the overall mean slopes of bare peat and vegetated ground in individual 0.25 km^2 squares was less than 1^o in 18 of the 20 squares. Hence, on the grounds of slope alone, the occurrence of bare peat reflects the slopes in the whole of each 0.25 km^2 sample square generally and, at this scale, is not associated with particularly steep or gentle gradients.

Figure 17 The mean slopes of bare peat and vegetated ground in individual 0.25 km² sample squares in the Grudie/Knockfin study areas. Results were calculated using 1m resolution TTN models. Vertical lines indicate +/- 1 standard deviation.



The above results can be assessed on a broader basis by examining the overall combined distribution of the slope values of bare peat in all the sample squares in the Grudie/Knockfin study area. This is shown in Figure 18 where the area of bare peat in each 1° slope class is expressed as a cumulative percentage of the total area of bare peat. The graph shows that 50% of bare peat was on slopes of less than 3° and 80% on slopes of 4° or less. These slopes for bare peat were only marginally less than those for the squares as a whole (i.e. regardless of whether the ground was eroded or not), which reinforces the previous observation that slope is not a strong determinant of where erosion occurs in these particular sites.

Figure 18 The area of bare peat on different slopes shown as a cumulative percentage of all bare peat in the Grudie/Knockfin study area.



Again it must be stressed that the sample squares are selected for having some erosion present and are distributed across only four sub-catchments. Consequently, the slope information given above is not strictly comparable with the other study areas. However, the study areas were selected as a representative sample of erosion in the different study areas and the above results suggest that erosion tended to occur on less steep slopes in the Grudie/Knockfin group than in either the Ladder Hills or the Monadhliaths study areas.

Conclusion: Overall, 80% of bare peat in these study areas occurred on slopes of 4^{o} or less. Analyses of paired data showed that the mean slopes of areas of bare peat were not significantly different from vegetated ground in the same squares; hence slope apparently has no strong influence on where erosion occurs in these sites at the 0.25 km^2 scale.

7.3.2. *Relationship between bare peat and local drivers other than slope*

The same parameters used previously were examined in each of the 0.25 km^2 images to try to identify the effects of drivers at the local level. The results (Table 19) are shown in ascending order of percentage bare peat to facilitate assessments of relationships. For results ordered by sites, the full set of data is given in Appendix 3, Table A3.2.

As elsewhere, there was insufficient variability in the data to carry out meaningful statistical analyses of the animal densities in relation to the extent of bare peat. Erosion that was considered to be due to trampling was rare in the study areas in the project as a whole but the clearest example was in one of the squares in Srath an Loin (Figure 19). Here, many animal paths in the north-east of the square converged into a few paths that ran south-east through valleys; animals then seem to have dispersed from these, mostly onto the flanks of adjacent knolls or small hills. The resultant damage accounted for a large proportion of the 11% of peatland in the square that was eroded to bare peat.

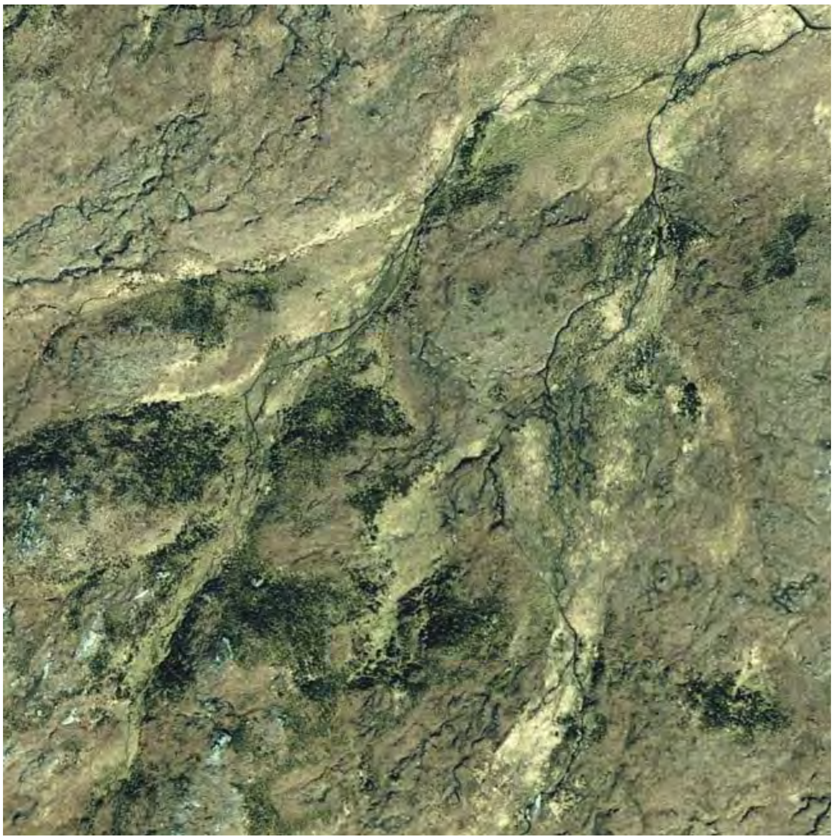


Figure 19 Erosion (dark areas) probably due to trampling in Srath an Loin sample square 8.

Apart from examples such as this, there was little relationship between bare peat and animal numbers. Indeed, it is notable that out of the four study areas, Knockfin had the highest overall percentage of bare peat but slightly lower estimated densities of both red deer and sheep (Table 19).

Clearly factors such as topography can confound these comparisons and, hypothetically, the same density of animals may trigger different amounts erosion in, say, a low-energy pool system compared to a high-energy gully system. However, the current data are not adequate for making such assessments and no reference has been found about research on this topic. Across all four study areas, there is therefore nothing to suggest that recent herbivore densities are a dominant factor in determining the current amounts of bare peat, although, as elsewhere, they could have been more important historically.

Climatic effects varied very little across the three study areas in the Grudie region due to their geographic proximity. Hence the main source of information is in comparisons with the Knockfin study area which had lower rainfall (both mean and maximum) and higher exposure values. Here again, the nature of the erosion can confound the results. For example, the rainfall – though less than elsewhere – may still be enough to have a strong impact on the flat area of a pool system, whereas it might have less impact on steeper sites. The dominant force in the Knockfin study area therefore appears to be exposure, mainly the effects of wind. Sample squares in Grudie (G1) and Srath an Loin (SaL7) had similar amounts of bare peat to some squares in Knockfin but they had lower exposure index values, so presumably the driving forces of erosion were somewhat different there, though it is not clear which they were. Consequently, the overall conclusion is that climate is, without doubt, a driving force for erosion, but the key to the relationship is in how it interacts with other site-specific local factors (for which we do not have adequate data).

Regression analyses of the 20 squares showed a marginally significant negative relationship between the % cover of bare peat and the mean slope of the study area but this was strongly influenced by the two Knockfin sites that had 37% bare peat. Analysis of slopes without these two sites was not statistically significant ($p>0.5$). Other regressions were similarly affected by the large amounts of bare peat in these pool systems. This was notably the case for altitude where there was a significant positive relationship between bare peat and altitude across all sites ($F=21.9$, $p=0.0002$). This became less significant without the two Knockfin sites mentioned above ($p=0.033$), and when all the Knockfin sites were excluded, the result was not significant ($p= 0.409$).

Conclusion: The extensive pool systems of the Knockfin Heights were atypical of the Grudie/Knockfin study area as a whole and their large area of bare peat constituted excessive weighting in statistical analyses. Analyses were conducted with and without the Knockfin data and when they were excluded none of the climatic, topographic or animal density parameters was significantly correlated with the area of bare peat at the 0.25 km^2 scale. Presumably the current erosional processes are influenced by a combination of several of the above factors, but it is not possible to assess their relative impacts without more detailed local data.

Table 19 Grudie region and Knockfin - the proportions (%) of peat vegetation (LCS88) in 0.25 km^2 sample squares that were classified as bare peat and the associated published data for potential drivers of erosion. Results are arranged in ascending order of bare peat %.

(Note red deer density per km^2)

Sample square	**Bare peat as % of total peat vegetation**	Red deer density 1987-02 (mean no. per km^2)	Sheep density 1986 (no. per ha)	Sheep density 2006 (no. per ha)	% change in sheep density	Altitude (m) Mean	Altitude (m) Min	Altitude (m) Max	Monthly rainfall (mm) Mean	Monthly rainfall (mm) Max	Exposure index	Frost index
BS2	**3**	30.8	0.42	0.35	-16	257	222	285	143	239	3	4
SaL4	**4**	30.8	0.42	0.35	-16	293	280	312	131	232	3	4
BS5	**4**	30.8	0.42	0.35	-16	254	227	277	143	239	3	3
G2	**4**	30.8	0.42	0.35	-16	326	295	344	103	175	4	4
SaL2	**4**	30.8	0.42	0.35	-16	298	281	315	131	232	3	4
SaL3	**4**	30.8	0.42	0.35	-16	297	280	316	131	232	3	4
SaL6	**5**	30.8	0.42	0.35	-16	268	259	282	131	232	3	4
SaL5	**5**[a]	30.8	0.42	0.35	-16	285	263	322	131	232	3	4
BS1	**5**	30.8	0.42	0.35	-16	256	230	284	131	232	3	4
SaL1	**5**	30.8	0.42	0.35	-16	327	313	347	131	232	3	4
BS4	**5**	30.8	0.42	0.35	-16	289	270	314	143	239	3	4
BS3	**6**	30.8	0.42	0.35	-16	292	274	314	131	232	3	4
G3	**8**	30.8	0.42	0.35	-16	338	325	346	103	175	3	4
SaL8	**11**[a]	30.8	0.42	0.35	-16	299	266	335	131	232	3	4
K3	**11**	9.1	0.39	0.28	-27	419	400	430	95	141	4	4
G1	**14**	30.8	0.42	0.35	-16	338	318	350	105	172	3	4
K1	**15**	9.1	0.39	0.28	-27	420	408	430	95	141	4	4
SaL7	**17**	30.8	0.42	0.35	-16	270	259	283	131	232	3	4
K2	**37**	9.1	0.39	0.28	-27	430	423	437	95	141	4	4
K4	**37**	9.1	0.39	0.28	-27	431	425	437	95	141	4	4

[a] *Most vegetation was recorded as 'sub-montane' in LCS88 with eroded peatland as a sub-class. Figures are based on visual estimates of the peatland component using the original 1988 imagery.*

7.4. Visual assessments from the imagery of local effects of human activity and animals within sub-catchments

To make detailed assessments of the localised effects of human activity and animals, we outlined 122 polygons of selected erosion systems and of the immediately adjacent uneroded ground (giving 61 paired sets of data). Records were then made for the same set of anthropogenic drivers examined in the other two study areas (Table 20).

7.4.1. *Muirburn*

There were no detectable signs of burning in or near any of the sampled sub-catchments, so there is no evidence that relatively recent burning might be associated with current erosion, although this does not preclude the possibility that historical burning might have some effect.

7.4.2. *Animal paths*

The first assessment was at a broad scale, made across the sample of polygons as a whole (i.e. irrespective of whether the land was eroded or not), and showed that animal paths were present in 73% of the selected polygons in the Grudie/Knockfin study area (Table 20), compared to 67% in the Ladder Hills and 48% in the Monadhliath study areas. Relative to the total densities of deer and sheep (i.e. about 95 animals per km^2 in the Ladder Hills and 45 animals per km^2 in the Monadhliath and Grudie/Knockfin areas), the occurrence of paths in Grudie/Knockfin was disproportionately large. There is no obvious reason for this – it could be that the terrain in Grudie/Knockfin results in animals travelling more along particular routes, rather than dispersing widely and not creating paths, but could equally be related to how applicable the animal density data are at the local level.

The second set of assessments involved detailed examinations of the selected polygons using the occurrence of animal paths as an index to assess:

- whether or not animals appear to congregate in certain types of erosion (green bars in Figure 20); and
- when animals are present whether or not they appear to be in greater numbers in any particular type of erosion (yellow bars in Figure 20).

Figure 20 shows only those types of erosion where at least six polygons were recorded and therefore suitable for statistical analysis.

The numbers of paths were very variable, with double figures recorded in three instances: 12 paths in a polygon of erosion in a pool system in Beinn Sgreamhaidh, 15 paths in uneroded vegetation in the same study area and 12 in uneroded vegetation in Srath an Loin. All instances were due to rapidly converging paths which, in the uneroded examples, were concentrated between patches of erosion in one case and between eroded ground and a stream in the second instance.

Analyses of variance showed no statistically significant differences between the mean numbers of paths in different erosion types, either overall - our surrogate measure of general animal presence (green bars) - or for only those polygons where paths were present, an indicator of the intensity of occupancy (yellow bars) ($p>0.25$ in both cases). These broad measures therefore suggest that animals were dispersed fairly evenly over these different principal types of erosion and, when present, did not tend to congregate more in one type than another.

Figure 20 The mean number of animal paths in selected polygons of different types of erosion in the Grudie/Knockfin study area. Vertical bars indicate one standard deviation.

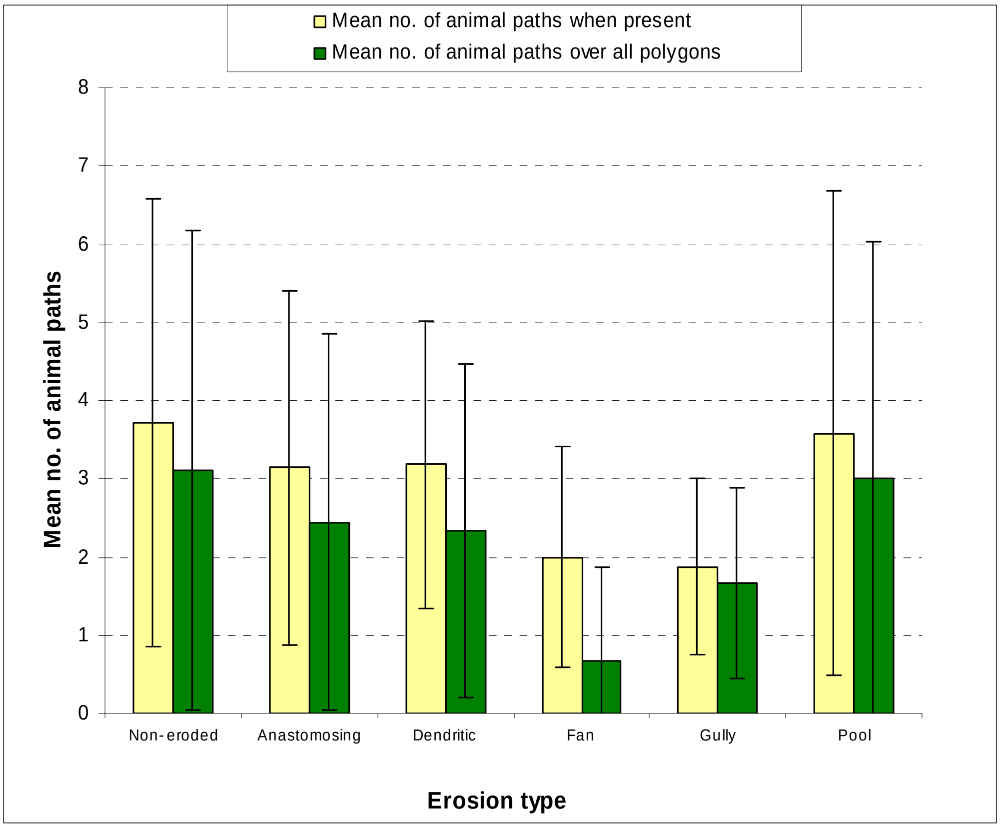


Table 20 The occurrence of potential drivers of erosion due to animals and human activity in different types of erosion and in adjacent non-eroded land in selected polygons in the Grudie/ Knockfin study area.

	Number of polygons recorded	Number of polygons with animal paths	Proportion (%) of polygons with animal paths	Mean no. of animal paths per polygon **when present**	Mean no. of animal paths over all polygons	No. of polygons with vehicle tracks	No. of polygons with recolonisation	Proportion (%) of polygons with recolonisation	Mean index of recolonisation **when present**	No. of polygons with detectable mineral soil/rock	Proportion (%) of polygons with mineral soil/rock[1]	Mean index of mineral cover **when present**
Non-eroded	61	46	75	3.7	3.1	2	6	10	1.0	16	26	1.4
Eroded												
Anastomosing	9	7	78	3.1	2.4	0	4	44	1.5	5	56	1.5
Dendritic	15	11	73	3.2	2.3	0	7	47	2.3	8	53	1.8
Fan	6	2	33	2.0	0.7	0	2	33	1.5	1	17	3.0
Gully	9	8	89	1.9	1.7	0	5	56	1.4	7	78	1.1
Pool systems												
Gully fed by pools	3	1	33	4.0	1.3	0	0	0	1.0	1	33	2.0
Pool	15	12	80	3.6	3.0	0	8	53	1.5	6	40	1.2
Other												
Trampling	3	1	33	3.0	2.0	0	0	0	0.0	0	0	0.0
Terrace (case example)	*1*	*1*	*100*	*7.0*	*7.0*	*0*	*0*	*0*	*0.0*	*0*	*0*	*0.0*
OVERALL	122	89	73	3.4	2.6	2	32	26	1.6	44	40	1.4

[1]One pair of eroded/adjacent polygons in Srath an Loin and five pairs in Knockfin could not be assessed accurately for the presence of mineral substrates due to snow lie. Percentages are based on the consequent reduced sample sizes.

The next comparison (Table 21) examines if there was any evidence that animals tended to be present more, or less, in polygons within an erosion system compared to polygons in the adjacent uneroded ground. Analyses of the paired data (eroded and uneroded) showed one statistically significant result, for anastomosing systems, and a marginally significant result for gully systems (two-tailed t tests, $p = 0.028$ and 0.092 respectively). In both cases there were more paths in the non-eroded adjacent vegetation than in the associated eroded areas. This suggests that, overall, animals tend to avoid travelling in these systems. However, these results do not preclude the possibility that *some* systems are used as routes, as demonstrated in Figure 15 and noted in the RSPB report for Knockfin (see Section 7.1.2), although some of the lesser paths recorded in RSPB's field survey would probably not be visible in the imagery.

Table 21 Paired comparisons of the mean number of animal paths in selected polygons of eroded and adjacent non-eroded vegetation in the Grudie/Knockfin study area.

Type of erosion		**Eroded**	**Non-eroded**
Anastomosing	Mean	2.4	3.4
(9 paired polygons)	s.d.	2.4	3.1
Dendritic	Mean	2.3	2.9
(15 paired polygons)	s.d.	2.1	2.5
Fan	Mean	0.7	0.8
(6 paired polygons)	s.d.	1.2	1.6
Gully	Mean	1.7	4.3
(9 paired polygons)	s.d.	1.2	4.1
Gully - fed by pools	Mean	1.3	1.0
(3 paired polygons)	s.d.	2.3	1.7
Pool	Mean	3.0	3.5
(15 paired polygons)	s.d.	3.0	3.0
Trampled	Mean	2.0	2.0
(3 paired polygons)	s.d.	1.7	1.7
Terrace	Mean	7.0	1.0
(case example)	s.d.	-	-
Overall	Mean	2.3	3.0
(61 paired polygons)	s.d.	2.3	2.9

Amongst the less frequently sampled erosion types, there were few animal paths in gullies connected to pool systems but the gullies were often deep and in some cases were piped beneath the surface before re-emerging. These two factors are likely to inhibit animals from getting close to them. The deep gullies may be the result of seasonal high-energy flows direct from the pool systems but this is conjectural because many of the pools were dry when the imagery was taken and it was not obvious which of them might become filled in winter.

Bare peat that appeared to be created by trampling was rare amongst all sites studied in the project and detected only in the Knockfin study area. There it was mostly confined to small knolls - the sorts of locations where animals generally gather in winter to get into the sun or in summer to take advantage of any breeze.

The single example of terrace erosion was a series of numerous small cross-slope slippages. There was a relatively large number of paths present - and far more than in the adjacent uneroded vegetation - but these paths were at 90^o to the terraces, travelling directly upslope and concentrated between areas of terracing (Figure 16). Therefore it seems unlikely that animals would have been the cause of the erosion but this convergence of several tracks into a few heavily used ones is likely to exacerbate erosion and may cause gullying to develop.

Conclusion: There is no clear evidence from the numbers of animal paths in the Grudie/Knockfin study area to indicate that animals occurred more frequently in, or made greater use of, any particular type of erosion. The results suggest that animals tended to travel more in the uneroded vegetation adjacent to anastomosing systems, and possibly gully systems, rather than in the systems themselves. Otherwise, animal paths were just as frequent on eroded as adjacent uneroded ground.

7.4.3. *Vehicle tracks*

Only two vehicle tracks were recorded, probably due to quad-bikes. Both were on uneroded land and in locations that were unlikely to affect or cause erosion.

7.4.4. *Recolonisation*

The occurrence of apparent recolonisation (probably by higher plants) was quite high and present in 43% of eroded polygons. Small patches of recolonisation were also present in 10% of the predominantly non-eroded polygons, giving an overall mean of 26% occurrence (Table 20). Sample sizes were too small to permit formal statistical comparisons between the types of erosion, but the differences were relatively small and unlikely to have been statistically significant. There were clear differences between study areas, however, with recolonisation present to some degree in 36% of the eroded polygons in Beinn Sgreamhaidh but only 13-20% in the other three study areas. The reasons for this are not clear and warrant further examination. However, they do not appear to be related to local animal use as there was no significant relationship between path numbers and the occurrence of recolonisation ($F=0.032$, $p=0.86$).

In terms of the percentage cover of recolonising vegetation, this was noticeably high in dendritic systems where three of the seven polygons with recolonisation had at least 25% cover and the mean index suggests an average cover of 15% or more. Recolonisation in these systems was nearly always confined to feeder branches/subsystems that were on fairly level ground. Speculatively, there may be some sort of hydrological balance here that helps to maintain conditions of soil moisture that are suitable for re-growth in the header system but without the flooding that occurs in similarly low-energy pool systems or the drying out present in higher-energy gully systems, often associated with slightly steeper slopes. The mean recolonisation indices in other systems with reasonable sample sizes were remarkably similar to each other and about one-third lower than the dendritic systems.

Exactly half of the polygons with regeneration had no mineral surfaces present, so there was no indication that regeneration was particularly associated with polygons where mineral surfaces were present, unlike samples at the other two study areas. Similarly, there was no relationship, positive or negative, between the coverage of recolonisation and the area of mineral surfaces.

The suite of factors affecting recolonisation is probably the most complicated of all aspects of peat erosion dynamics. Several studies have examined specific aspects and individual sites (see review in Evans & Warburton, 2007) but there appears to be scope for more integrative field studies to assess the localised interactions of these factors, particularly in these north-eastern study areas.

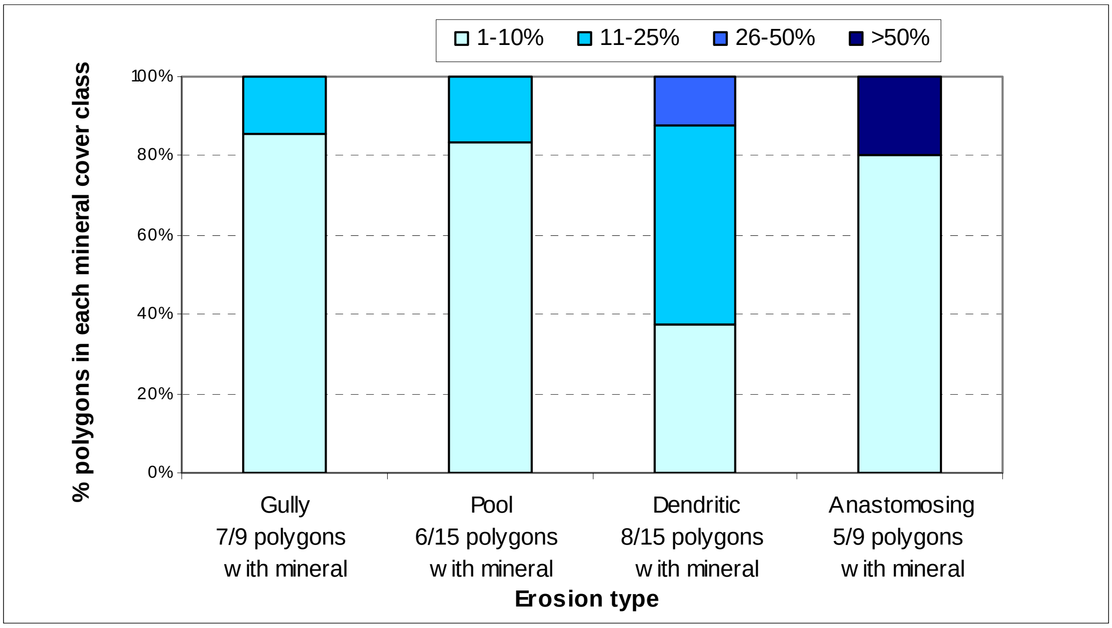
Conclusion: Recolonisation was more common than at the other two study areas and, unlike them, was not especially associated with mineral surfaces. From the information available, there was no indication that animals were a limiting factor in recolonisation. A study of the relatively high cover of recolonising vegetation in the feeders of dendritic systems could be of benefit.

7.4.5. *Mineral soils/rock*

As before, the frequency and extent of mineral substrates are used as broad indicators of the severity of erosion. Noticeable here is that about one-quarter of the selected polygons on non-eroded land had at least some mineral substrate visible (Table 20); of those, all but one were associated with polygons on the rocky plateaus in the Grudie and Beinn Sgreamhaidh study areas. Against that background, the mean percentages of 'polygons with mineral soil/rock' in the eroded systems are not as high as first appears. Even so, discernible mineral substrates were observed most frequently in gullies, which tend to be high-energy systems in terms of water flow. There was no real difference in frequency between dendritic and anastomosing systems but this can be ascribed to different drivers of erosion and, although the latter are usually much lower in energy, they tend to occur more on exposed sites where erosion is driven principally by climate rather than water flows. Like the anastomosing systems, pool systems are low in hydraulic energy but they were apparently subject to less severe erosion, having less mineral showing. This is only partly accounted for by the substrate not being visible in pools that had standing water and, in fact, the large majority of pools appeared to be dry when the imagery was taken. However, it is likely that at least some of these would have standing water during the winter, which would help to buffer the more severe erosional effects of climate at that time of year. The small sample of fan systems had the lowest frequency of mineral ground, probably because the energy of these systems becomes more dispersed downhill; none of them displayed obvious re-deposition of peat or mineral soils in the fan part of the system.

While the above assessment examines how widespread severe erosion is, the within-site estimate of the severity of erosion is given by the estimated cover of mineral substrate calculated only for those polygons where it is present. This reduces sample sizes even further and it is reasonable to make only fairly generalised comments. There was little difference between the mean index of bare mineral cover in anastomosing and dendritic systems (1.5 and 1.8 respectively – Table 20). However, the distribution of that cover was quite different (Figure 21), and the index for anastomosing systems was heavily weighted by just one polygon with more than 50% bare mineral substrate present. The mean indices for these two systems were somewhat larger than those for pool (mean 1.2) and gully (mean 1.1) systems – the latter being the lowest value for these systems in all three study areas (1.3 in the Ladder Hills and 1.6 in the Monadhliaths). This is probably because some of the gully systems in Grudie/Knockfin appeared to be on relatively gentle slopes (hence low energy flow rates), resulting in areas of diffuse narrow gullies that were often apparently isolated and so did not connect to form the larger continuous gully systems present elsewhere. Overall, the severity of erosion within systems was apparently greatest in dendritic systems where more than 60% of the eroded polygons had at least 25% cover of mineral substrates. This would be expected because of the increasing concentration of hydraulic energy in the lower reaches of such systems.

Figure 21 The proportion (%) of eroded polygons with mineral substrate in each cover class in the Grudie/Knockfin study area. Column labels show the number of polygons with mineral substrates present out of the total number of polygons recorded of each erosion type.



Conclusion: Some sample sizes were relatively small and in those cases conclusions must therefore be tentative. Signs of severe erosion (i.e. presence of mineral substrates) were most frequent in gully systems, but the severity of erosion within these systems (indicated by the percentage area of mineral substrates) was lower than the other principal types of erosion. The frequencies of severe erosion in anastomosing and dendritic systems were similar and about two-thirds that of gully systems. In contrast, the severity of erosion within these systems was about 50% greater than in gully systems. Signs of severe erosion were least common in pool systems and these also had one of the lowest severity levels within the system, perhaps due to the buffering effect of standing water during the winter. There were no clear associations between the severity of erosion and any of the anthropogenic impacts recorded here.

7.5. Summary of results from the Grudie Region and Knockfin Heights study area

- **Historical evidence of changes in extent of erosion**
  - Comparisons of earlier monochromatic aerial photographs and current imagery showed similar patterns of erosion but quantifying any changes in extent was beyond the resources of this project.
- **Slope**
  - Analyses of 1 m resolution slope data for the twenty squares showed that 50% of bare peat was on slopes of 3^{o} or less and 80% on slopes of 4^{o} or less – somewhat gentler slopes than in the Ladder Hills and Monadhliath study areas. Practically, there was no difference between the mean slope of eroded and uneroded ground as it was less than 1^{o} in 18 of the 20 sample squares.

- **Climate**
  - As with the other two study areas, there was insufficient variation within the climatic factors (frost, exposure, rainfall) to analyse statistically their relationship with the occurrence and extent of erosion, but informal inspection of the data revealed no clear trends.
  - There was a statistically significant positive relationship between altitude and the amount (%) of bare peat at the 0.25 km^2 scale, but the results were heavily weighted by the large amounts of bare peat at higher altitudes in Knockfin. The extensive pool systems and associated erosion in this study area were atypical of the study areas generally, and analyses repeated without this study area showed no significant relationship with altitude.
  - Despite its pool systems, Knockfin had the lowest mean monthly rainfall of all the study areas, so presumably drivers other than rainfall currently predominate there.

- **Animals and human activity as drivers**
  - At the 0.25 km^2 level, no single- or multivariate relationships with bare peat were identified using the published data on animal densities. Comparisons of path numbers on eroded and immediately adjacent uneroded ground indicated that animals avoided entering anastomosing and gully systems to some degree, preferring to move on the adjacent uneroded ground.
  - Localised field studies would be needed to determine the role of animals in causing or exacerbating erosion.
  - Only two vehicle tracks were recorded, probably due to quad-bikes. Both were on uneroded land and in locations that were unlikely to affect or cause erosion.

- **Recolonisation**
  - Recolonisation was more common than at the other two study areas but, unlike them, did not appear to be particularly associated with mineral surfaces.
  - From the information available, there was no indication that animals were a limiting factor in recolonisation.
  - The cover of recolonising vegetation in the feeders of dendritic systems was relatively high and a field study of these sites could be informative.

- **Severity of erosion**
  - Erosion down to the mineral substrate was used as the indicator of severe erosion. It was most common in gully systems (78% of polygons), but the actual severity of erosion within those systems was apparently lower than in any other type of system.
  - Conversely, mineral substrates were detectable in about half of the selected polygons in anastomosing and dendritic systems but severity within these systems was, overall, about 50% greater than in gully systems.
  - Signs of severe erosion were least common in pool systems and these also had one of the lowest levels of severity within the system, perhaps due to the buffering effect of standing water during the winter.
  - There were no clear associations between the severity of erosion and any of the anthropogenic impacts recorded here.

7.6. Evidence-based management recommendations: Grudie Region and Knockfin Heights study area

7.6.1. *Background*

Like the Ladder Hills and Monadhliath study areas, much of the erosion in the Grudie/Knockfin study area is in an advanced state and may have been occurring over hundreds of years. Similarly, the erosion is likely to have been initiated by a combination of natural and anthropogenic processes, but natural processes, related to peat accumulation and inherent instability along with climatic influences, probably played the major role. The dubh lochan areas in this study area are distinctive and their formation will also have been strongly influenced by the local topography. However, in addition to natural processes, trampling by deer has been suggested as a potential causal factor of the drainage of these pool systems. The effects of human activity in more recent centuries, in terms of grazing, burning and atmospheric effects, may have exacerbated erosion and created additional pressures in certain locations. Hence, the drivers of change are complex, interrelated and have operated over a long period of time. Below we explore each of the drivers in turn to determine what potential there is for management action.

7.6.2. *Climate*

Much of the eroded peat occurs in relatively exposed locations, suggesting that climate is a main driver of erosion, although the results showed no clear correlations between any of the climatic factors examined here and the current amounts of bare peat. While rainfall is commonly the predominant agent of erosion, its role is less clear in the Knockfin Heights where the precipitation is relatively low; perhaps here it is no longer adequate for keeping the peat moist enough to prevent it drying out and eroding by wind action. This is particularly important for the dubh lochans which, historically, had coalesced into larger systems in Knockfin. Where these had constant standing water, there would be little vegetation to bind the substrate, and any subsequent drainage (or decrease in rainfall) would result in a very unstable bare peat surface becoming exposed to the other climatic agents of erosion such as wind and frost heave. In terms of the future climate, Hulme *et al.* (2002) predicted a likely increase in climatic perturbation, with a resultant increased likelihood of exacerbated erosion.

While managing climate itself is impractical, it is possible to ameliorate its impacts by encouraging revegetation to bind the soil and reduce surface wind speeds. The signs in the Grudie and, particularly, Knockfin study areas are encouraging for this management practice as there is currently natural revegetation in several sites, mostly on fairly level ground at the heads of some dendritic systems and in the pool systems, but also in some gently sloping gullies that have become dry due to the development of new channels. The potential for revegetation is further illustrated by the fact that, overall, 80% of the erosion in these study areas occurred on slopes of 4^o or less (i.e. the figure indicated by studies in the Pennines for natural revegetation and infill by sediments).

7.6.3. *Grazing and trampling*

There is no doubt that excessive grazing and trampling by domestic livestock (mainly sheep) and wild herbivores (mainly red deer) can reduce the vegetation cover in peatlands and increase the chances of bare patches of peat developing, which are then exposed to other agents of erosion. Here, no relationship was found between the presence of bare peat in the imagery and recent animal densities. However, the available density data were probably not suited to establishing whether or not a relationship exists because all counts were made in March, whereas damage at higher altitudes and, for example, in wallow areas, is more likely to occur in the summer when animals, especially deer, move on to the high tops.

In the Grudie/Knockfin study area, there has been a marked decline in recent years in sheep numbers and red deer numbers are relatively low, although estimates of the latter vary widely. Field surveys indicate that the impacts of herbivores over most of the sites are not a major cause for concern. While herbivores are unlikely to be a significant widespread driver of erosion, the evidence from path counts indicates high local aggregations of animals - albeit perhaps transitory - and these have the potential to initiate or exacerbate erosion. In particular, it has been suggested that even low densities of deer (<5 per km^2) can have a significant impact on pool drainage and subsequent erosion of dubh lochan systems, purely by trampling and not by grazing (RSPB, 2005; Baker, 2008). From the imagery, and supported by field observations, it is clear that animals (predominantly deer?) have been using narrow routes to negotiate erosion systems and the resulting trampling of narrow strips of vegetation could open up new drainage channels and thereby expose bare peat to other erosive forces, particularly in pool systems.

Fencing animals out of susceptible areas would be an option but might only serve to shift the problem elsewhere and, because erosion is more readily created than recovered, this might actually increase the amount of erosion. Conversely, there may be 'hot-spots' where fencing could be considered. As the intention would be to severely reduce impacts and not necessarily to exclude animals completely, occasional breakthroughs would be acceptable. In this case, wind-powered multi-strand electric fences would be a cheaper option and more acceptable in conservation terms than the standard netting deer-fences.

Otherwise, in view of the densities reported in section 7.3.2, there appears to be little further scope, in practical terms, for a general reduction in grazing and trampling impacts, apart from a complete removal of sheep and further reductions in deer populations.

7.6.4. *Drainage*

Artificial drains were rare in the study areas overall and therefore not considered to be a problem.

In terms of 'natural' drainage, the dubh lochan systems are particularly vulnerable where they are on fairly level ground and have coalesced, notably on the plateau in the Knockfin study area. In such areas, relatively small reductions in water levels can expose disproportionately large areas of bare peat. Drainage channels can develop due to either hydrological pressures or, possibly, due to damage by animals, as suggested by some field studies. However, there was no evidence *at the scale of the imagery* to suggest that animals are currently a prime cause of drainage in the Grudie and Knockfin study areas (see below).

The results indicate that the large majority of erosion in the study areas occurred on gentle gradients and so there is apparently considerable scope for reducing erosion by blocking and/or modifying drainage gullies that have developed over time. On these gentle slopes, only relatively low barriers may be needed to raise water levels over a considerable area. However, any such blocking would need to be carefully engineered so as to avoid animal traffic being further concentrated onto adjacent vegetated areas that are already vulnerable. Consideration would also have to be given as to the type of vegetation required – for example, current climatic conditions may no longer be suitable for the establishment of *Sphagnum* on the more exposed sites, regardless of groundwater levels.

7.6.5. *Burning*

There was very little evidence from either the current imagery, or other fairly recent aerial photography, of burning on blanket bog or adjacent vegetation in the selected study areas.

Further action is unnecessary except to ensure that the Muirburn Code (Scottish Government, 2008) is followed.

7.6.6. *Recreation*

The Grudie/Knockfin sites are remote and do not contain the higher or more distinctive hills that attract hikers and mountain-bikers. There were no clear ‘point-to-point’ paths indicative of recreational walking, and so it is concluded that recreational pressure is not an issue in this area, or a driver of peatland erosion in any wider sense.

7.6.7. *Atmospheric pollution*

Atmospheric pollution is not considered to have been a major driver of peat erosion in this area because it is remote from major sources of inputs and has a relatively low precipitation rate, and hence is less subject to pollutants dissolved in rainfall.

7.6.8. *Management recommendations*

There is a limit to the options that can be taken to reverse or even mitigate peat erosion in the Grudie/Knockfin area, but one option - as suggested for the Ladder Hills and Monadhliaths study areas - would be to explore the effects of gully blocking on a pilot area. This has more potential in the Grudie/Knockfin area than in the other study areas due to the prevalence of erosion on very gentle gradients. Gully blocking would aim to re-establish water levels in pool systems or to prevent further widening and deepening of existing gullies and to encourage the accumulation of sediments. The hope would be that this would initiate and encourage re-vegetation in the bases of gullies and drainage channels and, in the longer term, lead to a state where they no longer form channels for excess run-off. However, as in the other study areas, this would be expensive, especially over any extensive area, and would need to be carried out in a well-planned and consistent way to stand a chance of being successful.

The use of heather brash could be considered where *Calluna* forms a significant proportion of adjacent vegetation, but clearly the wetness of the site would have to be taken into account, especially in winter when seasonal standing water is a possibility. This process still requires large amounts of manpower and of all the potential management strategies is usually the most expensive.

From the information obtained in relation to herbivores, there is only limited scope for further reductions in sheep numbers, as they have already been removed from many areas in the past five years or so. Red deer numbers are also relatively low to moderate and are being controlled to prevent an increase in numbers. Multi-strand electric deer fencing would be a possible option for reducing impacts on sensitive areas of a few hectares.

Evidence suggests that peat erosion in the Grudie/Knockfin area is largely driven by factors outwith human control, so there is a degree of uncertainty about the efficacy of any of these proposed management methods. At the same time, there is some 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. A useful contribution to our knowledge would be to ensure that any management intervention is monitored and, preferably, experimental studies incorporated.

8. IDENTIFICATION OF COMMON THREADS AND THEIR WIDER APPLICABILITY

8.1. Detecting and measuring the extent of peat erosion

Satellite remote-sensing imagery has been widely used for studies of erosion, but most of the earlier imagery was at a relatively coarse scale and more recent multi-spectral high resolution imagery is not readily available to, or easily analysed by, non-specialists. The methodology developed for this project (see Section 3.5) used high definition (25 cm) digital imagery that is readily available via the Web and was successful in identifying bare peat and measuring its area without manual digitising. The website of the supplier of the imagery (GetMapping^{R}) has an easy to use search engine for scrolling through low resolution images before purchasing, and even these low resolution images can be enlarged considerably on-screen. Due to occasional differences in tone, the image analysis procedure for identifying bare peat is not completely automatic and should be checked for accuracy against sample images, especially if being used across a wide area. Despite this, the methodology has much to offer for assessments of peat erosion elsewhere.

8.2. Causes of erosion

This section compares the results from the three study areas with the broad-scale effects indicated by the Scotland-wide analyses to assess to what extent the results from the study areas might be extrapolated to other areas of erosion in Scotland.

8.2.1. *Limitations of comparisons*

It is important to recognise that these comparisons are limited to varying degrees by different baselines and different scales in the two parts of the study.

First, the parameter of erosion used in the country-wide analyses was the LCS88 ‘blanket bog vegetation: eroded’ category, whereas the parameter in the three study areas was bare peat soil. Although there is likely to be a broad relationship between the area of eroded blanket bog and the area of bare peat, the correlation would probably be tenuous because the LCS88 classification contained no quantitative criterion of what constituted ‘eroded’. Hence an LCS88 area of blanket bog would be classified as ‘eroded’ regardless of whether it contained a few small gullies or large areas of bare peat in anastomosing or pool systems. One consequence of this is that there can be a meaningful correlation between a driver and the area of eroded vegetation, but that relationship may not apply when the same analysis is carried out for the area of bare peat.

A second factor is that the minimum area mapped in LCS88 was 1 ha, which is several times greater than the smallest area of bare peat identified in the imagery and is also closer to the scale of the data for potential drivers of erosion. As a result of this scaling, the LCS88 data may be better suited than bare peat for detecting relationships with the broader scale data on drivers - although, as pointed out above, the relationships would be with the vegetation and not necessarily the actual amount of erosion. When the data on drivers were applied to local study areas, there were commonly only two or three values for each of the drivers, and these were often closely related (e.g. data for altitude, frost index, exposure). This lack of variability makes it difficult to disentangle the impacts of individual drivers and to extrapolate results to the wider countryside. However, it must be stressed that a lack of clear correlations at the local level does not mean that there were no relationships between the various drivers and the area of bare peat. It is possible that those relationships exist but that the information on drivers was not at a fine enough scale of resolution to detect them. This applies to data on both climate and animal densities which will be discussed in more detail below.

Finally, some of the preliminary countrywide analyses indicate that SSSIs may be atypical of peatlands generally in terms of eroded vegetation. For example, the relationship between the area of eroded vegetation and the proportion of SSSI in 0.25 km^2 sample squares was always negative (although not always statistically significant). This is not surprising because SSSIs are chosen for being high quality examples of the particular features for which they are designated and therefore severely eroded blanket bogs are commonly excluded. This suggests that SSSIs are towards one end of the spectrum of erosion and therefore the results from the three selected study areas may not be typical of eroded blanket bogs elsewhere.

8.2.2. *Drivers*

8.2.2.1. Climate

Analyses at the country-wide level showed that the most important explanatory variables of eroded peat vegetation were mean monthly rainfall, median altitude, latitude and the index of exposure (Birse & Dry, 1970). Notably, the correlation with maximum monthly rainfall was not significant and therefore it appears that, country-wide, monthly rainfall is a more important driver of eroding vegetation than more extreme events (although the mean monthly rainfall figures are obviously weighted to varying degrees by the maximum rainfall within the month). There are plenty of reports to show that very heavy short-term rainfall (e.g. flash storms) can cause severe erosion and so this result is, perhaps, surprising. However, as discussed above, the answer probably lies, at least to some degree, in the properties of the LCS88 classification. For example, if a severe storm caused more erosion within an area already classed as 'eroded blanket bog', the classification of that area would not be affected.

In contrast, such an event would increase the area of bare peat and we might expect it to be reflected in the more detailed analyses of the three main study areas where 'bare peat' was the parameter of erosion. This was not the case and no consistent relationship was found within individual study areas or for all study areas combined. However, this result is not conclusive and there are several possible explanations, for example:

- heavy rain events are not related to the area of bare peat…………………..*(Unlikely)*
- heavy rain has an effect only at certain vulnerable locations and these are too infrequent to be detected with a sample of 13 sites ………………………..(*Possibly*)
- average monthly rainfall is a stronger overall influence than isolated heavy rainfall events at the scale of the study as…………………………………………..(*Probably*)
- the scale of the climate data is too broad to identify the impacts of weather at the more local scale of study areas……………..……………………………………(*Very probably*)

The above discussion illustrates a general point about the climatic parameters when applied at the local level. The lack of significant relationships between climatic drives and the area of bare peat in any of the study areas is contrary to what might be expected from the literature. The implication is that there is a generic problem in trying to relate broad-scale climate data to areas of bare peat that are relatively localised. The mismatch in the scales of the data mentioned above almost certainly has a strong influence on the results, although it could be that three study areas and thirteen sites is not enough to detect any relationships. Nevertheless, it is unlikely that the impact of climate on the area of bare peat can be determined without local measurements.

In conclusion, our only indicators of the effects of climatic variables as drivers of erosion are those for the country-wide associations which refer to the presence of erosion features in blanket bog/peatland vegetation and give no indication of the severity of erosion.

8.2.2.2. Grazing and trampling

A common thread throughout this study is the lack of statistically significant correlations between estimated herbivore densities and the two measures of erosion (i.e. eroded vegetation for national assessments and bare peat for localised studies).

However, we must recognise that the data on herbivore densities and the LCS88 'eroded vegetation' data may not be sensitive enough to detect any such relationships at the national scale (see above and Section 3.4.2).

In contrast, it would be reasonable to expect any herbivore impacts to be detected more readily using the area of bare peat as a parameter of erosion because it is likely to be a far more responsive indicator than eroded vegetation. Also, the imagery used for detecting bare peat was much more recent than LCS88 and therefore more relevant to the selected 15-20 year timespan of animal density data. However, the limitations of the scale of the herbivore density data became even more acute when applied to the selected sites; all of which were 2 km^2 or less and likely to contain localised concentrations of animals – perhaps seasonal - which would not be represented by the density data.

Thus we have two scales of data:

(a) national data, where the eroded vegetation is probably not sensitive enough to reflect the impact of animals; and

(b) local data where the animal density data are probably not sensitive enough to relate to the amounts of bare peat.

In an attempt to resolve the latter problem, counts of animal paths were used as a surrogate measure of animal density but those results also showed no significant relationships with the extent or type of erosion. It appeared from the imagery that animals tended to avoid travelling through deeply eroded areas in some sites; otherwise the occurrence of paths in eroded areas was generally the same as on adjacent uneroded land. Therefore, the overall evidence is that there was no detectable impact of herbivores over the 15-20 years prior to acquisition of the imagery in 2004-2006.

None of the above points precludes the possibility that sheep and deer *may* be drivers of erosion but, if so, the available data are not adequate to detect this. It appears that the only way that this can be resolved is by establishing fairly long-term local field monitoring of animal numbers throughout the year (e.g. using dung deposition counts) and measuring accurately any changes in the areas of bare peat. Current DCS/SNH experiments using fenced exclosures will provide very useful information on the impacts of grazing and trampling on existing areas of erosion, although more frequent counts of dung deposition would have provided improved estimates of animal densities that would have been useful for management purposes.

8.2.2.3. Muirburn, vehicle tracks, recreational impacts

These three features were rare in the sites and, where present, showed no signs of being instrumental in initiating or exacerbating erosion. Hence the results provide no useful information for guiding management elsewhere. Of the three, muirburn is clearly the most widespread driver and may have had an impact historically but in the absence of any clear evidence, it is important to adhere to the Muirburn Code (Scottish Government, 2008).

8.2.2.4. Slope and topography

These two features are not drivers as such but modifiers of how the impacts of other drivers are expressed. Detailed assessments of the slope characteristics of different types of erosion in the Ladder Hills study area showed that anastomosing and dendritic erosion systems occurred on similarly shallow slopes with maxima of about 12^o, compared with up to 20^o for gully systems and 32^o for areas of slippage. These values broadly reflect the hydraulic energy of the systems. Even so, there was considerable overlap in the ranges of slopes of the different systems and it was clear from the imagery that this was often due to local topography (e.g. affecting how quickly the upper branches of dendritic systems focused into the main stem or, conversely, in the direction and number of outlets from anastomosing systems on ridges).

The numbers of inlets and outlets of erosion systems were counted but it soon became evident that detailed information on associated topography and geomorphology was required if the results were to provide useful information about erosion processes. Overall, the results indicate that slope alone is not a good predictor of the potential extent of erosion, although subjective impressions were that it was likely be correlated with the severity of erosion in terms of the depth of gullies.

The conclusion from the above is that the interaction of slope and topography is very variable and almost site-specific. This has important implications for how an area of erosion might be managed or, indeed, whether erosion at a site can be managed at all without major engineering work to alter the topography.

The calculations of slopes in individual 0.25 km^2 sample squares showed that 50% of erosion occurred on sites of 6^o or less in the Ladder Hills study area, 5^o in the Monadhliath study area and 3^o in the Grudie/Knockfin study area. The DEFRA (2008) report recommended that management effort should be concentrated on slopes of 6^o or less and so at least half of the eroded peat in the study areas should be appropriate to management techniques such as gully blocking or mulching (although animal control would usually be important as well).

Careful selection of sites could benefit a considerably larger area than that actually treated – for example, if the feeder for a dendritic system was on fairly level ground, controlling outflows there could also reduce downslope erosion. This emphasises the point made in the above discussions that every site is different and it is difficult to generalise about the impacts of drivers, especially remotely. Each site should be visited to assess its characteristics.

8.3. **Management**

The remit for this section was to examine the results from the three study areas to examine if

(a) there are any management practices that might have contributed to erosion; and

(b) the results provide any guidance for pre-emptive or *post-facto* mitigation of erosion.

In terms of remit (a), there was only one example in the imagery where management had clearly contributed to erosion and that was the trampling damage due to high densities of animals in one sample square in Srath an Loin (see Figure 19). Otherwise, there were no *detectable signs in the imagery* of the three study areas where erosion could definitely be attributed to poor management such as over-stocking, over-burning or vehicle usage. Those italics emphasise an important conclusion of this project - there may well be other examples of poor management, particularly with regard to stocking rates of sheep and/or deer but these were either not obviously associated with the amount of bare peat present or were not discernible on the imagery. Some conditions can only be detected by field studies and surveys. On the other hand, it may be that thirteen study areas were insufficient to detect examples of poor management, although this is counterbalanced to some degree by the fact that the majority of study areas were targeted at eroded sub-catchments, hence locations where impacts were most likely to be apparent. Obviously these arguments also apply to detecting examples of good management.

In the absence of good evidence from this project, guidance has to come from the literature but even this is often inconclusive and, as concluded in Section 1: "*Apart from experimental studies, assessments of grazing animal numbers - whether by visual counts or agricultural parish returns - have rarely been made at a suitable scale or over a long enough period to correlate them with the relatively slow process of peat erosion*." Even then, the experimental studies often suffer from being at relatively small scales relative to free-ranging animals and open moorland.

The literature quotes many references as '*pers. comm*' or '*unpublished*', indicating that there is much unpublished data on peatlands and erosion generally (not just on the effects of grazing animals) that is highly relevant but unavailable - a point also made in DEFRA's report in 2008. Identifying and collating that information would be a valuable exercise but even then might only be useful as guidance. One major conclusion of this project is that there are few relationships that can be readily identified remotely, suggesting that local impacts, their interactions and their effects are highly site-dependent and need to be assessed in the field before effective management procedures can be determined.

For remit (b), the results of this project again provide little direct evidence upon which guidance can be based. The methodology for identifying bare peat could be used to identify small areas of bare peat that might indicate the initiation of erosion and field visits could then assess the likely cause. Pre-emptive action might include small gully blocks to arrest early channel development. If the condition of adjacent vegetation suggested that animals were having an impact, reducing stocking rates would be important. In the case of sheep, this might be achieved by improved shepherding or removing animals from the hill during winter when vegetation and ground conditions are most vulnerable. The much quoted maximum densities of 15 deer per km^2 and 0.5 sheep per ha may be used pre-emptively and applied without visiting sites. However, they cannot take into account damaging local concentrations of animals or the susceptibility of individual sites to erode, both of which need to be identified by a site visit or from local knowledge. It is therefore important to continue to follow SNH's current practice of using the condition of sites to assess impacts rather than some overall estimate of animal numbers.

Methods of *post hoc* mitigation are essentially those obtained from the literature and are given in Section 4.

9. DISCUSSION and CONCLUSIONS

9.1. Objective 1 – to review and assess appropriate methodologies and techniques to measure changes in the extent and pattern of peat erosion, erosion risk and the role of different drivers

The various methods differed in their accuracy, costs, spatial and temporal scales, sensitivity, and security and stability on site. Many of the methods were judged to have low sensitivity or no applicability in either the vertical or horizontal dimension. Temporal sensitivity was generally high for field methods, while LiDAR was considered to have the greatest potential among the remote methods.

The review highlighted difficulties of resolution and registration when imagery taken at different times or from different platforms is used to assess detailed changes in erosion extent and severity. Although these difficulties can be resolved, it is a complicated procedure (for example see Scottish Government, 2009) and the considerable resources required were beyond the scope of this project. Even when fully registered, determinations of rates of erosion are limited by the lowest resolution of the different sets of imagery that are being compared. For example, the very recent imagery used in this project has a pixel size of 25 cm and is considered to be very high resolution but this is equivalent to between 5 and 25 years erosion. Such imagery is also relatively recent and so the prospects of being able to accurately determine rates of erosion retrospectively are severely limited.

9.2. Objective 2 – to evaluate the wider role of different drivers of peat erosion, individually and in combination; and to assess their impacts in three study areas selected as being of high conservation value

It is important to recognise the difference between two common parameters of ‘peat erosion’, especially when comparing different studies:

- Studies often refer to ‘eroded vegetation’ but rarely stipulate how much bare ground has to be present to qualify as ‘eroded’. In most cases, it would be more accurate to refer to ‘vegetation with erosion features present’. Without criteria for the amounts of bare ground, areas mapped as ‘eroded vegetation’ can be subjective, difficult to replicate and could encompass very different amounts of bare soil. Data from a single source, such as LCS88, are more likely be internally consistent and can be useful for large-scale assessments at one point in time. They can also provide a valuable filter for identifying suitable areas for more detailed studies.
- In contrast, ‘bare peat soil’ is a direct measure of erosion *per se.* It is more precisely defined and can be mapped more consistently, either visually or using image analysis systems, although this is usually resource-intensive. Rules may be required about how to treat small areas of vegetation within otherwise bare areas, but the image analysis methodology developed for this project greatly reduces the subjectivity associated with such rules because it classifies each 25 x 25 cm pixel as bare peat soil (occasionally mineral substrate) or vegetated.

It must be stressed that the relationships between the potential drivers and the different parameters of erosion are assessed by correlations and so we should not assume a causal relationship just because there is a geographical coincidence between erosion and present day conditions. Conversely, we should not assume that a relationship does not exist just because it has not been detected.

Climate and geography

The above caveat about correlations is illustrated by the national-scale analyses of the area of eroded blanket bog vegetation and rainfall. A statistically significant correlation was identified between the area of eroded vegetation and the mean monthly rainfall but not with the maximum monthly rainfall - an indicator of more intense events. However, this does not mean that no relationship exists with the latter. Indeed, extreme climatic events, including prolonged warm dry periods as well as intense rainfall, are considered to be the most important triggers for specific erosion incidences (Warburton *et al.* 2004; Lilly *et al*., 2009). However, these instances tend to be localised compared to the mapped areas of eroded blanket bog in LCS88, most of which are several hectares or more in extent. A possible scenario is that the main impact of intense rain is to increase the area of existing erosion features within the mapped boundaries. Such impacts would not be reflected in the data. With this scenario as a possibility, the conclusion has to be that, *with the data available*, we could not *detect* a significant impact of extreme rainfall events on the extent of eroded blanket bog vegetation across the country as a whole.

The other factors that were significantly correlated with eroded vegetation at the national scale were exposure, altitude and latitude. Unlike rainfall, these factors can be determined quite precisely for specific locations and, in practical terms, do not vary with time. This consistency probably increases the chances of detecting relationships with long-term erosion which, according to the evidence of field visits and the SNH/SNIFFER report (Lilly *et al*., 2009), constitutes a considerable proportion of current erosion.

The wide range of values for climate and topographic drivers in the national study allowed their impacts to be analysed statistically. In contrast, the three areas selected for detailed studies were relatively compact and, with the exception of slope, there was too little variation in the data to permit statistical analyses.

In all three study areas, the gradients of bare peat locations were less than those of adjacent vegetated ground, but the mean differences were all less than 2^o and therefore of little practical consequence. Therefore, slope alone was not a strong determinant of where erosion occurs, although it was related to the general patterns of erosion and is likely to be important in terms of the depth of erosion.

Herbivores

Herbivores are often implicated as a cause of erosion but critical examination indicates that this is often supposition and not supported by the evidence presented. For example, the trampling effect of deer sheltering amongst haggs does not mean that they caused the hagging. The evidence suggests that hagg systems are usually many decades old, at least, and likely to have been caused by other drivers, particularly severe climate. Similarly it cannot always be presumed that animals are preventing revegetation in these areas. Aggregations of animals certainly disturb the seedbed but it may be that other drivers would prevent revegetation, or cause erosion, regardless of herbivore activity.

'Overgrazing' is commonly cited as a cause of erosion but this is usually no more than a presumption and is rarely considered in the context of other drivers and the potential erodability of a site. In fact there is a marked shortage of empirical information about how reductions in vegetation cover affect the risk of erosion relative to other drivers, especially for the graminoid component of blanket bogs. The PESERA model of sediment yields, one of those examined in the SNH/SNIFFER project (Lilly *et al*., 2009), identified loss of vegetation cover as an important factor affecting the risk of erosion at the 1 km^2 scale. However, that report contains some caveats about the model, including the lack of validation data, and it should be noted that the model includes organo-mineral soils (podzols) as well as peat *per se* and therefore encompasses a range of vegetation types from wet heaths to blanket bogs. To manage herbivores successfully in any particular site, it is important to acquire more detailed and localised data about how the gross numbers of animals – as given by existing data - are distributed over the landscape. Pakeman (2009) reached a similar conclusion in his report assessing indicators of herbivore impacts on blanket bog habitats (N.B. not erosion *per se*), and considered that dung deposition is the best indicator of animal density at the requisite local level. Even with those data, long-term experiments would be required to establish the extent to which herbivores initiate or accelerate erosion.

The on-going exclosure trials undertaken by DCS/SNH in the Monadhliath Mountains should provide valuable information about the effects of large herbivores on *existing* eroded areas of blanket bogs. However, only experiments of the type mentioned above will provide information on the interactions between herbivores and other drivers at a local scale.

Other drivers

Generally there were few occurrences of burning, recreation or vehicle tracks in the imagery, and there was no indication that any of them were especially associated with areas of erosion.

Summary of impacts of drivers

Erosion is usually the result of multiple drivers but it is not feasible with the data available to accurately quantify the relative effects of the different drivers, some of which act to damage surface vegetation cover and thus increase the susceptibility of surface soil horizons to erosion, while others control the occurrence and rates of erosion (usually from sites with prior surface damage).

9.3. **OBJECTIVE 3 – Prepare evidence-base management recommendations**

The results provided no firm evidence on which to base management recommendations for individual sites or study areas. As stated above, relationships either do not exist or are not detectable using the available data. Some site-specific information was available for the selected study areas but was not suitable for the aims of this project due to its type, frequency or spatial scale, or because it was qualitative.

Another possible reason for the apparent lack of relationships is if the study areas were very variable in their response to impacts. It is difficult, therefore, to make management recommendations without field visits to sites, and it is recommended that managers should do so before deciding on any management options. Generalised prescriptive measures could have a low success rate.

Climate appears to be the principal driver of erosion. Possible methods to ameliorate its impacts are based principally on the extensive (and expensive) work in the Pennines. They include blocking of gullies, mechanical reprofiling (with or without geo-textiles), spreading of heather mulch and the use of nurse crops to assist natural regeneration.

Application of the above methods should be assessed on a site-by-site basis. Success rates are likely to be higher on gentle gradients, and those greater than 6^o should be avoided. At least half of the area of bare peat in all three study areas was on gradients below this limit.

High densities of animal paths indicated that there were some large local concentrations of animals, out of proportion to overall stocking rates. If the management of herbivores is to be effective, it is essential to make site visits to determine: (a) if there are any local concentrations of animals; (b) the sensitivity of the vegetation to animal impacts, and (c) to assess other ground characteristics that could affect the susceptibility of a site to erosion. High-altitude sites are particularly vulnerable, even at very low densities of animals.

While the much quoted maximum densities of 15 deer per km^2 or 0.5 sheep per ha may be used as pre-emptive guidelines, the importance of site visits cannot be over-emphasised.

9.4. OBJECTIVE 4 - Identify common threads and their wider applicability

The methodology developed for the detection and measurement of bare peat can be applied at a wide range of sites. However, cost-effectiveness for wide-ranging studies is improved if data such as LCS88 are used as a filter to help identify key areas.

A common thread throughout all three study areas was a lack of suitable quantitative data to assist in making informed decisions, especially for the management of deer and sheep but also for localised influences of climate and hydrology. Therefore management decisions must be made on a local basis after local assessments of impacts.

Care must be taken when making any extrapolations from the study areas: first, because blanket bogs within SSSIs tend to be less eroded than elsewhere; and, second, because the sub-catchments selected for detailed study are unlikely to be a representative sample of eroded areas in a designated SSSI and its surrounds.

Climate appears to be the predominant driver of erosion. Practically, we can do little to alter the climate but there is a range of management techniques to ameliorate its impacts. These techniques result in varying degrees of disruption and none is cheap, especially when applied to large areas. Policy decisions may be required about whether to treat high quality sites with a limited chance of success or lesser quality sites with a higher chance of success.

It is unrealistic to try to recreate peat-forming vegetation and conditions due to the very long timescale involved. Apart from pool systems, there were few sites where raising water levels *per se* would be the primary aim. Management would usually be targeted at controlling flow rates and direction, and promoting revegetation.

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APPENDICES

APPENDIX 1: LADDER HILLS SITE DATA

Table A1.1 Sites, locations and OS grid references of component sample squares in the Ladder Hills study area.

		Sample square A		B		C		D		E		
Site	**Location**	**Easting**	**Northing**	**Easting**	**Northing**	**Easting**	**Northing**	**Easting**	**Northing**	**Easting**	**Northing**	**Notes**
LH1	Tom Bhuirich	320800	813000	320800	812500	320800	812000	321300	812000	-	-	Just outside SSSI. Contrasting W & E slopes
LH2	Lurg Dhubh	322550	814150	-	-	-	-	-	-	-	-	Single 'CONTROL' sq. - lower altitude example of uneroded site
LH3	Carn Liath	325400	815530	324900	815530	325900	815530	325900	816030	325400	815030	Catchments at all aspects except due north
LH4	Carn Liath-Carn Mor ridge	326500	816740	326000	816740	325500	816740	-	-	-	-	W-E transect across ridge, picking up catchments both sides
LH5	Dun Muir & ridge to south	327980	818940	327480	818940	327980	818440	327980	817940	-	-	NE - SW ridge, erosion either side
LH6	Kymah burn catchment	330225	821450	330225	821950	329725	821950	-	-	-	-	Just outside SSSI. Mostly uneroded, low relief

Table A1.2 The proportion (%) of peat vegetation (LCS88) in 0.25 km^2 sample squares in the Ladder Hills study area that was classified as bare peat soil and the associated published data for potential drivers of erosion.

Sample square ref.	OS Easting	OS Northing	Image	Non-eroded peat vegetation area from LCS88 (ha)	Eroded peat vegetation area from LCS88 (ha)	Eroded vegetation as % of total peat vegetation	Area of bare peat from imagery (ha)	**Bare peat as % of total peat vegetation**	% of area in SAC	% of area in SSSI	Exposure index	Frost index	Red deer density (mean no. per km^2 1987-02)	Sheep density (no. per ha) 1986	Sheep density (no. per ha) 2006	% change in sheep density	Aspect	Altitude (m) Mean	Altitude (m) Range	Altitude (m) STD	Mean monthly rainfall (mm)	Max. monthly rainfall (mm)	Min. monthly rainfall (mm)
LH1a	320800	813000	09E9A	0.0	24.9	100	0.36	**1**	0	0	3	5	8.2	0.4	0.4	8	46	611	42	12	94	231	22
LH1b	320800	812500	09E9C	0.0	17.5	100	0.81	**5**	0	0	4	5	8.2	0.4	0.4	8	280	630	76	16	94	231	22
LH1c	320800	812000	0B3FA	0.0	17.7	100	0.35	**2**	0	0	4	5	8.2	0.6	0.6	-3	253	657	58	14	94	231	22
LH1d	321300	812000	09EA0	0.0	9.0	100	0.58	**7**	0	0	4	5	13.1	0.6	0.6	-3	117	657	95	23	94	231	22
LH2a	322550	814150	09EA8	6.4	0.0	0	0.00	**0**	100	100	3	5	8.2	0.4	0.4	8	342	554	68	18	94	231	22
LH3a	324900	815530	09E92	0.0	19.2	100	1.94	**10**	100	100	4	5	10.3	0.4	0.4	8	252	722	91	20	85	198	23
LH3b	325900	816030	09E96	0.0	8.6	100	0.88	**10**	100	100	5	5	10.3	0.6	0.6	-3	87	700	152	40	103	253	26
LH3c	325900	815530	09E94	0.0	11.5	100	1.81	**16**	100	100	5	5	10.3	0.6	0.6	-3	113	730	107	28	103	253	26
LH3d	325400	815530	077B4	0.0	25.0	100	5.63	**23**	100	100	5	5	10.3	0.4	0.4	8	223	769	45	10	103	253	26
LH3e	325400	815030	09E98	0.0	24.6	100	0.65	**3**	100	100	4	5	10.3	0.6	0.6	-3	210	737	74	19	103	253	26
LH4a	325500	816740	09E8A	0.0	11.5	100	1.05	**9**	100	100	5	5	10.3	1.8	1.8	2	321	745	66	17	103	253	26
LH4b	326000	816740	09E88	0.0	17.8	100	1.22	**7**	100	100	5	5	10.3	0.6	0.6	-3	146	732	153	36	103	253	26
LH4c	326500	816740	077AE	0.0	21.0	100	1.48	**7**	100	100	5	5	10.3	0.6	0.6	-3	137	726	123	30	103	253	26
LH5a	327480	818940	09E8C	0.0	23.1	100	4.91	**21**	100	100	5	5	10.3	1.8	1.8	2	146	742	72	17	103	253	26
LH5b	327980	818940	077B2	0.0	11.1	100	1.20	**11**	96	96	5	5	10.3	0.6	0.6	-3	260	731	64	17	103	253	26
LH5c	327980	818440	09E8E	0.0	18.9	100	2.01	**11**	100	100	5	5	10.3	0.6	0.6	-3	157	689	112	25	103	253	26
LH5d	327980	817940	09E90	0.0	18.1	100	2.21	**12**	100	100	4	5	10.3	0.6	0.6	-3	102	666	76	20	103	253	26
LH6a	329725	821950	09EA6	0.0	21.1	100	2.44	**12**	0	0	3	5	10.3	1.8	1.8	2	50	624	94	19	88	214	22
LH6b	330225	821950	09EA4	0.0	19.5	100	2.36	**12**	0	0	3	5	10.3	1.8	1.8	2	352	616	100	24	101	266	22
LH6c	330225	821450	09EA2	0.5	18.5	97	1.02	**5**	0	0	4	5	10.3	1.8	1.8	2	137	637	57	15	101	266	22

Table A1.3 Example of field verification recording sheet.

<table>
<tr><td colspan="2">Ladder Hills Peat Erosion Study - Field Survey Data</td><td>A J Nolan and S Chapman, 11-08-08</td></tr>
<tr><td>Sample Area: 5.1</td><td>Sample Point: LH001</td><td>GPS GR: 327810 817890</td></tr>
<tr><td colspan="3">Photographs (with signboard): = Number 1 (looking NNE)</td></tr>
<tr><td colspan="3">Ground Truth related to Image Classification (bare mineral, bare peat, grey/pink/ green/shadow tones, depth of eroded peat, width of eroded banks in shadow, etc.)</td></tr>
<tr><td colspan="3">Bare grey slaty mineral in foreground, bare eroded peat (mid-distance) with some re-distributed peat 'flats' and un-eroded banks</td></tr>
<tr><td colspan="3">Veg type (NVC, species/cover, condition of dwarf shrubs, moss cover and spp.)</td></tr>
<tr><td colspan="3">Calluna-Eriophorum mire (lichen-rich) M19c</td></tr>
<tr><td colspan="3">Topography (slopes, patterns of erosion related to ground features, break points, etc.)</td></tr>
<tr><td colspan="3">Relatively level area - most of the erosion taking place on this broad 'saddle' of the ridge. Bare eroded peat surfaces predominant. Peat depth around 1.5-2.0 m</td></tr>
<tr><td colspan="3">Impacts (animal presence, tracks, dung, wallows, sheep/deer scrapes, human impacts, burning, ditching, Light/Moderate/Heavy impact assessment (MacDonald, et al.)</td></tr>
<tr><td colspan="3">Few signs of animal or human impact. Very occasional sheep, hares relatively frequent, no burning. Overall impact = Light</td></tr>
<tr><td colspan="3">Apparent state of erosion (active, increasing or decreasing, is grazing limiting recovery?)</td></tr>
<tr><td colspan="3">Peat erosion active and in an advanced state. This would appear to be largely climatically-induced - rainfall, wind and frost. Grazing not limiting recovery</td></tr>
<tr><td colspan="3">Summary notes (restoration potential and methods to promote this, etc.)</td></tr>
<tr><td colspan="3">Very little re-vegetation evident, apart from occasional areas of former peat banks dominated by Empetrum nigrum. Erosion continuing to mineral base</td></tr>
</table>

Table A1.4 Ladder Hills field data collection 11-08-08 (A J Nolan and S Chapman) - photograph reference index. The photographs are presented in table A1.5.

Photo	Grid Reference		Sample	Sample Point	Description
Number	Northing	Easting	Area		
1	327810	817890	5.1	LH001-NNE	See field data recording sheet
2	327824	817924	5.1	LH002-NNE	See field data recording sheet
3	327855	817910	5.1	LH003-NNE	See field data recording sheet
4	327875	817930	5.1	LH004-NNW	See field data recording sheet
5	327875	817932	5.1	LH004-Close-up	Close-up of re-vegetation
6	327835	817930	5.1	LH005-NNW	See field data recording sheet
7	327826	817975	5.1	LH006-E	See field data recording sheet
8	327825	817976	5.1	LH006-N	See field data recording sheet
9	327825	817974	5.1	LH006-S	See field data recording sheet
10	327824	817975	5.1	LH006-W	See field data recording sheet
11	327840	818080	N of 5.1	LH007-N	See field data recording sheet
12	327846	818116	N of 5.1	LH008-N	See field data recording sheet
13	327638	818822	SE of 5.3	LH009-NW	See field data recording sheet
14	327600	818848	SE of 5.3	LH010-NE	See field data recording sheet
15	327545	818905	5.3	LH011-SSE	See field data recording sheet
16	327510	818950	5.3	LH012-NW	See field data recording sheet
17	327480	818950	5.3	LH013-N	See field data recording sheet
18	327481	818951	5.3	LH013-NE	See field data recording sheet
19	327479	818951	5.3	LH013-NW	See field data recording sheet
20	327432	818943	5.3	LH014-NW	See field data recording sheet
21	327425	818966	5.3	LH015-E	See field data recording sheet
22	327426	818965	5.3	LH015-SE	See field data recording sheet
23	327384	818938	W of 5.3	LH016-SW	See field data recording sheet
24	326406	816832	4	LH017-E	See field data recording sheet
25	326407	816833	4	LH017-Steve	See field data recording sheet
26	326407	816831	4	LH017-SE	See field data recording sheet
27	326407	816830	4	LH017-Surface	See field data recording sheet
28	326407	816829	4	LH017-Close-up	See field data recording sheet
29	326382	816791	4	LH018-S	See field data recording sheet
30	326371	816755	4	LH019-SE	See field data recording sheet
31	325417	815585	3.1	LH020-N	See field data recording sheet
32	325417	815587	3.1	LH-020-Close-up	Close-up of peat surface
33	325448	815575	3.1	LH021-E	See field data recording sheet
34	325459	815540	3.1	LH022-N	See field data recording sheet
35	327700	817900	5.1	General A1a	Distance view of A 5.1 from E
36	327700	817800	5.1	General A1b	Distance view of A 5.1 from E
37	327900	818200	5.1	General A1c	Distance view of A 5.1 from N
38	327800	818200	5.1	General A1d	Distance view of A 5.1 from N
39	327700	818000	5.1	General A1e	Distance view of A 5.1 from E
40	327300	818800	5.3	General A2a	Eroded peat surface
41	327300	818810	5.3	General A2b	Eroded with Steve Chapman
42	326400	816800	4	General A4a	General photo of Area 4
43	326410	816800	4	General A4b	With *E. nigrum* re-vegetation
44	325450	815520	3.1	General A5a	Extensive peat erosion
45	325450	815500	3.1	General A5b	Extensive peat erosion
46	325800	815800	3.2	General A6	General photo of Area 3.2
47	327200	818800		General re-veg1	*Calluna, Erio. vag.* and *Rubus cham.*
48	327200	818802		General re-veg2	Close-up of vegetation
49	326900	818400		General re-veg3	Erosion and re-vegetation
50	326900	818300		General re-veg4	Erosion and re-vegetation
51	325700	816300		General re-veg5	*Calluna* and *Des. flex.* re-vegetation
52	325200	815100		General re-veg6	*E. nig.* re-vegetated channed
53	325180	815100		General re-veg7	*Calluna* and *Emp. nig.* re-vegetation
54	325160	815100		General re-veg8	*Calluna and Emp. nig.* re-vegetation
55	325140	815100		General re-veg9	*Calluna and Emp. nig.* re-vegetation
56	325120	815100		General ReBrPt	Reddish brown peat surface

Table A1.5 Ladder Hills field data collection 11-08-08 (A J Nolan and S Chapman) – Ladder Hills site photographs.

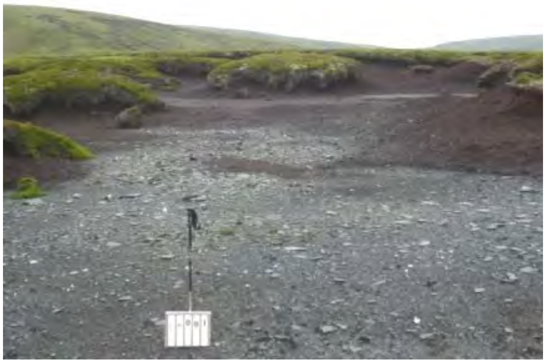


Photo 1

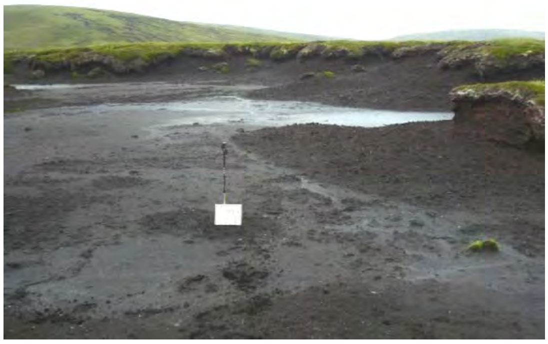


Photo 2

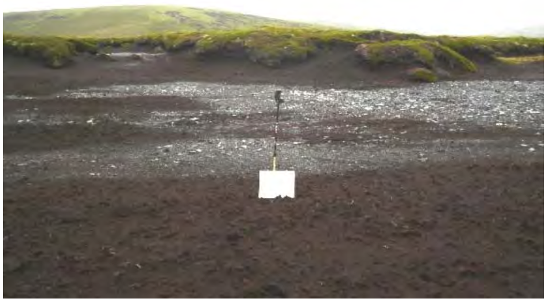


Photo 3

Photo 4

Photo 5

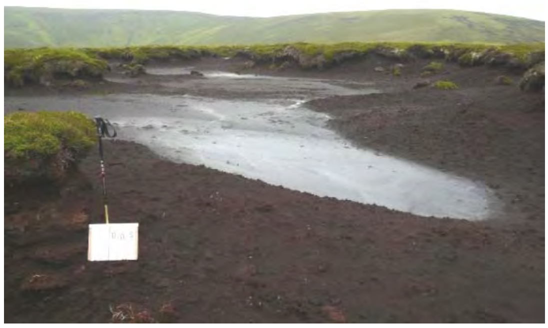


Photo 6

Photo 7

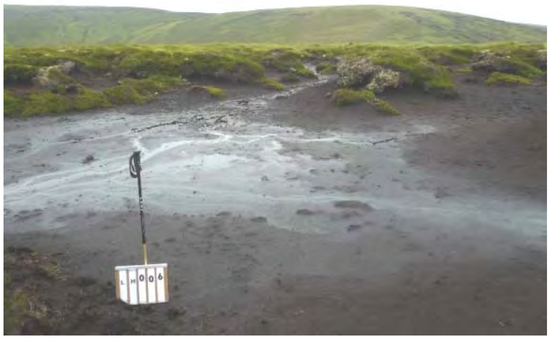


Photo 8

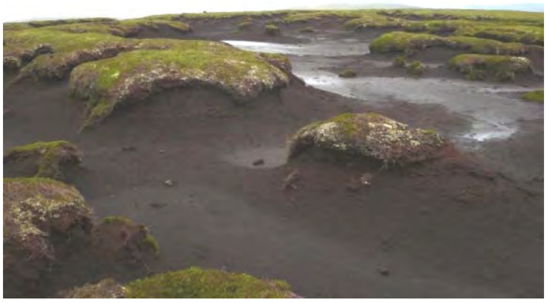


Photo 9

Photo 10

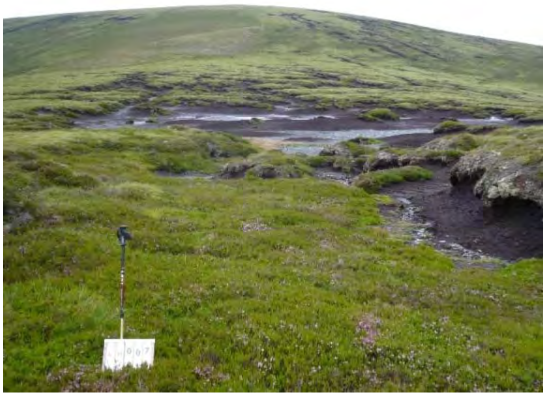
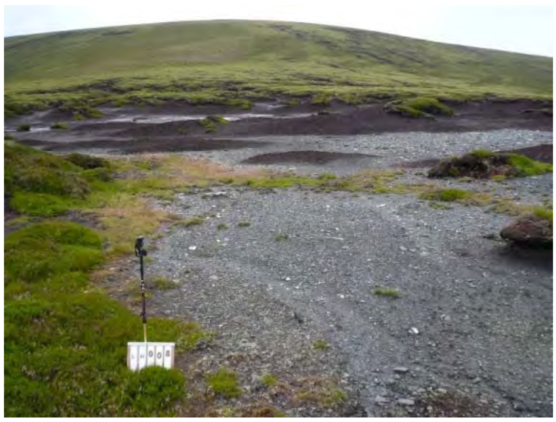


Photo 11



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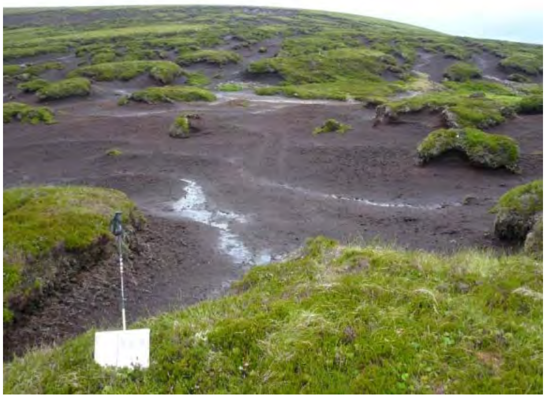


Photo 13

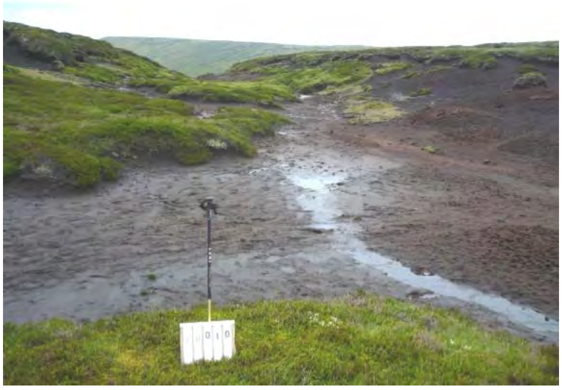
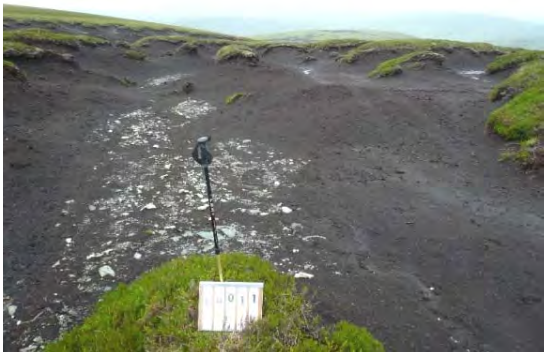


Photo 14



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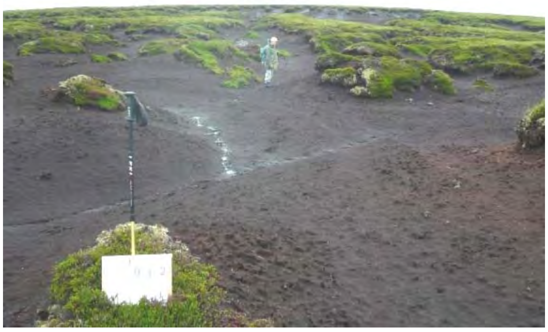

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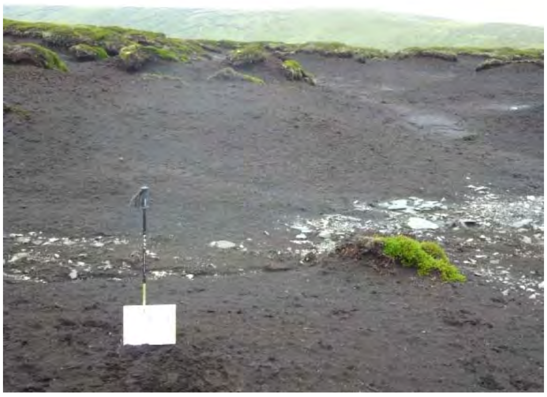
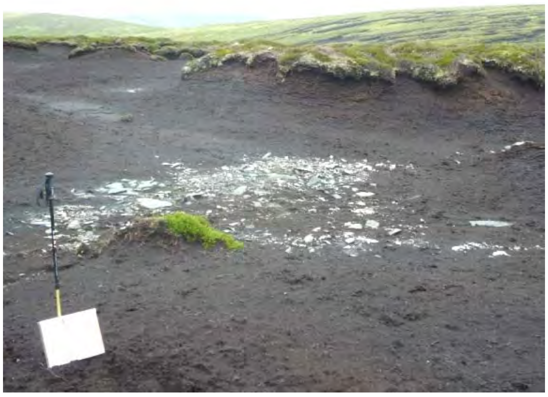


Photo 17



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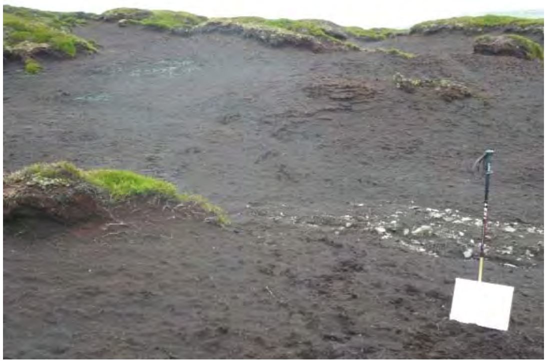

Photo 19

Photo 20

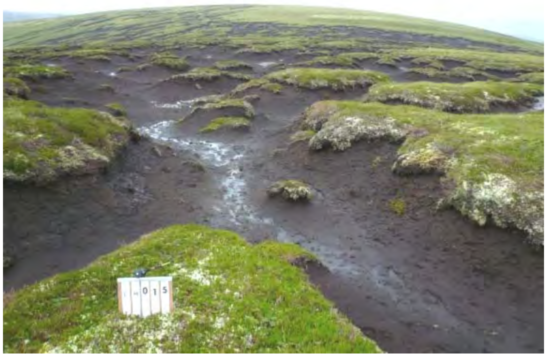

Photo 21

Photo 22

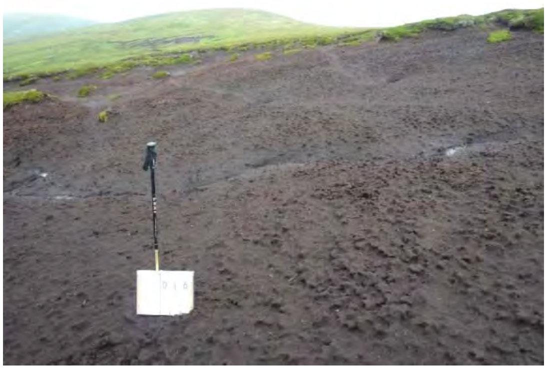

Photo 23

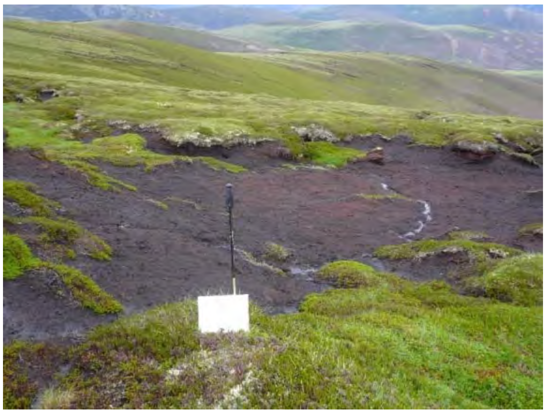

Photo 24

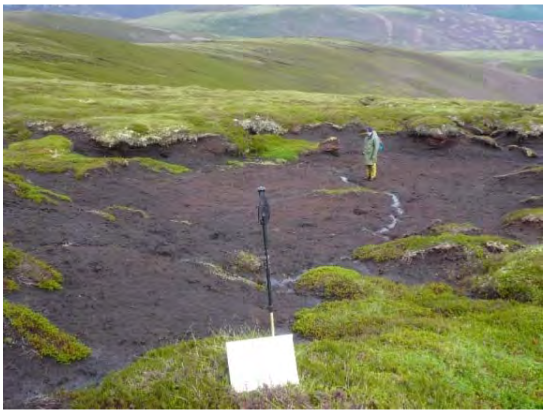

Photo 25

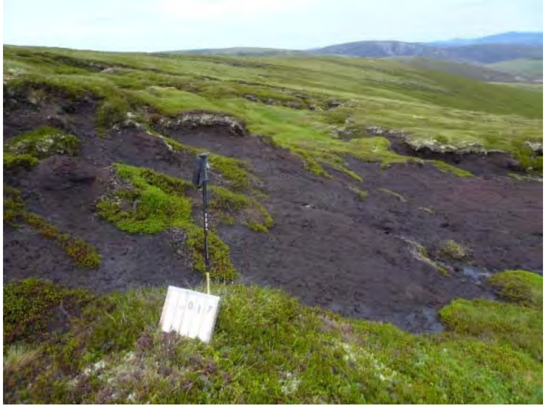

Photo 26

Photo 27

Photo 28

Photo 29

Photo 30


Photo 31

Photo 32


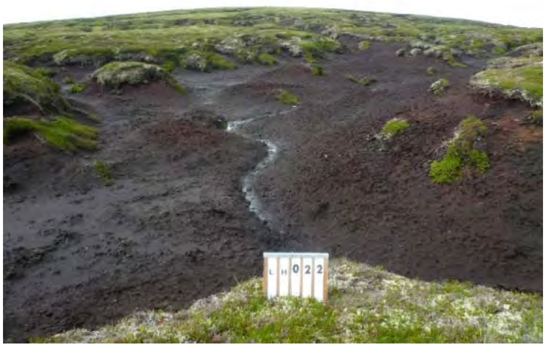

Photo 33

Photo 34


Photo 35

Photo 36


Photo 37


Photo 38


Photo 39

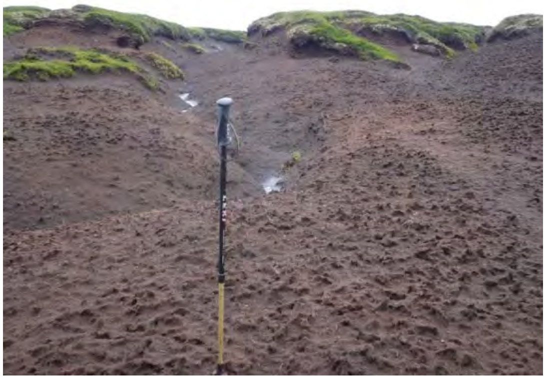
Photo 40


Photo 41


Photo 42

Photo 43

Photo 44

Photo 45

Photo 46

Photo 47

Photo 48

Photo 49

Photo 50

Photo 51

Photo 52

Photo 53

Photo 54

Photo 55

Photo 56

Table A1.6 Imagery examined for assessing the practicality of detecting changes in erosion.

Source	Year	Photo references		
Monadhliath SSSI		*North-east*	*Central*	*South-west*
OS[1]	1963	63.110.110 to 112	-	(1977) 77.041.083 to 086
SDD[2]	1989	22.89.143 to 145	14.89.184 to 186	20.88.089 to 093
GetMapping	2004-05	By OS grid ref.		
Ladder Hills SSSI				
-	pre-1989	N.A.		
SDD[2]	1989	64.88.090 to 091		
GetMapping	2006	By OS grid ref.		
Grudie Peatlands SSSI				
OS[1]	1976	76.206.132		
SDD[2]	1989	53.89.139 to 140		
GetMapping	2004	By OS grid ref.		

[1] *Crown copyright*
[2] *SDD Crown Copyright Scottish Office CRU*

APPENDIX 2: MONADHLIATH SITE DATA

Table A2.1 Groups of sites, locations and OS grid references of component sample squares in the Monadhliath study area.

		Sample square A		B		C		D		E		F		G		H		
Site group	Location	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Notes
M1	Beinn Mhonicag ridge, Meall an Driuchain Ridge, Coire Ceirsle Hill	228878	785254	226305	786391	225805	786391	224704	785612	224204	785492							Three sites on summits/ridges
M2	Meall a' Chaorainn Mor	248483	791403	248983	791683	248983	792183	247460	792070	247460	792570	247240	793070	246740	793070	246740	793570	Two sites, one completely within SSSI, one partially within
M3	Carn Ban, Lochan Uisge, Gleann Ballach	263048	803975	263288	804475	262788	804475	263668	804975	263168	804975	264090	802790	264370	802290			Two sites - one on gentle/moderate slopes of plateau, one on moderate slopes above stream

Table A2.2 The proportions (%) of peat vegetation (LCS88) in 0.25 km² sample squares in the Monadhliath study area that were classified as bare peat soil and the associated published data for potential drivers of erosion.

Sample square	OS easting	OS northing	Image ref	Non-eroded peat vegetation area from LCS88 (ha)	Eroded peat vegetation area from LCS88 (ha)	Eroded vegetation as % of total peat vegetation	Area of bare peat from imagery (ha)	**Bare peat as % of total peat vegetation**	% of area in SAC	% of area in SSSI	Exposure index	Frost index	Red deer density (mean no. per km 1987-02)	Sheep density no.per ha 1986	Sheep density no.per ha 2006	% change in sheep density	Aspect	Altitude (m) Mean	Altitude (m) Range	Altitude (m) STD	Mean monthly rainfall (mm)	Max. monthly rainfall (mm)	Min. monthly rainfall (mm)
M1a	228878	785254	B_8431I_1	0	8.2	100	0.16	**2**	0	100	3	4	16.0	0.5	0.4	-15	206	468	98	19	149	289	57
M1b	226305	786391	B_8431I_2	0	21.2	100	0.94	**4**	0	95	4	4	16.0	0.5	0.4	-15	86	530	86	19	149	289	57
M1c	225805	786391	B_8431I_3	0	20.4	100	0.73	**4**	0	23	4	4	16.0	0.5	0.4	-15	322	538	80	20	149	289	57
M1d	224704	785612	B_8431I_4	0	25.0	100	0.46	**2**	0	22	4	4	16.0	0.5	0.4	-15	214	574	78	18	152	292	58
M1e	224204	785492	B_8431I_5	0	25.0	100	0.23	**1**	0	0	3	4	16.0	0.5	0.4	-15	302	511	99	24	152	292	58
M2a	248483	791403	B_8431I_6	0	12.5	100	1.42	**11**	100	100	5	6	16.0	0.3	0.2	-28	347	865	73	22	150	280	66
M2b	248983	791683	B_8431I_7	0	11.3	100	1.21	**11**	100	100	5	6	16.0	0.3	0.2	-28	347	827	83	24	150	280	66
M2c	248983	792183	B_8431I_8	0	3.1	100	0.83	**27**	100	100	4	5	16.0	0.3	0.2	-28	170	670	180	43	150	280	66
M2d	247460	792070	B_8431I_9	0	5.2[a]	100	1.57	**30**[a]	40	40	4	5	16.0	0.3	0.2	-28	40	620	101	25	150	280	66
M2e	247460	792570	B_8431I_10	0	13.9	100	0.25	**2**	18	18	4	5	16.0	0.3	0.2	-28	25	549	123	28	150	280	66
M2f	247240	793070	B_8431I_11	0	12.1	100	0.52	**4**	0	0	4	5	16.0	0.3	0.2	-28	308	501	50	12	150	280	66
M2g	246740	793070	B_8431I_12	0	10.5	100	0.49	**5**	0	0	4	5	16.0	0.3	0.2	-28	35	488	90	21	150	280	66
M2h	246740	793570	B_8431I_13	0	25.0	100	2.38	**10**	0	0	3	5	16.0	0.3	0.2	-28	317	465	30	7	150	280	66
M3a	263048	803975	B_8431I_14	0	19.8	100	1.10	**6**	100	100	4	5	14.6	0.4	0.2	-49	338	820	67	16	124	204	63
M3b	263288	804475	B_8431I_15	0	6.8	100	1.84	**27**	100	100	5	5	14.6	0.4	0.2	-49	310	807	47	10	124	204	63
M3c	262788	804475	B_8431I_16	0	6.2	100	1.10	**18**	100	100	4	5	14.6	0.5	0.3	-38	92	768	54	12	124	204	63
M3d	263668	804975	B_8431I_17	0	8.7	100	1.34	**15**	100	100	4	5	14.6	0.5	0.3	-38	19	819	31	6	124	204	63
M3e	263168	804975	B_8431I_18	0	1.4	100	1.34	**96**	100	100	4	5	14.6	0.5	0.3	-38	295	781	48	13	124	204	63
M3f	264090	802790	B_8431I_19	0	17.4	100	0.96	**6**	100	100	5	6	14.6	0.4	0.2	-49	230	640	58	11	124	204	63
M3g	264370	802290	B_8431I_20	0	21.7	100	0.38	**2**	100	100	5	5	14.6	0.4	0.2	-49	116	610	66	14	124	204	63

[a] *In LCS88, vegetation recorded as sub-montane in LCS88 with eroded peatland as secondary component. Figure is visual estimate of peatland component only, using original imagery*

APPENDIX 3: GRUDIE REGION / KNOCKFIN HEIGHTS SITE DATA

Table A3.1 Sites, locations and OS grid references of component sample squares in the Grudie/Knockfin Heights study area.

		Sample square															
		A		B		C		D		E		F		G		H	
Site	Location	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing
Grudie	Flanks of ridge SE of Cnoc nan Imrichean	249700	909400	250200	909400	250200	908900										
Beinn Sgreamhaidh	N-facing slope above middle reaches of Allt Cer burn	244750	916650	245250	916650	244750	916150	245250	916150	245750	916400						
Srath an Loin	Upper catchment of Allt Cer burn. Mostly S-facing slopes	242130	918760	242130	918260	242630	918260	243130	918260	242130	917760	242630	917760	243130	917760	242130	917260
Knockfin Heights	Mostly flat pool systems on summit plateau	291700	934900	292200	934900	291700	934400	292200	934400								

Table A3.2 The proportions (%) of peat vegetation (LCS88) in 0.25 km^2 sample squares in the Grudie/Knockfin study area that were classified as bare peat soil and the associated published data for potential drivers of erosion.

Key: G – Grudie, BS – Beinn Sgreamhaidh, SaL – Srath an Loin, K – Knockfin Heights

Sample square ref.	OS easting	OS northing	Image ref	Non-eroded peat vegetation area from LCS88 (ha)	Eroded peat vegetation area from LCS88 (ha)	Eroded vegetation as % of total peat vegetation	Area of bare peat from imagery (ha)	**Bare peat as % of total peat vegetation**	% of area in SSSI (also SAC)	Exposure index	Frost index	Red deer density (mean no. per km 1987-02)	Sheep density no.per ha 1986	Sheep density no.per ha 2006	% change in sheep density	Altitude (m) Mean	Altitude (m) Range	Altitude (m) STD	Mean monthly rainfall (mm)	Max. monthly rainfall (mm)	Min. monthly rainfall (mm)
G1	249700	909400	B_8916I_1	19.6	2.2	12	3.0	14	100	3	4	10.3	0.42	0.35	16	338	32	5	105	172	52
G2	250200	909400	B_8916I_2	24.6	0.0	4	1.0	4	100	4	4	10.3	0.42	0.35	16	326	48	13	103	175	52
G3	250200	908900	B_8916I_3	25.0	0.0	8	2.0	8	100	3	4	10.3	0.42	0.35	16	338	21	4	103	175	52
BS1	244750	916650	B_8916I_4	25.0	0.0	5	1.2	5	100	3	4	10.3	0.42	0.35	16	256	54	14	131	232	56
BS2	245250	916650	B_8916I_5	25.0	0.0	3	0.8	3	100	3	4	10.3	0.42	0.35	16	257	64	16	143	239	65
BS3	244750	916150	B_8916I_6	17.0	0.0	4	1.0	6	100	3	4	10.3	0.42	0.35	16	292	39	8	131	232	56
BS4	245250	916150	B_8916I_7	25.0	0.0	5	1.3	5	100	3	4	10.3	0.42	0.35	16	289	44	9	143	239	65
BS5	245750	916400	B_8916I_8	25.0	0.0	4	1.0	4	100	3	3	10.3	0.42	0.35	16	254	50	11	143	239	65
SaL1	242130	918760	B_8916I_9	7.4	17.6	5	1.2	5	100	3	4	10.3	0.42	0.35	16	327	34	8	131	232	56
SaL2	242130	918260	B_8916I_10	24.2	0.0	4	1.1	4	100	3	4	10.3	0.42	0.35	16	298	34	9	131	232	56
SaL3	242630	918260	B_8916I_11	15.4	9.6	4	1.1	4	100	3	4	10.3	0.42	0.35	16	297	36	10	131	232	56
SaL4	243130	918260	B_8916I_12	18.9	6.1	4	0.9	4	100	3	4	10.3	0.42	0.35	16	293	32	7	131	232	56
SaL5	242130	917760	B_8916I_13	22.0	0.0	4	1.0	5[a]	100	3	4	10.3	0.42	0.35	16	285	59	13	131	232	56
SaL6	242630	917760	B_8916I_14	20.1	0.0	4	0.9	5	100	3	4	10.3	0.42	0.35	16	268	23	7	131	232	56
SaL7	243130	917760	B_8916I_15	25.0	0.0	17	4.3	17	100	3	4	10.3	0.42	0.35	16	270	24	7	131	232	56
SaL8	242130	917260	B_8916I_16	24.0	0.0	10	2.5	11[a]	100	3	4	10.3	0.42	0.35	16	299	69	18	131	232	56
K1	291700	934900	B_8916I_17	25.0	0.0	15	3.7	15	100	4	4	9.1	0.39	0.28	27	420	22	5	95	141	54
K2	292200	934900	B_8916I_18	25.0	0.0	37	9.1	37	100	4	4	9.1	0.39	0.28	27	430	14	3	95	141	54
K3	291700	934400	B_8916I_19	25.0	0.0	11	2.7	11	100	4	4	9.1	0.39	0.28	27	419	30	7	95	141	54
K4	292200	934400	B_8916I_20	25.0	0.0	37	9.1	37	100	4	4	9.1	0.39	0.28	27	431	12	2	95	141	54

[a] *In LCS88, vegetation recorded as 'sub-montane' with eroded peatland as secondary component. Figure is visual estimate of peatland component only, using original imagery*

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