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CRANFIELD UNIVERSITY AT SILSOE

Submitted for the degree of Ph.D. 2000

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**EXTENT, CAUSES AND RATES OF UPLAND
SOIL EROSION IN ENGLAND AND WALES**

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Extent, causes and rates of upland soil erosion in England and Wales

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August 2000

The uplands of England and Wales are internationally important for nature conservation and are prized nationally for their landscape, recreational and cultural value. Reflecting this status, recent appeals have prompted fundamental research into degradation of the upland habitat. This work was instigated as part of that research to determine the current extent, causes and rates of upland degraded soil.

The research was based principally upon a statistically robust and objective selection of 399 field sites. Erosion extent and condition were recorded and related to morphology, environment and management conditions within both field sites and sub-catchments. The short-term rate of soil loss was determined through the completion of cross-sectional traverses on erosion gullies in 1997 and in 1999. Longer-term variations in the extent and causes of upland erosion were established through the interpretation of aerial photographs taken between 1946 and 1989.

Erosion measured on field sites in 1999 was estimated to represent 24 566 ha and 0.284 km³ in upland England and Wales. Of this, 18 025 ha and 0.242 km³ was attributed to water erosion, which included large-scale blanket peat degradation. Biotic factors accounted for 6 541 ha and 0.041 km³ of erosion, evident on 68% of eroded field sites. Wind was a negligible contributor to upland erosion.

Upland eroded area in England and Wales increased by over 518 ha between 1997 and 1999: humans and animals were responsible for 99.9% of this increase. Within the last half-century, the creation and perpetuation of erosion was also principally due to humans and animals. Water-eroded features on both peat and mineral soils showed stabilisation and revegetation throughout the same period.

These results expose the highly degraded state of the upland environment and the alarming rate at which erosion is proceeding. The implications of this erosion and proposals for mitigation policies are discussed.

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and to the memory of my much-missed father, Johnny.

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Chapter 1

Accelerated soil erosion in the uplands of England and Wales: an overview

1.1 INTRODUCTION

The uplands of England and Wales are of international importance for nature conservation (Thompson *et al.*, 1995) and are prized nationally for their landscape, recreational and cultural value. In addition, they provide economic support to agriculture, field sports and tourism. Currently there is concern that excessive areas of the uplands are eroded, and that more land is at risk of accelerated soil loss (Evans, 1990a) because of the sensitivity of this marginal environment to intense agriculture and recreational use (Morgan, 1995).

At present it is impossible to distinguish erosional trends or the differences between natural and human-induced processes or between contemporary and historical degradation (Evans, 1997; Evans and Felton, 1987; Warburton, 1998b). Although previous studies have specifically addressed upland erosion (Evans, 1974, 1990b; Grieve *et al.*, 1995; Phillips *et al.*, 1980) the lack of fundamental data on upland soil degradation prompted recommendations for research from the Royal Commission on Environmental Pollution (RCEP, 1996).

In this research, the present-day and historical erosional activity of the English and Welsh uplands are investigated. The basic concepts of the upland environment and of accelerated soil erosion are introduced in this chapter, including, in Section 1.2, the history of upland settlement and agriculture and the current levels of agricultural and amenity use in the uplands. In Section 1.3, accelerated soil erosion is distinguished from natural soil degradation using examples of the most common features of erosion found in the uplands. The research objectives are then defined, and followed by a description of the thesis contents.

1.2 THE UPLANDS OF ENGLAND AND WALES

The vegetation communities of upland England and Wales are defined by several factors, including the underlying upland soils. These communities are shaped further by the harsh upland climate and by centuries of upland farming. The existing landscape, however, represents only one stage in an ongoing process; the evolution of a landscape by environmental and anthropogenic factors.

1.2.1 The history of the upland environment

Until 5000 years ago, the landscapes of England and Wales were dominated by mixed deciduous and pine forests (Evans, 1975; Rackham, 1976; Warburton, 1998a). Heath was confined to where the combination of poor soils and wind exposure provided conditions unsuitable for tree growth.

Gradually, the forests were cleared for hunting and agriculture by Neolithic man, who had first arrived between 5000 and 6000 BC, and then by mid-Mesolithic man (Warburton, 1998a). By repeatedly clearing forests to carry out cultivation of the organic-rich forest floor, permanent grasslands developed (Mitchell and Ryan, 1997). At the same time as this land clearance by the first farmers, an outbreak of Dutch Elm disease destroyed swathes of elm-rich virgin forests in both Ireland and Britain, aiding Neolithic forest-clearance.

Until c. 1000 BP, agricultural communities had comparatively little impact on the environment: thereafter, there was rapid and permanent deforestation (Macklin *et al.*, 2000). The removal of forests, along with the cooler wetter climate of the early Middle Ages, allowed the area of heath to expand (Hester, 1996). Further clearance initiated after the Norse invasion allowed local erosion rates to increase in the North of England (Harvey *et al.*, 1981; Pennington *et al.*, 1976; Tallis, 1985a). Both the Romans and later the Saxons destroyed large tracts of woodland, finally turning the country into an agricultural and pastoral one (Tansley, 1949). At the end of the seventeenth century, the estimated cover of heath, moor and mountain land was only 25% of the total land in England and Wales (Tansley, 1949).

Intensive sheep farming was first promoted in Britain at the time of monastic expansion in the 12th century (Orr, 2000). The development of large tracts of upland

dominated by *Calluna* is also associated with extensive grazing. Burning to encourage young stands of *Calluna* was pioneered by the Cistercians (Maltby, 1980).

In the Middle Ages and again under the Tudors, the area devoted to sheep increased with the rise of the great export trade in wool and cloth. This extension of grassland for sheep pasture was at the further expense of woodland (Environment Agency (EA), 1999) and the decline in native tree cover continued until the present century (RCEP, 1996).

In the last 1000 years the intensity of upland agriculture has continued, and has culminated in the 20th century in increased mechanisation, land drainage schemes and further increases in hill-farm stocking rates, leading to a monoculture of intensive sheep farming. While farm subsidies had been introduced as early as the 1930s (EA, 1999), the first hill-farming headage payments were made in 1947 (RCEP, 1996), and in the 1960s the range of financial sources available increased again (EA, 1999). Today, farmers can claim subsidies from the Sheep Annual Premium Scheme (SAPS) and the Hill Livestock Compensatory Allowance (HLCA) which both encourage the maximising of stock numbers (EA, 1999; Harvey, 1997; Phillips *et al.*, 1981).

The associated increases in sheep flock sizes have been impressive: sheep numbers in Bleasdale rose from 5500 in 1895 to 8500 in 1970, before a dramatic rise to over 15 000 animals between 1970 and 1988 (Mackay and Tallis, 1996). Since the 1940s, the number of sheep in both the Peak District and Wales has trebled. Between 1980 and 1993 alone, the number of sheep in Britain rose by 40% (Fuller and Gough, 1999; RCEP, 1996; National Sheep Association (NSA), 1995). In 1993, EC member states acquired optional powers to impose environmental restrictions on headage payments, designed to control stock numbers. In spite of these, and the implementation of the Moorland Scheme where farmers are paid to remove upland stock, stocking levels in the uplands remain at an all time high. In the Medieval period, there were eight million sheep in Britain: by 1940, this number had increased to twelve million. Today there are 44 million sheep in Britain, 70% of which are confined to the uplands (NSA, 1995). This proportion rises to 85 and 88% in Scotland and Wales respectively (EA, 1999). At the same time as these

increases, the number of people employed in farming has decreased. In particular, pre-war ratios of shepherds to sheep were 1:2-3000 compared with the current ratio of 1:12-15000 (EA, 1999).

1.2.2 The extent of the uplands

No generally accepted figure for the upland area of England and Wales exists (Bunce, 1987) because the range of latitude in Britain means that sea level in Cornwall supports lowland vegetation while upland vegetation is found at the same altitude in Scotland. The extent of upland, an environmental definition, is therefore frequently inferred from vegetation composition (Bunce, 1987). Mitchell and Ryan (1997) defined the uplands as areas above 150 m that were often covered by blanket bog but also differentiated between the uplands, lowlands and wetlands in terms of their vegetation and use.

The Institute of Terrestrial Ecology (ITE) defined the extent of upland ecosystem in Britain using the basic upland area, as defined by high rainfall, low evapotranspiration, low insolation and generally poor soils. Within that area, vegetation of upland character was separated from the agricultural grasslands of lowland species that exist in the uplands on improved pastures (Bunce, 1987). In this way, the overall extent of upland within Great Britain (Scotland, England and Wales) was established at between 23% (Bunce, 1987) and 25% (Thompson *et al.*, 1987). The area of ground in Britain above 300 m was estimated at 30% by Orr (2000).

1.2.3 Upland soils

Patterns of upland soils in England and Wales are described by Findlay *et al.* (1984), Jarvis *et al.* (1984), Ragg *et al.* (1984) and Rudeforth *et al.* (1984), with soil classes described by Avery (1980). The following is summarised from Harrod *et al.* (2000).

In the cool, wet climate of the uplands *raw peat soils*, thicker than 40 cm, cover much of the highest ground. Over much of Wales *stagnopodzols*, with peaty surfaces up to 40 cm thick, gleyed and bleached subsurface horizons and frequently a thin iron pan over ochreous subsoils, flank the blanket peat. At lower altitudes, and often on steep slopes, stagnopodzols are replaced by *brown podzolic soils* with ochreous (red/orange pigmented) subsoils, but lacking other podzolic features. In

large parts of the Pennines, *surface-water gley soils* form over impermeable, less acidic parent materials. In the wetter sites *stagnohumic gley soils* have organic tops which can merge laterally into the thicker blanket peat, but in drier localities the surface peaty horizons are thin and, where replaced by mineral topsoils, give way to *stagnogley soils*.

Some diversity is added to the overall soil patterns in basins, at extremes of altitude and slope and on distinctive parent materials: examples include peat soils, groundwater gley soils and surface-water gley soils in valley floors and basins. At low altitudes or on base-rich parent materials such as some Pennine limestones and the West Dartmoor metadolerite, the widespread peat, podzolic and surface-water gley soils are replaced by freely drained *brown earths*. Over very hard rocks soil profiles are attenuated giving *rankers* (less than 30 cm of soil) or scree and rock outcrops. On the highest mountain tops intense frost action produces patterned ground in mineral rock waste.

1.2.4 Soil distribution

With limited exceptions (Furness and King, 1972; Hartnup, 1987; Hogan and Harrod, 1982), detailed soil maps are not available for the uplands. Understanding of the relationships between soil patterns and landscape comes from the 1:250,000 Soil Map of England and Wales and the accompanying Soil Survey Bulletins, e.g. Rudeforth *et al.* (1984). The list of soil associations in Table 1.1 is based on the legend of that map (Mackney *et al.*, 1983), supplemented by percentages for each upland soil subgroup. The percentages are derived from the National Soil Inventory, where soils were described systematically at 5 km intervals. Only sites with unequivocal soil profiles and upland heath, upland grass, montane or bog vegetation were accounted for. Intergrades, minor soil groups and subgroups were omitted and hence the total percentage equals 82%. Omissions include brown earths (5% of the upland NSI), other podzols (5%), groundwater gley soils (2%), stagnogley soils (2%) and brown rankers (1.5%). The upland NSI, with a population of 399 field sites, represents about 10,000 km².

1.2.5 Soils and upland vegetation

Blanket bog, dominated by *Eriophorum* spp. (cotton grasses), *Molinia*, *Sphagnum* mosses, cross-leaved heath (*Erica tetralix*) and deer grass (*Trichophorum*

cespitosum), covers most of the raw peat soils. In drier regions such as the North York Moors, bog heather moor can be present. Bog moss water track develops in flushed sites.

Vegetation on stagnohumic gley soils and stagnopodzols varies between heather moorland, when grazing pressure is relatively light, and *Molinia* moorland or *Nardus* grassland when grazing or burning intensity is high. Partly reverted, rushy moorland is evidence of attempts at agricultural improvement of these soils.

Freely draining acid soils, including brown podzolic soils on steep valley sides, carry bent-fescue (*Agrostis-Festuca*) grassland, often with stands of bracken (*Pteridium aquilinum*) and gorse (*Ulex* spp.). Where grazing pressure is light, heather (*Calluna vulgaris*) and bilberry (*Vaccinium myrtillus*) moor is common, and *Nardus* grassland develops in eastern regions. Old deciduous woodland provides locally important diversity around the upland fringes in sheltered sites.

Parent material base-status influences the vegetation communities that develop on the shallow profiles of rankers. Bangor soils on acid igneous rocks in Wales and the North of England support heather moor and *Nardus* grassland, while over limestone the Wetton Associations carry herb-rich grassland with *Sesleria* or *Agrostis-Festuca*. Deeper brown earths over limestone also provide herb-rich grassland in limited areas of the Pennines.

In the mountains, exposed summits support *Rhacomitrium* heath, while on inaccessible crags on base-rich rocks, alpine assemblages survive (Ragg *et al.*, 1984; Rudeforth *et al.*, 1984).

Table 1.1 Upland soil associations, approximate area of cover and principal locations within England and Wales after Avery (1980). Soil Associations refer to map units of Soil Map of England and Wales.

*Enclosed land included in areal total.

Soil group	Soil Association	Area (km ²)	% of upland NSI	Principal locations
Raw peat soils	Winter Hill	2,575	24	Pennines, Lake District, Northumberland
	Crowdy 1 & 2	813	6	Wales, SW England
Stagnohumic gley soils	Princetown	135	18	Dartmoor
	Onecote	414		Pennines, N York Moors
	Wilcocks 1 & 2	4,477*		Pennines, Wales
	Wenallt	237		S Wales
Stagnopodzols	Belmont	859	9	Pennines
	Hexworthy	370		SW England
	Maw	215		N Yorkshire
	Hafren	1,510	8	Wales
	Lydcott	283		S Wales
	Gelligaer	281		S Wales
Brown podzolic soils	Malvern	646*	5	Lake District, Snowdonia, Cheviots
	Moretonhampstead	550*		N Wales, Lake District, SW England
	Manod	5,354*		Wales, SW England, Lake District
	Withnell	664*	2	S Wales
	Parc	157*		SW Wales
	Moor Gate	379*		SW England, Wales
Podzols	Anglezarke	457	3	Pennines, Wales
Rankers	Revidge	103	7	Peak District
	Skiddaw	138		Lake District
	Wetton 1 & 2	298		Pennines
	Bangor	533		Lake District, Cheviots, Wales

1.3 FORMS OF UPLAND SOIL EROSION

Soil depletion is part of a natural geological cycle. Just as weathering of rocks creates soil in the first place, so the forces of water and wind act to expose, degrade and eventually remove soil. Accelerated erosion occurs when the rate of soil denudation and removal exceeds the pace of background, natural erosion. It is perpetuated when the protective surface vegetation is compromised or removed, and the soil is exposed to weathering (Evans, 1995; Imeson, 1974). In this section, the most common forms of accelerated upland erosion are described and their causes, where these have been established, are discussed.

1.3.1 Peat erosion

Peat is the highly organic soil formed by the partial decomposition of plant remains under high water and low oxygen conditions. The unconsolidated nature of peat makes it susceptible to movement by water or wind when it has dried out, and to compaction from walkers or grazers. Erosion in peat may begin as a gully or linear channel cut through the soil substrate by the accelerated movement of soil by water, but can develop into large-scale, hagged areas (Plate 1.1).

The peat erosion discussed here is historical peat degradation: evidence of the antiquity of this degradation has come from palaeostratigraphic cores taken from lakes and surviving bogs. The recent acceleration of peat erosion is considered to be entirely due to the activities of humans such as fire and peat cutting, and grazing animals and is considered in Section 1.3.3.

There are two forms of peat gully erosion. Type I erosion is found on sloping peat areas and is composed of nearly linear gullies that rarely produce bare peat exposures except on almost vertical gully sides. It is rarely found above 600 m (Bower, 1962; Mackay and Tallis, 1996). Summit, or Type II, erosion occurs on blanket peat on high, flat ground and consists of close set gullying of deep peat. Type II gullying results in exposure of the underlying mineral substrate and leaves only residual peat mounds or haggs (Bower, 1960; Burt *et al.*, 1998).

The origins of historical peat erosion remain uncertain although there are many theories. The coincidences of Type I dissection with pool and hummock topography suggested to Bower (1960) that gully erosion derived from natural causes. Alternatively, the movement of grazers across a peat bog could induce the breakdown of paths to result in Type I dissection (Radley, 1962; Ratcliffe and Oswald, 1988).

Extensive drainage of peat by subpeat pipe systems may induce erosion by creating devegetated peat surfaces that act as foci for subsequent erosion (Glaser and Janssens, 1986). Large and Hamilton (1991) associated large-scale peat erosion with slumping caused by river channels. Once established, stream retreat increased summit erosion, and resulted in total removal of peat. Cotton grass or wavy-hair grass may then recolonise the underlying mineral layer (Radley, 1962).

The mechanism of channelled erosion through peat bogs described by Mitchell and Ryan (1997) and Rudeforth *et al.* (1984) required an initial drying out of the bog surface to suspend peat growth and cause the channelling of excess runoff. The contemporary appearance of such eroded bogs is of a mosaic of deep channels dissecting the still continuous peat. Elsewhere, narrow channels show some mineral exposure and are surrounded by residual peat islands (Plate 1.1), while in a third area, mineral exposure dominates and isolated peat hags remain.

Peat erosion may be a natural endpoint to peat bog accumulation as its high water content, unconsolidated nature and the slopes over which it develops facilitate the onset of erosion (Aiton, 1805; Conway, 1954; Mackay and Tallis, 1996; McGee and Bradshaw, 1988; Moss, 1913; Tallis, 1985b). Alternatively, wind may initiate erosion on topographically uniform mires (Large and Hamilton, 1991; Radley, 1962). The increased air pollution that resulted from and after the onset of the Industrial Revolution is also suggested as a cause of erosion. With the death of *Sphagnum* on peat bogs, the water holding capacity of peat bogs falls and runoff and breakdown of the peat increase (Labadz *et al.*, 1991).

Bog bursts are described by Mitchell and Ryan (1997) as regular features of blanket bog development. Under conditions of high rainfall, the weight of peat on steep slopes may become sufficient to overcome its strength, causing the vegetation mat to tear. The lower peat may then undergo a thixotropic reversal to the liquid state before flowing out from under the upper, fibrous peat, carrying floes of vegetation with it. The association of bog bursts with waterlogging is supported by Large and Hamilton (1991).

1.3.2 Slope mass movements

Large- or intermediate-scale erosion on soils other than peat is considered here. Although soil creep, sheet erosion and slope failures are considered natural forms of erosion, the accelerated removal of vegetation by humans and animals also increases their rate of development (Plate 1.2; right).

Soil creep is the downward movement of soil under gravity, and is stimulated by various causes which move the soil, including wetting and drying, freeze thaw cycles

and bioturbation (Agafonov and Agafonov, 1998; Collard, 1988; Strahler and Strahler, 1989; Yamada, 1999). Heavy rainfall that induces large soil moisture changes and produces a near saturated soil condition also allows active soil creep (Agafonov and Agafonov, 1998). Terracettes are sometimes cited as evidence of soil creep accelerated by the passage of animals on steep slopes (Collard, 1988).

Soil creep may be measured in a number of ways; by using probes (Yamada, 1999), painting lines on the slope (Matsuoka, 1998) or using trees, rocks and other fixed reference points (Agafonov and Agafonov, 1998). The speed at which soil creep proceeds can be proportional to the number of frost heave cycles, the thickness of the layer of fine debris within the top 15 cm of sediment and the second power of the slope gradient (Matsuoka, 1998). In Britain, average surface rates of soil creep were estimated at 5 mm year⁻¹ (Collard, 1988).

Sheet erosion is the slow unchannelled removal of a thin soil layer from a slope (Kelley, 1990). It occurs on cleared land after the action of rain has broken down the soil aggregates and sealed the large soil pores. Overland flow can then proceed to remove the soil in uniform thin layers (Strahler and Strahler, 1989). The amount of soil involved is usually so slight that failure to notice the erosion is frequent (Kelley, 1990), until the topsoil is completely removed or greatly thinned (Strahler and Strahler, 1989). Instances of accelerated sheet erosion, aggravated by sheep overgrazing, were recorded by Thomas (1965) in the Plynlimon area of mid-Wales. There, heavy storms in areas of sheep scars (Section 1.3.3) resulted in the mass movement of soil to a maximum depth of up to one metre.

Slope failures occur on steep slopes that are vulnerable to erosion, such as on clays or sands. Deforestation followed by intensive rainfall events promotes erosion on these slopes (Evans, 1993). The creation of sheep scars on steep slopes may also act as foci for the initiation of scree chutes up to 25 m long (Thomas, 1965).

1.3.3 Erosion caused by grazing animals and by humans

The erosional effect of grazing animals on the landscape is the most contentious issue in the current debate on upland erosion. While sheep have been grazed in Britain since Neolithic times, recent increases mean they have reached the highest stocking intensities ever (Section 1.2.1). The other large herbivorous animals that

graze in the uplands, such as cattle, horses, ponies and goats, do not exist in numbers approaching those of sheep and their effects are not discussed here.

The severe erosional impacts of sheep overgrazing have been considered by a number of authors (Evans, 1977, 1997, 1998; Evans and Felton, 1987; Fenton, 1937; Harvey, 1997; Loxham, 1997; Rawes and Welch, 1966). The most frequent signs of intense sheep grazing include sheep scars and paths. As sheep shelter on hillslopes, often below a slope convexity, they may remove the surface vegetation to form an arc-shaped scar with a bare back wall and floor (Thomas, 1965). Sheep scars may extend to several metres in width although they more often remain as discreet scars and may even revegetate from the front as the back wall retreats. 'A' scars have a height to width ratio less than 1.5 while that of 'B' scars, which are actively eroding, is greater than 1.5 (Brunstrom, 1976; Evans, 1977). If the scar penetrates to unstable subsoil such as scree the eroding area can expand rapidly, and can produce an apron of redeposited material directly in front of and downslope of the scar (Plate 1.3). Otherwise, these bare patches actively erode through weathering and the breaking down of the scar backwall by sheep (Plate 1.2).

The influences of humans on the upland environment are principally restricted to the effects of recreational and agricultural use, although indirectly humans are also responsible for the erosion caused by grazing animals, particularly sheep. Human-induced erosion here refers to footpaths and tracks, land drainage and to machinery rutting and poaching. Poaching refers to the disruption, by humans, animals or by machinery, of a thin layer of the soil surface, usually under wet conditions when soil shear strength is reduced.

Most of the extensively eroded upland footpaths in England and Wales are within areas attractive to tourists. In the 20th century, amenity use of the uplands increased substantially and the vast majority of visitors concentrated in the National Parks and other favoured upland regions (Hogan and Harrod, 1982; Phillips *et al.*, 1981). In 1972-3, there were 16 million car-borne visitors to the Peak District National Park alone (Anderson *et al.*, 1997). In 1973, it was calculated that use of the Pennine Way had increased three-fold in the previous three years (Bayfield and Lloyd, 1973) and this rate of increase was then expected to continue. A survey in 1990 found that

erosion on the Pennine Way was five times worse than it had been in 1971 (Peak District National Park, 2000).

Heavy traffic at points with restricted access, often on steep gradients, can result in severe path and track erosion (Coleman, 1981; Evans, 1996). Once the vegetation is removed the soil becomes exposed, runoff and sediment increase and habitat, plant and animal biodiversity are compromised. Coleman (1981) outlined the factors that affect erosion as exposure of the site to frost heave and wind, the volume and turbulence of runoff water and the slope which affects both runoff and the transport of detached particles. George and Jarvis (1979) created a guide to the suitability of sites for amenity resources, using knowledge of site and soil susceptibility to erosion.

Footpath erosion is usually a localised problem, confined close to the path. Although paths may become several metres wide as walkers spread out to avoid damaged areas, as on the Pennine Way, footpaths are rarely eroded along their entire length (Aitken, 1982). Erosion is usually, but not always, confined to the more susceptible wet, rough and steep areas (Bayfield, 1973; Plate 1.4). Between the 1960s and the late 1970s the degree of damage to upland landscapes by eroded footpaths was sufficient to result in the formation of the first footpath repair teams (Davies *et al.*, 1996).



Plate 1.1 Type I peat erosion in the South Pennines (left) and Type II peat erosion, with residual hags, in the Yorkshire Dales (right).



Plate 1.2 Sheep scars scattered across hillside (left; Howgill Fells) and slope failures associated with sheep scars (Co. Durham; right).



Plate 1.3 Sheep resting in hollow on intermediate slope (left) and, nearby, highly eroded sheep scar located on unstable subsoil (right) (Bugeilyn, Wales).

Sheep also create and maintain paths, although these are usually narrower than amenity paths and run along the contour. Damage is usually confined to soil compaction and stunted vegetation. In wet or constricted areas, complete vegetation removal is common although, as with amenity paths, damage is usually localised.

Erosion is not limited, however, to the agricultural and recreational activities of humans. Construction, military and Forestry Commission activities also cause degradation of the landscape. The causes of erosion are discussed further in Chapter 2 (Section 2.3.7).

1.3.4 Riparian erosion

Riverbank erosion is a natural process but there is concern that its rate has increased in recent years. More rapid runoff from the land can initiate changes in the flow regime of a river, resulting in erosion of its channel bed and bank and downstream deposition of silt, sand and gravel (Evans, 1996). Changes in hydrology have been caused by the removal of the original woodland of the UK, as well as rising stock numbers and the increased area of arable land (Orr, 2000). Vegetation removal and the creation of bare soil result in shorter precipitation run-off times and thus reduce the time during which infiltration can occur. In addition, unrestricted access to grazers allows physical damage to the bank itself (Plate 1.5).

Shorter runoff times lead to more frequent and faster flooding of river channels, conditions that wider and shallower eroded channels are less able to deal with. The result is further erosion of the riverbank and bed, and flooding of adjacent land. In addition, rivers have an increased suspended sediment load, due in part to erosion within the catchment and to erosion within the channel itself. Deposition of this material is detrimental to salmon spawning grounds and to reservoirs (Butcher *et al.*, 1992; EA, 1999; Theurer *et al.*, 1998).

1.4 RESEARCH OBJECTIVES

This research was designed to estimate the



Plate 1.4 Footpath erosion in the Brecon Beacons. On the left, the different paths show alternative routes used by walkers both for ascent and descent, and to avoid a precipitous route along the cliff top to the right. The photograph on the right shows extensive soil movement on a steep footpath.



Plate 1.5 Cattle allowed access to streams and rivers may cause damage, including bank breakdown and poaching.

1.4 RESEARCH OBJECTIVES

This research was developed to eliminate gaps in the understanding of upland erosion. It was completed by addressing the basic issues of erosion extent and cause using a multi-faceted approach that employed both long- and short-term time scales. The determinants of erosion were also assessed using a variety of procedures, including a range of parametric statistical tests. Finally, information on the rates of erosion was essential to underpin erosion prevention and remediation proposals.

The primary aim of the project was to quantify the current spatial extent of erosion within the uplands of England and Wales. The lack of basic information on upland erosion prompted the Royal Commission Report on Environmental Pollution (RCEP, 1996) to recommend fundamental research into the extent and causes of accelerated soil erosion in the uplands. Arising directly from that report, the Ministry of Agriculture, Fisheries and Food have commissioned an extensive project into upland soil erosion, of which this research forms part (Harrod *et al.*, 2000).

The project was also designed to fulfil certain other objectives: to assess the principal causes of upland erosion and to identify the rate of upland erosion, over both the short- and long-term. Currently, it is believed that erosion is more prevalent than in the past, although the lack of data on erosion trends and the difficulties of distinguishing between erosion processes have been stressed (Evans, 1997; Evans and Felton, 1987; RCEP, 1996; Warburton, 1998b).

1.4.1 Thesis structure

The research is presented in a sequence that begins with an appraisal of current literature on the issue of soil erosion (Chapter 2). Following the introduction to the uplands and to erosion features given in this chapter, the causes, rates and implications of upland soil erosion are considered. The effects of land management and of the environment on erosion initiation and promotion are discussed separately.

Chapter 3 focuses on the large-scale field survey conducted in 1997 and repeated in 1999, which formed the basis for assessment of the extent, causes and rates of soil

erosion. The field protocol is described and results that relate erosion to the environment of the field site are presented.

Within the field survey, a novel approach to the precise measurement of soil loss within erosion gullies was developed. The *Traverse Procedure* consisted of detailed measurements completed across linear gullies and marked for repetition to identify erosional changes that occurred within a two-year period. The results of the traverse procedure, as well as a full description of the protocol, are provided in Chapter 4.

The influence of the environment on the extent and positioning of erosion had been assessed by recording and relating environmental characteristics of the field site to the incidence of erosion. To incorporate the attributes of the wider catchment in the determination of erosion cause, the area of ground considered to contribute water flow to the field site was defined as the field site sub-catchment. Various descriptors of sub-catchment morphology were then related to the area and volume of field site erosion. The results of this study are presented in Chapter 5.

The research reported thus far concentrated on the contemporary extent and causes of erosion. Chapter 6, however, is concerned with longer-term changes in erosion, as captured by the aerial photographs taken in England and Wales since 1946. Interpretation of these photos increased the temporal scale over which erosion was assessed.

Finally, the fundamental questions posed by this research are answered. The extent of erosion in England and Wales, its causes, and the rates at which it develops are discussed in Chapter 7.

Chapter 8 discusses the significance of the results obtained and the efficacies of the different approaches used. Recommendations for future research into upland soil erosion, for the remediation of existing erosion and for the rehabilitation of degraded areas are made.

Chapter 2

A review of the causes, rates and implications of upland soil erosion

2.1 INTRODUCTION

Concern about upland erosion has grown since the nineteenth century, when the large-scale erosion of peat masses in the uplands was discussed by Aiton (1805). Today, with heightened environmental awareness and increased leisure time and financial security, interest in the uplands has never been greater. This has been reflected in the high levels of upland amenity use (Bayfield, 1973), in the growing attention to upland habitat preservation (Anderson *et al.*, 1997; Charman and Pollard, 1995) and in the concern about rates and causes of accelerated soil degradation (Evans, 1997; RCEP, 1996).

This chapter reviews current information on the causes, rates and effects of upland soil erosion. Both environmental and anthropogenic influences on erosion are examined as climate, geomorphology and soil determine susceptibility to erosion and the activities of humans and animals create opportunities for the exploitation of that erosion risk.

Erosion rates measured within England and Wales vary according to the location, duration and form of records made, as reviewed in Section 2.5. Section 2.6 puts the discussion of upland erosion into context by examining the financial, social and agricultural impacts of continued upland soil degradation.

2.2 THE UPLAND ENVIRONMENT AND SOIL EROSION

Soil erosion does not occur evenly across the uplands: it is controlled in its distribution and severity by both environmental and anthropogenic factors. The environment influences the positioning of erosion and determines the degree to which erosion, once initiated, develops. The actions of humans and animals and, to a lesser extent, the incidence of extreme weather events directly cause upland soil

erosion by initiating bare soil. The contributions of environmental factors to erosion are considered here and the erosional impacts of humans and animals are discussed in Section 2.3.

2.2.1 Soils

The erodibility of soils, defined as the resistance of the soil to both detachment and transport processes, depends on a number of soil characteristics, including particle size, aggregate stability, moisture and organic matter content (Morgan, 1995; Vandekerckhove *et al.*, 1998). In Table 2.1 upland soils and their erosion risks are summarised as determined through interpretation of a range of soil characteristics during the original soil survey (Findlay *et al.*, 1984; Jarvis *et al.*, 1984; Ragg *et al.*, 1984; Rudeforth *et al.*, 1984).

Soil texture is an important determinant of erodibility (Morgan, 1995). Large soil particles resist transport by water, while fine particles that are more cohesive are more resistant to detachment (Govers and Takken, 1998). Soil aggregation also affects resistance to erosion: some fine (<10 mm) aggregates, such as angular blocks (Hodgson, 1997) can be readily transported once detached. Other larger aggregates, such as columns of prisms, usually associated with clayey soil horizons, have considerable internal cohesion that inhibits detachment while their size (>50 mm) resists transport (Harrod *et al.*, 2000). When clay particles are joined with organic matter, erosion-resistant stable soil aggregates are formed (Morgan, 1995). Soils that contain basic minerals are also generally more stable as the minerals help to chemically bond the soil aggregates (Morgan, 1995).

The reduction in erosion susceptibility that results from the addition of organic material is principally due to aggregate stabilisation. Highly organic soils are erodible by both water and wind (Evans, 1990a; Harrod *et al.*, 2000). The relationship between organic matter and erosion depends on the amount, origin, form and function of the organic matter (Morgan, 1995). Organic matter from grass leys and farmyard manures contribute to aggregate stability as they improve the cohesiveness of the soil, increase water retention capacity and promote a stable aggregate structure (Morgan, 1995). Partially decomposed plant remains in peat can act as a mulch, however, without conferring stability to the soil structure (Ekwue *et*

al., 1993). Peat soils are also particularly prone to erosion because of the sensitive water, climate and landscape conditions under which they develop. A change in water content, surface vegetation or landuse can expose the peat to rapid subsidence, oxidation and removal by water or wind (Curtis *et al.*, 1976).

Soil structural stability is also due to biological activity, biological, chemical and physical bonding and cultivation history. Continuously cultivated soils have less structural stability because of their reduced biological activity (Curtis *et al.*, 1976). The presence of both micro- and macro- soil organisms increases pore size and number and increases the incorporation of organic matter into the soil. As soil organic matter increases soil stability, a lack of biological activity restricts conditions for plant growth and reduces stability in waterlogged conditions (Curtis *et al.*, 1976). Drier soils meanwhile are permeable and are able to absorb water readily without surface ponding (George and Jarvis, 1979).

Soil fertility, determined in the uplands by soil depth, drainage and pH, also influences erodibility. Highly fertile soils give good plant cover and therefore minimise the erosive effects of rainfall, runoff and wind. They do not easily break down and have a high infiltration capacity, determined by pore size and soil stability (Morgan, 1995). Soils that swell, such as those with larger clay or unstable mineral content, have smaller infiltration capacities and are therefore more prone to runoff; this situation is aggravated by traffic on clay soils during wet periods (George and Jarvis, 1979). As shallow clayey and sandy soils have less available water when compared to deep loamy or silty soils, they have a correspondingly reduced capacity to provide water to plants during the summer. Consequently, re-establishment of vegetation following erosion on these soils can be slow (George and Jarvis, 1979).

Resistance to erosion is also conferred by soil shear strength, which is a measure of soil cohesiveness and resistance to the forces of gravity, moving water and mechanical load (Morgan, 1995). Shear strength relies on density (Harrod, 1979) and on water content. With increased soil moisture, the soil particles move more freely, reducing the strength of the soil. Consequently, when soil is below field capacity it has enough strength, stability and consistency to withstand machinery and grazing animal traffic but this resistance is reduced or eliminated when soils are

wet (Curtis *et al.*, 1976). On wetting, clay aggregates swell, lose strength and separate as the bonds holding soil particles together are weakened. In some soils however, a thixotropic reaction to wetting means the soil regains its shear strength as its water content increases. This reaction may allow the fluid mass movement of peat during bog-bursts and peat slides (Mitchell and Ryan, 1997). Poaching caused when shear strength is reduced by wetness results in damage to plant roots and shoots, invasion of the sward by weeds, soil compaction and structure deterioration (Harrod, 1979). Soil density is itself related to particle size, packing density and organic matter content (Harrod, 1979), which determine the risk of trampling damage to soil. Clay soils and highly organic soils such as peat can quickly lose strength and become difficult to walk or drive on (George and Jarvis, 1979).

Table 2.1 Upland soil associations and their susceptibilities to erosion.

Soil group	Erosion risk
Raw peat soils	Susceptible to gully erosion
Stagnohumic gley soils	Poaching and amenity erosion
Stagnopodzols	Footpath erosion and poaching risk
Brown podzolic soils	Little poaching risk, but susceptible to erosion caused by cultivation.
Podzols	Footpath erosion and poaching risk
Rankers	Persistently wet and liable to poaching, footpath erosion and overgrazing

2.2.2 Landscape

Different sections of the upland landscape are more vulnerable to erosion initiation. Morphology, angle and length of upland hill slopes particularly influence erosion risk.

The effect of slope on erosion varies with soil and the erosion process. On mineral soils, runoff becomes the dominant erosive process after a threshold inclination of between 4-5° (Kamalu, 1994) and 7-8° (Moss *et al.*, 1979). Runoff increases with slope, and the proportion of soil moved downslope by rainsplash increases as slope steepens (Morgan, 1995). In Ireland, gullies on peat were particularly abundant where slope was greater than 10° (Bradshaw and McGee, 1988). Rill erosion increased substantially more with increasing slope gradient than interrill erosion (Fox and Bryan, 2000). A combination of results suggest that erosion increases rapidly with slope up to a maximum on slope of 8-10° before decreasing with further increases in slope: this relationship does not, however, take gully, pipe or landslides

into account (Morgan, 1995). Harvey (1996) found that hillslope failures were most developed on steeper slopes, especially when these occurred on highly convergent slopes. In contrast, there was little erosion on linear slopes. Similarly, Jackson (1984) found that converging slopes produced more runoff, and hence erosion, than diverging slopes. Evans (1990b), meanwhile, found that erosion was particularly evident on convex slopes when there was enough rainfall to exceed surface storage on the crests. Similarly, Warburton and Higgitt (1998) found that a peat landslide occurred below slight slope convexities.

Little work has related erosion to the altitude at which it develops, largely because the limited scale of much research is unaffected by an altitudinal range. Bower (1962) linked Type II gully erosion to certain altitudes, but did not assess the relationship between altitude and erosion. Higher altitudes experience more frequent freeze-thaw cycles, a slower rate of vegetation germination and growth, a reduced viable seed pool and higher wind speeds, particularly on flat mountain plateaux (Evans, 1990b). All of these factors increase the potential for compromised vegetation and soil loss, and decrease the likelihood of revegetation of bare soil. Conversely, Large and Hamilton (1991) found undisturbed peat soils at higher altitudes and a greater extent of eroded soil at lower altitudes because of the practice of marginal agriculture. In Scotland, the extent of peat erosion and eroded footpath length both increased with altitude, while debris flows and sheet erosion increased with both altitude and amplitude of relief (Grieve *et al.*, 1994). Comparisons of erosion rates for exposed peat showed a clear increase with altitude (Tallis, 1985b) and prompted Evans (1990b) to determine that for an increase in altitude from <435 m to >530 m, erosion increased by a factor of 10.

Evans (1990b) reported that erosion of scars caused by sheep is also greater at higher altitudes. Scars on exposed slopes above 425 m retreated ten times faster than those at lower altitudes. Eight years were required for plant cover to increase from 49 to 92% on high altitude mineral and peaty podzols while on mineral soils of lower altitude, revegetation to 90% took 5 years (Phillips *et al.*, 1981).

The directional aspect of a site may influence its susceptibility to erosion. Renner (Renner, 1936) considered that soils on S-facing slopes were more susceptible to

erosion because moisture and temperature differences on N-facing slopes meant vegetation was more effective at holding the soil together.

Factors that control soil erosion may also interact to influence soil loss (Romkens *et al.*, 1998). Hussain *et al.* (1998) showed the severity of accelerated erosion was affected by slope gradient, shape and length as well as tillage practices. In NW Ireland, between 75 and 100% of peat erosion occurred on slope lengths between 300 and 600 m and at altitudes above 300 m (Large and Hamilton, 1991). Bower (1962) related the incidence of erosion to climate, landform and geology and in the Peak District, areas of eroding bare peat recorded in Hey Clough were related to vegetation type and slope form (Evans, 1977).

2.3 ANTHROPOGENIC FACTORS AND UPLAND EROSION

The natural environment controls the location and development of soils and vegetation and determines the susceptibility of an area to degradation. Weather is responsible for erosion initiation only in extreme conditions that result in catastrophic erosion such as bog bursts. The majority of accelerated erosion is triggered instead by the deliberate or accidental removal of surface vegetation by humans or by animals. The extent of the erosion that then occurs is determined in part by the original susceptibility of the site to erosion, but also by environment and land use.

Humans impact upon the uplands through various agricultural activities, such as grazing, drainage and burning (Ratcliffe and Oswald, 1988), but also through their use of the uplands for recreation and for its water, mineral and vegetation resources. All of these activities may impinge upon the integrity of the surface vegetation and expose the soil to the erosive action of water and wind.

2.3.1 Grazing

Vegetation control is a desirable endpoint of management and in hill and upland areas this is primarily achieved through grazing (Hodgson, 1985). As described in Section 1.3, grazing sheep and cattle have been part of the rural landscape of Britain since the 12th century (Orr, 2000). Since then, the numbers of grazing animals in the uplands have steadily increased (Fuller and Gough, 1999; Phillips *et*

et al., 1981; Sansom, 1999). This century, in particular, has witnessed a dramatic boost in upland stocking rates, due principally to recent changes in economic policy that have removed the vegetation control-impetus of grazing and replaced it with economic returns (Hodgson, 1985).

Grazing is considered a problem when the carrying capacity of the land, or the number of grazing animals that the vegetation can support, is exceeded. However, the erosion carrying capacity, defined as the number of animals that can be supported before erosion processes begin, may be reached before this point (Evans, 1997). The link between grazing animals and the incidence of erosion is well supported: 35% of the world's land degradation is attributed to grazers (Oldeman *et al.*, 1991). Animals directly create, maintain and expand areas of bare soil upon which the external environment can act and indirectly, they can facilitate the rapid runoff of rainfall by the compaction of the soil and the removal of vegetation (Environment Agency (EA), 1996; Evans, 1977, 1997, 1998).

Sustained grazing increases compaction, reduces infiltration and increases runoff, erosion and sediment yield (Belsky and Blumenthal, 1997; EA, 1996; Evans, 1990a; Phillips *et al.*, 1981; Trimble and Mendel, 1995). Less litter is returned to the soil, compromising topsoil organic content and soil aggregate stability. Rooting depth is also reduced, below which the soil is wetter so shallow mass movements may be encouraged, particularly during rainstorms. Light rather than moderate grazing provides no hydrologic advantage (Blackburn, 1984) but heavy prolonged grazing accelerates erosion and runoff (Duce, 1918; Rich, 1911; Sampson and Weyl, 1918). The removal of grazers, meanwhile, can result in the cessation of accelerated erosion (Anderson *et al.*, 1997; Evans, 1996, 1997).

Grazing also affects vegetation cover, density and composition. Light grazing has a positive effect on upland dwarf shrub communities as their morphology makes them tolerant of moderate defoliation (Gimingham, 1972; Welch, 1984a). Removal by grazing of up to 40% of current heather growth is sustainable but this threshold is lower for older stands (Felton and Marsden, 1990). Under conditions of intense grazing heather may be out-competed by native grass species and bracken (Plate 2.1), which significantly reduces plant biomass and biodiversity (Grant *et al.*, 1985).

Declines in vegetation quality and reductions in native fauna species have been recorded on Ingleborough (Brack, 1978; Soil Survey Staff, 1960), in the Peak District (Anderson and Yalden, 1981) and in Connemara, Ireland (Bleasdale and Sheehy-Skeffington, 1994). In each case, the loss of biodiversity was associated with high grazing intensities on the hills.

Some vegetation associations are more sensitive to the formation of bare soil by animals than others. Scars form more easily in moorland acid grassland swards as these are more nutritious and more attractive resting-places for grazers (Evans, 1997). Lowland grass swards, meanwhile, are more resistant to scar formation because the grasses are denser and have better rooting systems (Evans, 1997; Tallis, 1985b). Grazed vegetation is also more susceptible to further grazing by smaller vertebrates such as rabbits and rodents (Evans, 1997; Johnston *et al.*, 1971).

Similarly, some soils are more at risk of damage caused by grazing animals than others. Due to its very low bulk density, peat is compacted by trampling animals, its oxygen content and hence the rooting conditions for growing plants are altered, and the vigour of sensitive plants such as *Sphagnum*, is compromised (Douglas, 1994; Evans, 1997).

2.3.2 Drainage

The objectives of land drainage are to improve the agricultural and economical potential of wet ground and to remove the risk to grazers and walkers. With drainage, blanket peat becomes more accessible and can support a more nutritive flora. Intensive drainage is also an important first stage in preparation of ground for afforestation. Drainage schemes were subsidised in England and Wales until the 1980s (MAFF, 1984) although it is believed that moor drainage, or gripping, has been practised for the last 150 years (Stewart and Lance, 1983).

Grips are defined as a method of removing excess water by a system of small surface channels, typically 45 cm deep, 40 cm wide and placed about 20 m apart (MAFF, 1973; Plate 2.2). Moorland gripping was expected to greatly increase grass production, particularly of more palatable species, and thereby to allow increases in

the stock carrying capacity of the land (MAFF, 1973). Extensive areas of upland Britain have been drained in this way, supported by government grant aid (MAFF, 1984) although the efficacy of moorland grips in improving grazing capacity has not been proved (Green, 1974; Stewart and Lance, 1983).

The effects of land drainage vary according to the soil type within the drained area (Robinson, 1986). On clay soils, where water storage is limited, drainage increases the time to runoff peak by retaining water within the soil. Peak flows increase, however, on more permeable soils that are not prone to surface saturation. In Moor House Nature Reserve, open moorland ditching caused decreases in the time to peak runoff and increased peak flows (Robinson, 1985). Most benefit is gained from drainage when relatively permeable mineral soils affected by either ground or surface water are drained (Harrod, 1979).

The effect of drainage on upland peatlands is essentially the disintegration of bogs through the desiccation and subsequent degradation of their peat (Ratcliffe and Oswald, 1988). Peat bogs are hydrologically distinct ecosystems where disruption of the catotelm, or saturated body of the bog, will cause the entire bog to dry out. With water loss, the temperature rises and the biological processes that lead to decomposition are accelerated. Decomposition results in shrinkage of the whole peat mass, a gradual increase in its mineral content and the dissipation of its organic content. These effects are more pronounced when a well-developed, *Sphagnum*-rich catotelm is drained. The changes in surface hydrology have profound effects on surface vegetation with a reduction in vigour of plants (Tallis, 1964) and vegetation change from a *Sphagnum*-dominated carpet to a ridge and hummock vegetation.

The scale of consolidation and wastage around upland blanket bog drains is low as the bogs tend to be shallower and much more humified than raised or lowland bogs (Ratcliffe and Oswald, 1988). They are also less prone to surface drying because of the higher and more constant precipitation (Ratcliffe and Oswald, 1988). Eroding peatland drains may also lose effectiveness with time (Fisher *et al.*, 1996) as erosion is affected by the location and depth of the drains. Drains dug to a blanket peat base may remain stable up to a 15° slope while those floored to a colluvial base may

experience lateral undercutting, irregular profiles, collapse and blockage (Newson, 1980: Plate 2.3).

The impacts of drainage extend downstream where sediment loading of watercourses and water colouring, due to the suspended organic material released by drained peat and to the dissolved by-products of peat oxidation, result from drainage of saturated peat soils (Butcher *et al.*, 1992). Suspended sediment can be removed by filtering while water colour usually requires more extensive treatment.

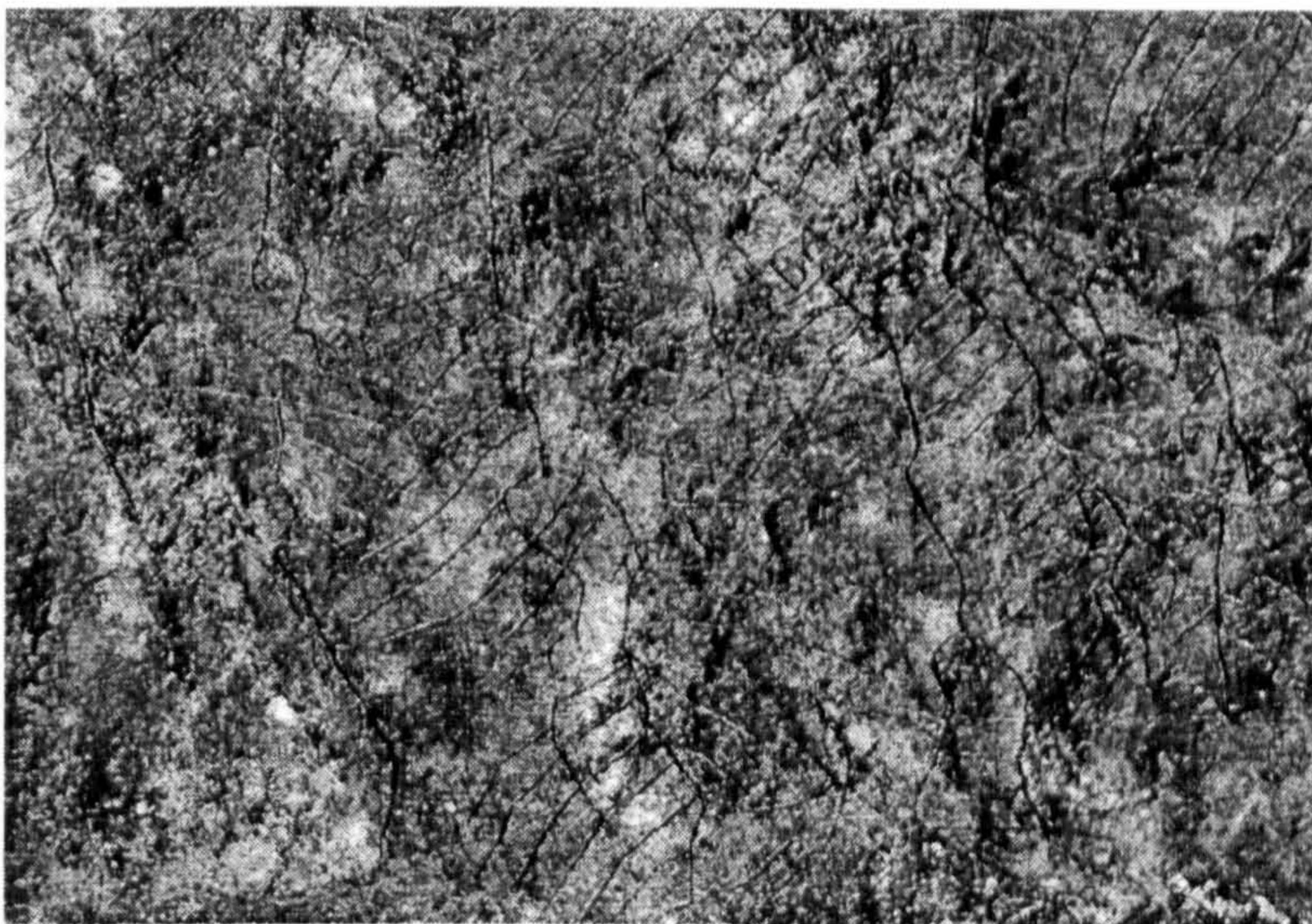


Plate 2.2 Aerial photograph of moorland gripping (mid-Wales). Reproduced from Ordnance Survey aerial photographs by permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office. © Crown Copyright NC/00/590.

2.3.3 Burning

Burning is the oldest form of human impact on moors and is the most widespread land management tool (Ratcliffe and Oswald, 1988). Until about 1800, moor burning was probably sporadic and casual: since then, however, with the intensification of sheep and grouse rearing, burning has become a regular practice (Rackham, 1987). Burning, or swaling as it is frequently known, is used as a tool for the management of vegetation in Britain, principally for the stimulation of new growth of grasses and heather.

The effect of fire varies according to the temperature and duration of the burn, on the landscape and on the interval since the last burn. Burning encourages some plants,

especially those with their meristems located at or below ground level, such as *Molinia*, *Trichophorum* and *Eriophorum* (Rowell, 1988). *Sphagnum* is killed by fire and its loss, which decreases water-holding capacity, is potentially very damaging to peatlands. Fire-tolerant species can regenerate quickly after burning while other species may survive only if the burning regime allows enough time between fires. While swaling is necessary to prevent dwarf shrubs becoming moribund, repetition more than every 12 years causes a decline in heather and allows bracken (*Pteridium*) and purple moor grass (*Molinia*) to invade (Rowell, 1988). At twelve years, heather is one third through its life cycle and can regenerate easily: longer periods between burns result in hotter and more destructive fires and more uncertain regeneration (Rackham, 1987). Aged heather does not sprout from the base of burnt stems and regeneration from seeds is slow and cannot compete with bracken and graminoids. The complete absence of burning, however, allows heather to senesce (Gardner *et al.*, 1993).

With fire, the nutrients held in the aerial parts of a plant are lost almost instantaneously as gas and blown ashes (Allen, 1964; Maltby, 1980). Ash that falls to the ground will contain some readily available nutrients, particularly phosphates, calcium and potassium, but all nitrogen is lost in peat ignited to ash (Maltby, 1980). Most of the lost minerals will be eventually replaced by atmospheric deposition although frequent and severe burning will severely reduce nutrients. Nutrient budgets calculated by Kinako and Gimingham (1980) indicated that phosphorus took 70-80 years to return to pre-burn levels while nitrogen and potassium took 14-27 years.

Burning increases surface pH and soil temperature fluctuations as burnt surfaces absorb more heat from the sun. These improved conditions for bacterial decay increase the rate of surface decomposition (Large and Hamilton, 1991). Fire also causes surface crusting of peat through the deposition of bitumens formed by the combustion of plant waxes. This layer presents increased difficulty of ground-penetration for germinating seeds and increases run-off which itself lowers the water table and further increases the risk of erosion (Rowell, 1988).



Plate 2.1 Differences in vegetation caused by sheep. To the right of the fence, sheep graze freely on common land. On the left, sheep grazing is controlled by private landowners (Long Mynd, Shropshire).



Plate 2.3 Eroding drain on marginal agricultural ground (Beddgelert, Wales).



Plate 2.4 Erosion of peat associated with a fire at Holme Moss (Peak District).



Plate 2.5 As well as detracting from the landscape, tracks across moorland are important runoff channels and sources of sediment (Quantocks, Somerset).

Revegetation following a severe fire can be very slow. Two years after a severe fire, Levisham Moor (North York Moors) was still devoid of all vegetation except moss (Maltby, 1980). Frequent or severe burning can kill both plants and buried seeds (Gardner *et al.*, 1993). A change from 90% heather cover to 90% *Molinia* on Dartmoor between 1975 and 1996 was attributed to a severe fire in the early 1980s (Weaver *et al.*, 1998).

Severe burns also lead to accelerated soil removal, although Imeson (1971) reported that erosion due to burning was short-term, and declined when the vegetation cover became re-established. The onset of widespread erosion at Holme Moss was associated with one or more severe fires in the 18th century that resulted in the loss of the surface horizons of peat (Tallis, 1987; Plate 2.4). Surface lowering of 5-10 cm recorded on Levisham Moor was attributed to erosion rather than physical wastage of the peat: the entire site also suffered from a lack of regeneration by *Calluna* (Maltby, 1980). Recently burned areas frequently show a network of meandering water channels where the peat has been eroded to a depth of up to 10 cm (Curtis, 1965). Burning exposes the soil surface to erosion but also increases the volume and intensity of throughflow, thus promoting gully development (Imeson, 1971).

2.3.4 Atmospheric deposition

The development of industry can be read from fossils in peat monoliths from ombrotrophic bogs (Gilbertson *et al.*, 1997; Weiss *et al.*, 1997) and as laminations in sediment cores from upland lakes (Fernandez *et al.*, 1996a). Both methods provide valuable records of historical environments.

Toxic chemicals may reach upland ecosystems by dry fallout or be washed out in rainfall. Upland areas of high rainfall located near to industrial centres are therefore prone to high levels of chemical deposition (Curtis *et al.*, 1976). In addition, the low pH of upland bogs and heaths increases the solubility and hence mobility of many trace elements (Curtis *et al.*, 1976). Polluted rain can affect the balance of nutrients by causing both acidification through sulphur dioxide content and eutrophication, usually through atmospheric ammonia deposition from animal husbandry and

intensive agricultural systems such as dairy farming (Bobbink *et al.*, 1992). The most important pollutants are acid gases, fluoride, particulates and ethylene, as well as heavy metals and dioxins. These last are usually controlled for human health but EC maximum acceptable levels are often too high for some particularly sensitive species (Farmer, 1993). Scavenging of pollutants from the atmosphere by conifer plantations could cause increases in soil concentrations of nitrates and heavy metals (Gordon, 1994).

While bogs are naturally acidic, they remain sensitive to mineral-derived acidity (Clymo, 1984). The input of nutrients through air pollution has particular adverse effects on mosses because they lack a protective cuticle. Of fly ash deposited on *Sphagnum*, 99% was retained by the moss, indicating that *Sphagnum* can be used to study the history of air pollution (Fernandez *et al.*, 1996b). Fumigation with ozone, an anthropogenic atmospheric pollutant, caused significant reductions in the growth of *Sphagnum* and *Polytrichum* by 15 and 22% respectively (Potter *et al.*, 1996).

In the Peak District, the death of bog mosses, especially *Sphagnum*, corresponded to the first appearance of obvious air pollution during the Industrial Revolution (Phillips *et al.*, 1981; Tallis, 1972; Tallis and Livett, 1994). This sensitivity to pollution also prevents recolonisation of bare peat surfaces as initial colonisation is usually by bryophytes and algae (Mackay and Tallis, 1996). Ombrotrophic bog surfaces are buffered by the cation exchange capacity of the peat and are less likely to be affected by moderate acid deposition than weakly basic soils or water (Proctor and Maltby, 1998).

Nutrient cycling is highly efficient in heathland communities. Because of the poor nutrient status of the soil, nitrogen that enters the ecosystem is concentrated in plant biomass and organic matter losses from the system are negligible. In contrast, some of the nitrogen that enters a *Molinia*-dominated community is lost to deeper soil layers, to the atmosphere and to herbivores (Berendse, 1990). Their nutrient-poor status means heathlands benefit from nutrient input: for example, application of nitrogen and sulphur to heathland resulted in significant stimulation of shoots, flowers and litter production (Uren *et al.*, 1997). However, application of nutrients in the long term has undesirable effects on upland vegetation communities. Increasing

nitrogen availability may change *Calluna* and *Erica* heathlands into grassland vegetation of *Deschampsia* or *Molinia* (Bobbink *et al.*, 1992; Brack, 1978; Weaver *et al.*, 1998). The effects of pollution at roadsides include enhanced growth of heather and an increase in the abundance of grasses, due to the changes in competitive ability following eutrophication by vehicle exhausts (Angold, 1997).

2.3.5 Forestry

Established forests protect the soil, maintain high rates of evapotranspiration, rainfall interception and infiltration and therefore generate little runoff (Calder, 1993; Morgan, 1995). Much of the land used for commercial forestry in England and Wales, however, is situated on steeply sloping, acid, well-drained slopes or on impermeable, wet blanket bog (Theurer *et al.*, 1998). As well as encroaching upon upland habitats, particularly heathland (Rackham, 1987), all stages of forestry operations, from ground preparation and planting through road building and harvesting have serious implications for accelerated soil erosion and runoff (Nesbit, 1996). The hydrological changes that occur in the first few years following drainage and planting are quite different, therefore, from those normally associated with mature forestry (Calder, 1993; Robinson, 1988) and are dominated by pre-planting drainage (Robinson, 1988).

Working wet soil, particularly under the wet climatic conditions of the uplands, increases the risk of sediment generation: following afforestation of moorland catchments Nesbit (1996) recorded a two-to-five-fold increase in sediment. Pre-afforestation drainage and the use of heavy harvesting machinery that compacts the soil both encourage soil erosion and runoff and increase sediment delivery to watercourses. Erosion of man-made, drainage channels occurs when the plough cuts through the surface peat layer into the underlying erodible mineral soil (Flintham and Carling, 1993).

Reduced catchment evaporation, shortened stream stormflow response times and enhanced dry weather baseflows were all recorded in Kielder Forest, Northumberland by Robinson (1988). Sediment yields of over 40 t km⁻² yr⁻¹ were recorded for up to a decade after planting, after which they declined to pre-planting levels of 12 t km⁻² yr⁻¹ (Foster and Lees, 1999). Sediment losses from forested areas

calculated from stream sediment loads and lake sediment accumulation were $1.3 \text{ t ha}^{-1} \text{ yr}^{-1}$, some 1.2 - 4 times those from unforested areas (Grieve *et al.*, 1995). Francis and Taylor (1989) also found a sharp and substantial increase in suspended sediment yield of between 246 and 479% following pre-afforestation ploughing (Francis and Taylor, 1989). Increased runoff from forested areas also causes bank erosion in rivers immediately downstream (Morgan, 1995). At Narrator River (Devon), both mean bank erosion and mean bed aggregation were significantly higher within a forested catchment than outside (Murgatroyd and Ternan, 1983). Stott (1997a) also established greater bank erosion rates within a forested catchment than in a moorland catchment. Mean bedload sediment yields within the Balquhidder paired catchments were also significantly greater on streams within forestry than within moorland (Stott, 1997b).

2.3.6 Recreational use of the uplands

The upland areas of England and Wales may be marginal agricultural areas, but they attract recreational use because of their outstanding scenery (Morgan, 1995). With increased financial security and leisure time, the 20th century has seen a sharp increase in amenity use of the uplands, particularly since 1945 (Bayfield, 1973; Bayfield and Lloyd, 1973; Grieve *et al.*, 1994). The marginality of many upland areas means that they are sensitive to disturbance however, and their ability to withstand recreational impacts is low (Morgan, 1995).

Heavy recreational use results in disturbance of native flora and fauna, the destruction of natural habitats and erosion on footpaths, bridleways and ski areas, all of which represent rapidly expanding problems within the uplands (Anderson *et al.*, 1997; Evans, 1996). Soil compaction, associated with heavy traffic, increases runoff and erosion on steep slopes and constricted areas, and results in soil deposition in watercourses. Plant habitats are also disturbed by constant traffic, and by deposition of disturbed soil. Sections of the Pennine Way provide striking evidence of the volumes of soil, particularly peat, which can be removed by heavy traffic.

Footpath overuse reduces overall vegetation cover, changes species composition as trampling-resistant plants develop an ecological advantage and causes soil compaction and changes in soil moisture (Morgan, 1995). The factors that affect

footpath morphology include soil, topography and hydrology, daily and seasonal weather fluctuations and the recreational pressure on the path (Coleman, 1981; George and Jarvis, 1979). Footwear, walker weight and gait, trampling manner and the transport of material on boots all contribute to total trampling pressure exerted on a footpath. As it is impossible to monitor these factors outside controlled environments, most research concentrates on trampling pressure as represented by the numbers of footpath users (Coleman, 1981). Although lateral spread by walkers decreases as slope angle increases, erosion is greater on steeper slopes as the pressure exerted on the ground increases with increasing slope (Coleman, 1981).

Recreation ecology deals with the impact of outdoor recreation on natural or semi-natural environments (Liddle, 1991). Environmental damage caused by trampling may be assessed by measuring changes in vegetation cover and height, bare ground cover, and the cover of individual species (Cole and Bayfield, 1993). While it is believed that heath species are susceptible to walking pressure (Coleman, 1981), trampling experiments conducted on heathland found no linear relationship between vegetation degradation and trampling intensity (Toullec *et al.*, 1999). The high level of footpath erosion measured on *Calluna* by Coleman (1981) may not be a feature of the susceptibility of the vegetation but a measure of the ease of degradation of the underlying soil. Toullec *et al.* (1999) found no difference between summer and winter in heathland resistance to erosion or degradation. In the Lake District, *Nardus* grassland was particularly resistant to trampling, while *Pteridium*, because of its loosely-bound grass turf, was very susceptible to damage (Barkham, 1972; Coleman, 1981).

2.3.7 Other upland uses and soil degradation

The rearing of grouse for sport on moorland is not usually associated with landscape degradation as the need for young heather stands means grouse moors are among the best managed habitats within the uplands. The need for easy access to moors, however, frequently leads to the creation of new sand- or gravel-surfaced tracks. Runoff and erosion associated with nonmetalled roads has not been widely researched within Britain, in spite of their constant use in forestry and for moor access. Smaller scale tracks also act as sediment sources: in particular, the use of four wheel drive all-terrain vehicles by upland farmers has increased substantially in

recent years (Plate 2.5). Research in America has recognised tracks as one of the primary sources of sediment in many watersheds (Elliot *et al.*, 1999). Most soil erosion is from concentrated flow in ruts or ditches, and can be reduced by adding gravel to increase hydraulic conductivity or by reducing vehicle tyre pressure. The final option to reducing erosion from tracks was their removal (Elliot *et al.*, 1999). Contrary to this, the creation of new tracks, particularly across open moorland, is a regular feature within upland England and Wales.

The uplands are also used for military purposes in England and Wales. Although there is little research into the impacts of military presence on erosion and runoff, the activities of large numbers of people and the movement of large and powerful vehicles mean the creation of eroded areas with increased turbid runoff is inevitable (Theurer *et al.*, 1998). Recovery of vehicle tracks on Dartmoor was rapid on grassland or heathland, and slow on higher moorland or blanket bog, which, it was acknowledged, may never return to their original species composition (Charman and Pollard, 1995).

2.4 RATES OF UPLAND SOIL LOSS

It is difficult to establish rates of accelerated erosion because of an absence of measurements of long term erosion rates (Boardman, 1996) and because, in plot studies, landscape variability and runoff and sediment storage are simplified or neglected. Scaling up from plot scales is also hampered by the lack of relevant and precise data at larger scales (Boardman, 1998; Evans, 1990a and 1993; King *et al.*, 1998). The influence of human disturbance efficiently masks the potential effects of topography and runoff on sediment yield between catchments (Foster and Lees, 1999) and further compromises comparisons of results. Rates also vary in time and space, making the concept of an average rate of erosion for an area such as Europe invalid (Boardman, 1998).

As with erosion, sediment yield is linearly related to a number of climatic and topographic variables. It increases with runoff, altitude, precipitation, temperature and rock softness, and decreases with increasing catchment area and protective vegetation (Jansen and Painter, 1974). The degree of sedimentation in a river or

lake is a good indication of the state of the catchment (Cooperrider and Hendricks, 1937). Rates of soil loss are frequently inferred from soil accumulation rates in reservoirs, which act as settling pools for suspended material (Phillips *et al.*, 1981). The sediment yield of rivers is, however, frequently and erroneously equated with erosion rate (Boardman, 1996). The use of a delivery ratio value to convert between the two is acknowledged to be an “unsatisfactory tool” (Novotny and Chesters, 1989; Walling, 1983; Wolman, 1977). River sediment yields do not therefore provide reliable estimates of erosion rates.

However, because of the inherent difficulties in measuring soil loss from land, sediment yield is frequently used as a more readily assessed alternative. While they do not account for time lags in the soil loss process, when soil is temporarily or more permanently stored on hillslopes (Boardman, 1996), river sediment yields and lake accumulated sediments can provide valuable information on catchment land use and erosion. At Blelham Tarn (Lake District) an exponential increase in sedimentation rates was ascribed to topsoil erosion within the catchment. A comparison between sedimentation and increases in sheep numbers within the catchment revealed that the recent sedimentation was probably a direct response to increased sheep grazing (van der Post *et al.*, 1997). Further core analyses have revealed increased sediment yields since 1964 in the Lake District (Oldfield *et al.*, 1999).

Calculated rates of sediment accumulation vary widely. From a catchment area of approximately 300 km², total sediment accumulation was 62 000 m³ yr⁻¹ for reservoirs in the Peak District (Phillips *et al.*, 1981). Walling and Webb (1981) suggested an average rate of sediment supply to British reservoirs of 30 t km⁻² yr⁻¹ for catchments of 10 km². In Yorkshire, Butcher *et al.* (1992) calculated sedimentation rates of between 28 and 212 t km⁻² yr⁻¹, with the higher rates from catchments with highly eroded deep peat. Sediment yields for Howden Reservoir, calculated using both Cs¹³⁷ and Pb²¹⁰, were 127.7 t km⁻² yr⁻¹ with an organic fraction of 31.3 t km⁻² yr⁻¹ (Hutchinson, 1995). Rates of sedimentation calculated in Stirlingshire were 205 t km⁻² yr⁻¹ from a deep-peat catchment (McManus and Duck, 1985). The low density of peat (0.3 compared with that of approximately 1.5 for other soils) means losses of peat are volumetrically much greater than those of other soils (Harrod *et al.* 2000).

Analysis of lake cores in South Devon revealed that average post-1953 yields from pasture, arable, moorland and forested catchments were 13, 31, 29 and 13 t km⁻² yr⁻¹, respectively (Foster and Lees, 1999). Short-lived disturbance, such as afforestation, produced high yields of over 40 t km⁻² yr⁻¹ for up to a decade after planting before yields declined to pre-planting levels (Foster and Lees, 1999).

Bull (1997) assessed that bank erosion was an important supply of suspended sediment within upland habitats and that, for individual events, bank erosion may contribute more to the sediment load than any other source. Measurements in the paired Balquhider catchments found that bank erosion contributed 1.5 and 7.3% of the sediment yields of an established forested and a moorland catchment respectively (Stott, 1997a), even though bedload sediment loads were greater within the forest catchment (Stott, 1997b). Stott (1997a) also found that bank undercutting and erosion rates were more pronounced on moorland streams.

2.5 IMPACTS OF UPLAND SOIL EROSION

As well as their economic importance for farming, forestry, water and game management, the uplands have a variety of other uses including amenity and recreation, biodiversity and archaeology. Upland erosion affects these activities and has off-site effects throughout the lowlands, particularly in river catchments. The major impacts of erosion are environmental degradation, the loss of grazing and amenity land, the loss of water storage capacity and the deterioration of water quality (Lee, 1995).

2.5.1 The environmental effects of soil degradation in the uplands

Once bare ground has been created, recolonisation can be very slow. On the Kinder Estate, recovery of vegetation only followed a reduction in grazing pressure sustained through shepherding (Anderson and Radford, 1994). Severely burnt moors can remain unvegetated for generations: part of the North York Moors was still bare 70 years after being burnt (Maltby, 1980). Bare ground represents a loss of aesthetic appeal in an area as well as representing reduced usable land for local plants and animals.

As habitats are replaced by bare ground and as compromised vegetation is invaded by more competitive species, upland plant species are lost (Evans, 1977). In the Peak District, declining plant and animal species attributed to the dissection and consequent drying out of the peat blanket include *Drosera* (sundew), *Andromeda* (Bog rosemary), *Lycopodium* (club mosses), *Pluvialis apicarius* (golden plover) and *Lyrurus tetrix* (black grouse) (Phillips *et al.*, 1981). The loss of these represents degradation of a unique and valuable upland habitat, both aesthetically and ecologically. As well as becoming less attractive to users, eroding footpaths, tracks and bridleways become difficult to access and negotiate (Evans, 1996).

The uplands of Britain are characterised by high rainfall and their surface waters are valuable sources of drinking water for several water authorities (Burton *et al.*, 1988). Mismanagement of the uplands, and the consequent erosion, has devastating effects on these dependants. The increased and faster runoff associated with soil and vegetation loss (Cooperrider and Hendricks, 1937) prevents seepage of water to aquifers and fails to replenish water tables (Biot and Lu, 1995). Summer droughts are now frequent in England and Wales, despite an adequate annual rainfall and increased precipitation over northern latitudes in this century (Nicholls *et al.*, 1995). Upland rivers also play an important role in regulating water flow from mountains to the sea and pronounced peak flows experienced by rivers within a shorter time of heavy rainfall cause flooding problems (EA, 1996).

Siltation of watercourses is an important effect of increased upland erosion and reservoirs expected to last a century may have a much reduced life span of 20 or 30 years (FAO, 1993). In the Peak District, rates of reservoir capacity loss were between 2 and 14% per century (Phillips *et al.*, 1981). Water discoloration, due to the organic matter in water, is another major cost to water authorities (Burton *et al.*, 1988). Increased colour intensity has been attributed to the more frequent incidence of drought in the uplands in recent years and to changes in upland management (Butcher *et al.*, 1992; Hudson *et al.*, 1988). Bacterial activity in peat increases during dry periods and releases long-chain humic substances that then colour the water (Butcher *et al.*, 1992). Mitchell (1990) found that *Winter Hill* series peat on slopes less than 5° and with high drainage densities was significantly correlated with water

colour. Such gentle slopes produce highly coloured water as the slower moving water has greater opportunity to dissolve organic material. There is also a positive relationship between water colour and increasing peat depth (Pattinson *et al.*, 1994).

Suspended peat in water reduces light penetration, limiting algal and plant growth and hence reducing both oxygen content and fish productivity (Phillips *et al.*, 1981). Increased suspended sediment loads cause the infiltration of spawning gravels by fine particles, which reduces water flow and hence the oxygen available to fish eggs. Reduced fish stocks, particularly of salmon, in many rivers and lakes are an important concern of upland management (Theurer *et al.*, 1998).

2.5.2 Assessing the economic cost of upland soil erosion

Estimations of the monetary cost of erosion are difficult to complete as they involve comparing current productivity, including conservation costs if necessary, with the output of the same area suffering erosion (Barbier, 1996). Even for definite conservation practices, such as conservation tillage, it has been impossible to assess the economic benefits of such practices because of the high number of site-specific variables that affect the outcome (Uri, 1999). Evans (1996) has costed the impacts of erosion using Retail Price Indices (from Economic Trends, in Nix (1992)). His estimates of the long and short term costs of upland erosion was over £2.5 m per year, based on 1991 prices (Evans, 1996). However, not all of the consequences of upland erosion are directly financial and it is difficult to estimate the costs of reduced biodiversity, diminished enjoyment of the countryside or of difficult or dangerous access.

In the Peak District, financial costs were calculated by multiplying the area of bare ground area by the sale price of the sheep that ground could support. When compared with the economic benefits of increased hill sheep numbers, losses due to erosion were negligible (Phillips *et al.*, 1981).

The loss of attractive heather moorland, increasingly difficult walking terrain and a compromised flora and fauna can cause economic losses to upland communities that depend on tourism. The tangible costs of footpath repair and site revegetation give an indication of the implications of erosion. Recent costing of footpath work at

Beinn Eighe (Scotland) averaged £50 per metre (Gordon, 1994). In Snowdon National Park, £200 000 is spent annually on footpath repair alone (Pardoe and Thomas, 1992). In the Lake District, footpath repair has been carried out at various levels since 1970. Today, millions of pounds are invested in repairs to extensively damaged footpaths that have eroded from grassy trails in less than thirty years (Davies *et al.*, 1996).

In the Peak District, the financial costs of sedimentation to water suppliers were estimated as tens of millions of pounds and resulted from the capital costs of building replacement reservoirs and the labour costs of removing sediment build-up regularly (Phillips *et al.*, 1981). In Nidderdale alone the cost of removing and disposing of water colour in 1986 was £34 000 (Edwards, 1986). It is reasonable to assume that, today, the costs of upland erosion and sedimentation are even higher. Without extensive erosion, however, the redistribution of soil within a catchment may not be economically damaging and may be considered part of the geomorphological cycle (Biot and Lu, 1995).

Environmental economics is currently concerned with the determination of economic values for ecological or natural resources (Scott *et al.*, 1998). Rather than attempting to cost non-tangible upland qualities such as beauty, peacefulness and solitude, however, it may be necessary to apply erosion performance standards to the uplands. An acceptable level of erosion that did not detract from the value of an area would then become the standard against which other upland areas were compared. Remediation measures could be applied to areas that are significantly eroded and that therefore fail to achieve the standard. The tools used to revegetate or repair erosion could then be costed as it is much easier to determine the cost of removing grazing animals, fencing land or redirecting walkers than to quantify the loss in value of eroded land. This theory is further discussed in Chapter 8.

2.5.3 Advantages of erosion

Accelerated erosion may be of benefit in a limited range of situations: it is unlikely, however, that these will ever be considered sufficient to compensate for the overwhelming negativity of erosion.

The removal of infertile upper soil layers by erosion often exposes more fertile sub-surface layers with higher pH and higher base status, thus contributing to increased floral diversity (Duck and McManus, 1990).

The wheatear (*Oenanthe oenanthe*), which hunts on the ground, and prefers the flattest, most open vegetation types, seems to have increased in the Peak District. It is now most common in areas of stony, bare ground and tight vegetation (Phillips *et al.*, 1981). Invertebrate species that are adapted to live on or near bare ground, including digger bees, may also increase in eroded areas (Dr. S. Bates (English Nature), personal communication).

2.6 CONCLUSIONS

The causes of upland erosion in England and Wales are numerous and complicated. The consequences of human activities accentuate erosion that may have already developed on sites of high erosion risk, but also contribute to erosion by accelerating the removal of vegetation and disruption of the soil. The variety of upland ecosystems, and the different recreational and agricultural pressures to which the uplands are exposed, further complicate the issue.

Previous research into upland soil degradation has principally concentrated on small areas of the uplands: exceptions include the analysis of erosion extents in Scotland (Grieve *et al.*, 1995) and in the Peak District (Phillips *et al.*, 1981). A consequence of the lack of large-scale work is that, in spite of much localised research, there is no overall knowledge on the state of the upland environment. Scaling up from small-scale studies is fraught with difficulties, and small-scale work does not reflect landscape and erosion rate variations.

Because of these restrictions, it is currently impossible to summarise the condition of the upland habitat. In areas, erosion is reported as advanced while, in others, either erosion itself is limited or no research has been completed. Sheep overgrazing has apparently damaged great areas of the upland landscape but the effects of road building and farming activities on soil loss and runoff have not been assessed.

Further research into soil erosion is obviously necessary. Information on erosion on a larger scale than previously studied is needed to assess the scale of the problem and to determine the most important causes of erosion in England and Wales. Information on the rates of accelerated soil erosion is also required as, for much of the uplands, no evaluation of the rate of soil loss soil has been attempted. This study was initiated to investigate these fundamental issues and, from its results, to provide the information needed to address upland erosion in England and Wales.

Chapter 3

Upland erosion in England and Wales: a field study

3.1 INTRODUCTION

This research into upland soil erosion used two approaches to assess the extent and severity of erosion. The principal method was a large-scale field survey that measured erosion in the field between 1997 and 1999: this survey and its results are described here. Preceding the description of experimental method and survey logistics, Section 3.1.1 explores the usefulness of fieldwork as a research tool. Section 3.1.2 addresses the issue of scale: while the scale at which work is completed is largely dictated by the desired outcome, scale also determines the significance of the results.

3.1.1 Fieldwork as a research tool

Field observation is fundamental to the study of soils and geomorphology as a long-established, reliable means of evaluating environmental processes. Fieldwork provides opportunities to examine and identify erosion features and surface deposits closely and allows direct interpretation of erosional history. In fieldwork, the fundamental environmental and management elements that cause and affect erosion may be identified. Working in the field also provides opportunities to meet people who depend on the uplands either for their livelihoods or for recreation, and can therefore provide a new perspective on the effects and implications of soil erosion.

The drawbacks of fieldwork include its labour- and time-intensity. Problems specific to the uplands include the difficulties of site access caused by inclement weather and featureless terrain. Working on erosion has its own suite of difficulties, such as the challenges of estimating quantities of eroded soil from highly irregular features (Harrod, 1993) and the assumptions made when working with peat (Tallis, 1972).

Fieldwork continues to be an important constituent of scientific research, in spite of numerous, more technical alternatives such as modelling and remote sensing. Even within these, fieldwork is still an essential tool necessary for ground validation of model output and the interpretation of remotely-sensed images.

This research uses fieldwork as the primary means of establishing information on soil erosion. By supporting the fieldwork with alternative survey procedures, such as the aerial photographic study in Chapter 6, the advantages of both methods are combined. The field survey assesses the evidence for accelerated erosion on the ground over a two-year period while aerial photographs expand the temporal scale of the work and allow verification of the field data.

3.1.2 Scale and method problems in soil erosion research

The scale of field research is limited by the desired outcome and by financial- and time-constraints. As this research required information on the degree of eroded soil in upland England and Wales, it was conducted as a large-scale study of the upland area of both countries. Other erosion research has been completed on a variety of scales, from plot to field, catchment and regional scales (Grieve *et al.*, 1995; King *et al.*, 1998; Kirkby *et al.*, 1996; Large and Hamilton, 1991; Lopez-Blanco and Garcia-Oliva, 1998; Phillips *et al.*, 1981).

The variety of research scales creates problems for comparison of experimental methods and results, as discussed by Evans (1974). The factors that influence erosion, including soil, landscape morphology and climate, all operate to a greater or lesser extent at different scales (Kirkby *et al.*, 1996). As complex erosion and deposition patterns exist in even short gully lengths (Blandford, 1981), determination of soil loss requires careful selection of sampling sites. Irrespective of the scale selected for research, some processes and variations are inevitably neglected (Lane and Richards, 1997) and limited site numbers may bias results by failing to reflect landscape variability. Comprehensive assessments must involve sites at all facets of the hillslope and within the river to account for riverbank erosion (Morgan, 1995).

Simulations have shown that there is no linear relationship between small and large-scale measurements (Bergkamp *et al.*, 1996), and that small-scale results are site-specific (Lane and Richards, 1997). As small and large-scale work may not be reliably compared unless weighting factors are used, research at a variety of scales is advisable (Valentin, 1996).

Erosion may be measured using a wide range of methods. Historical erosion has been assessed using pollen, charcoal, chemical, physical magnetic, mineral or radiocarbon dating, archaeological records and local documentary evidence (Mackay and Tallis, 1996; Tallis, 1994; Tallis and Johnson, 1980; Tallis and Livett, 1994; Valentin, 1996). Contemporary erosion is frequently investigated using erosion pins (Brunstrom, 1976; Evans, 1977; Fanning, 1994; Murgatroyd and Ternan, 1983). Fly ash resulting from railway traffic has also been used as a soil marker (Hussain *et al.*, 1998). Quantifying soil loss from relatively small areas may be done using permanent bounded plots or metal troughs from which runoff and soil loss are monitored (Morgan, 1995).

Caesium-137 is frequently used as a tracer for recent accelerated soil erosion as it is concentrated in topsoils since its release as a by-product of atomic weapons testing between the 1950s and 1970s. An evaluation of erosion may also be gained through comparison of the soil profile with an assumed undisturbed profile (Mitchell *et al.*, 1983; Walling and Quine, 1990).

Physical measurement of rills involves a series of cross-sectional transects to allow area and volume or, with bulk density, mass of soil loss to be calculated (Evans, 1974, 1978; Harrod, 1993; Morgan, 1995). Sediment yields in rivers can be assessed using bedload traps (Newson, 1980) or suspended sediment samples from weirs (Francis and Taylor, 1989) and can provide an indication of the degree of erosion within a catchment. Sediment traps at gully heads and floors also provide information on soil movement (Crisp, 1966). Pin frames may be used to study changes in vegetation resulting from soil movement or grazing (Johnston *et al.*, 1971; Welch, 1984b; Welch, 1984c).

To assess riparian erosion rates, analytical photogrammetry may be used to create digital terrain models of a riverbank (Barker *et al.*, 1997). Alternatively, both manual and photo-electronic erosion pins are used to measure bank erosion rates (Bull, 1997). Track erosion has been measured using a 35 mm camera to create digital terrain models (Warner and Kvaerner, 1998).

Although some attempt has been made to collate information on upland soil erosion (Evans 1990a, 1992a), little overall impression of the scale and severity of erosion

exists because of the range of scales and methods used in upland erosion research. Only studies that describe the same area of interest are reliably comparable, and it is only with difficulty that results from different spatial scales may be mutually examined. Similarly, a lack of standard survey procedures means research completed at different times may not be confidently compared. These limitations highlight the need for a consistent methodology, developed and perhaps conducted under the control of a single operator. With reduced error and uncertainty, the potential for consistent results from a reliably tested, repeatable and broadly applicable innovative method could transform erosion research.

3.2 FIELD SURVEY AREA

The primary objective of this research was to determine the areal extent and causes of upland soil erosion in England and Wales using an extensive field study. The position and form of field sites at which erosion was assessed and the field protocol used are discussed in the following.

3.2.1 Site selection

The first and most important requirement in fieldwork is the use of an objective sampling strategy. While it lacks subjectivity, the random selection of sites inevitably results in clustered sampling. The aim of objectivity can be maintained without random selection if a grid-based system of site selection is used. Once the grid interval, or the distance between sites, is decided, the form of the sites that results is entirely a matter of chance. Such a system was used by the Soil Survey and Land Research Centre (SSLRC; then the Soil Survey of England and Wales) in the completion of the first National Soil Inventory (NSI) between 1979 and 1982 (Jarvis *et al.*, 1984).

The sampling system used then was an orthogonal grid with a sampling interval of 5 km. An advantage of this grid system is that, unless the upland area is less than 25 km², it is likely to be sampled at least once. A disadvantage of the system is the number of field sites that result. While a large number of sites reduces the statistical variance of the results, it also requires considerably greater time and financial input at the data collection, input and analysis stages.

3.2.2 NSI field sites

Fieldwork was carried out throughout the uplands using a network of sites based on the National Soil Inventory (NSI). In the NSI, sites are situated at the intersections of the 1 km and 6 km eastings and northings. There are, therefore, four sites within each 100 km² area: an example is shown in Plate 3.1 where the field sites are SN 210 210, SN 260 210, SN 210 260 and SN 260 260.

Inevitably, some grid intersection sites fell upon tracks, roads, reservoirs, urban areas, forestry or similarly disturbed ground. Where this happened, substitute sites were sought by deviating systematically from the original location. The first deviation was 100 m to the north: if this failed to remove the site from the disturbed zone, deviation was 100 m to the east. If a suitable site was not found within two rotations through the principal compass points, the second being at 200 m from the intersection, the field site was abandoned.

The difficulty of defining the upland area has been discussed in Chapter 1 where it was shown that upland extent is frequently inferred from vegetation composition (Bunce, 1987). In this work, NSI sites on which upland plant communities were recorded by the NSI surveyors were used. Consequently, field sites were located on grassland, heathland and montane vegetation, or on bog above 200 m: sites on agricultural land or within woodland and forestry were disregarded.

Using this vegetation classification, 399 upland NSI sites were selected for survey (Table I; Appendix 1). The NSI reference of each site was based on the index letters of the appropriate 100 km square of the National Grid, followed by the number of the 1:25 000 O.S. 10 km square sheet. After a solidus (/), the co-ordinates of the site to the nearest 100 m are given. For example, a site at grid reference SD 260 310 has an NSI reference of SD 23/6010, thus distinguishing it from conventional grid references. Deviated sites, such as SH 71/6061 and SH 94/610100, have slightly different references due to their departure from the original NSI site.

3.2.3 Countryside Survey 2000 field sites

The Countryside Survey 2000 scheme (CS2000) is a database of randomly selected 1 km² National Grid Squares (www.nmw.ac.uk/ITE/, 2000). This major national audit of the habitats, plants, landscape features and land-types of the British countryside

provided a further collection of established field sites for inclusion in this project. In total, twenty-seven CS2000 sites with upland vegetation were selected and added to the NSI total of 399: a list of CS2000 sites is given in Table II (Appendix 1). As the centre of the square was used, CS2000 field sites are distinguishable by their grid reference, e.g. SD 23/7525. These sites were surveyed in the same manner as NSI sites and as described in Section 3.3. The distribution of all field sites is shown in Plate I (Appendix 1).

3.2.4 Site description

NSI and CS2000 sites, hereafter referred to collectively as the field sites, were treated in the same way during this survey. Each was a circular site, based on a central point called the node, and extending to a radius of 50 m. Circular sites have the advantage of a uniform distance between the circumference and the node and provide the greatest area to circumference ratio. However, while a 100 m-sided square has a uniform area of 1 ha, a 50 m-radius circular site has an area of 0.7854 ha.

Within each field site, the extent of erosion was examined initially within 10 m radius of the node and again within 50 m radius of the node. These arbitrary boundaries were used to gain some indication of the influence of field site size on erosion measurements, and thus to contribute to the development of sound protocols for assessments of erosion and other large-scale environmental processes.

Field sites were accessed during the summer months to avoid the harsher winter weather at high altitudes. Where possible, landowners were identified and permission obtained before land was accessed, although this was not always achieved. In many cases, sites were located on common land or on open-access estates: in those cases no contact was made with the landowner.

Ordnance survey maps, at 1:25 000 or 1:50 000 scale, were used to navigate to and from field sites. In addition, a Geographical Positioning System (GPS: Magellan 2000), correct to 100 m, was used on sites with few navigational features or in extreme weather conditions when visibility was limited.

3.3 FIELD SURVEY PROTOCOL

The original site visits were largely completed throughout the summer and autumn of 1997, although some residual sites were not visited until early spring 1998. A second, limited field survey was completed in the summer of 1998 and the final and complete field survey was carried out between April and October 1999. Here, these surveys are described, with full descriptions of the protocols used to assess soil erosion.

3.3.1 Field surveys

The original field survey was initiated in July 1997: because of the limited field season remaining after this date, additional surveyors were recruited to help complete the field survey. The same basic survey proforma was used by all surveyors, although some refinements were made throughout the first field survey: these adjustments were applied to all field sites in both the 1998 and 1999 surveys. In Appendices 2 and 3 the original and adapted survey forms are provided.

An abbreviated field survey, consisting of 100 field sites, was completed in 1998. In 1997, a system for measuring erosion within linear gullies was developed: the new protocol was applied in 1998 to all field sites on which gully erosion had been recorded but had not already been measured. In addition, access to CS2000 field sites was unavailable until the summer of 1998, necessitating a second, intermediate field survey. Finally, the 1998 survey permitted erosion assessment on the small number of field sites that had been omitted in the 1997 survey.

Between April and October 1999, every field site was revisited to allow changes in site status, particularly in erosion extent or state, between 1997 and 1999 to be assessed. All gully traverses were repeated (Chapter 4), as were measurements of field site attributes such as slope, aspect and grazing pressure. The 1999 survey was the first complete field survey to be conducted using the final, more comprehensive survey protocol. All results on erosion extent and severity presented in this chapter are based, therefore, upon details from that survey (Section 3.4).

3.3.2 Measuring erosion on field sites

An objective, reliable and quickly completed means of estimating erosion area and volume that was applicable to the wide diversity of upland erosion forms was required, as described in Section 1.3. As erosion features are caused by a single or several factors working together, they are usually irregular in form and extent. It is difficult therefore to estimate soil loss from a field site without risking over- or underestimation. Estimates of soil loss are usually insufficiently specific to lend themselves to calculations of erosion change over time.

To minimise these potential problems and to ensure that this survey measured erosion as thoroughly as possible, every discrete erosion feature located within the field site was measured individually. The length, depth and width of each feature were recorded in the spaces provided in the survey form (Appendix 3). Irregularly-shaped erosion features were split into their uniform constituent parts. Using these measurements, both area and volume of eroded soil were determined for individual features and for entire field sites. As each erosion feature was also subdivided into its bare and vegetated soil proportions, an impression of the degree of erosion recovery was also gained.

The advantages of this technique more than compensated for the effort of its completion. Firstly, the thorough measurements required ensured that erosion scars located within the field site were not accidentally omitted from the survey. Secondly, by recording the dimensions of individual features it was impossible to miscalculate seriously the extent of the erosion, a very real concern when erosion extent was estimated.

In addition to measuring the dimensions of each erosion feature, its type and most probable cause were recorded. Usually, visual assessment is sufficient to disclose the source of erosion scars: as described in Chapter 1, erosion features are highly distinctive in form and location. Recording this information allowed the contribution of erosion causes to the overall extent of degraded soil to be determined. The final advantage of the technique arose from the quick positional record made for each erosion scar. This small piece of information was not extensively used in this research, but will be useful in any future project that aims to return to some, or all field sites to investigate changes in erosion over time.

In addition to these comprehensive measurements of individual erosion features, particular attention was paid to linear erosion gullies located within the field site, from which it was intended to derive additional information on rates of soil loss. For this reason, a new and detailed protocol was devised for the exclusive measurement of gully erosion: details of this recording procedure, as well as the results it provided, are provided in Chapter 4.

3.3.3 Environmental variates recorded on field sites

Environmental variates were also recorded on each field site (Tables 3.1 and 3.2). Continuous data (variables) were limited to altitude and slope, while the grouped factors recorded were grazing pressure, vegetation and field site morphology. Although aspect is strictly a circular variable, it is treated here as a grouped factor. Information on the soil classification at each NSI was available from the original SSLRC field survey, completed between 1979 and 1982 and described in Avery (1980). Soil subgroups were also grouped hydrologically into dry mineral, wet mineral, wet peaty mineral and peat soil classes.

True slope is the greatest angle a surface makes with a horizontal plane at a given point. Using a hand-held clinometer, slope was measured across the diameter of the field site by determining the angle between eye-level of the observer and a fixed point at the same height at the field site edge. Where there was no break of slope within the field site, a single slope measurement was made. On field sites with irregular slopes, slope was averaged from measurements on each slope facet.

The principal aspect of the field site was recorded as one of the eight principal compass points. The morphology of each field site was visually assessed across the 50 m-radius of each site and classified as concave, convex or linear: the limited field site area ensured that complex landforms were avoided. Concave slopes focus water flow and are called receiving. Sites on convex slopes have a shedding, outward curvature with disparate water flow while linear sites have even, unfocussed flow (Soil Survey Staff, 1960). Assessment of landform was visual only, and no numerical classification was used.

Originally, the vegetation of each field site was classified as one of three groups according to the principal plant species growing immediately around the field site node. These were heathland, dominated by *Calluna*, *Erica* and *Vaccinium*; grassland, dominated by a range of upland grasses including *Agrostis*, *Nardus* and *Deschampsia*, and bog, colonised mainly by *Sphagnum*, but also by other bryophytes and *Eriophorum*. During the final field survey, however, it was necessary to modify the vegetation groups. Additional classes accounted for bracken-dominated sites, for sites where trees and brambles had invaded (scrub) and for sites where species diversity reflected two or more vegetation classes (grass/heath and heath/bog).

The intensity of grazing on field sites was recorded using an adapted version of the English Nature Grazing Index (English Nature, 1995), which determines grazing intensity from the height and condition of heather. Indications of overgrazing start with cropped vegetation and the loss of flowering heads and progress to signs of topiary. Heather subjected to intense grazing assumes a drumstick morphology, while *Ulex* or *Crataegus* shrubs may show acute pruning up to sheep-height of about 1 m; beyond this, the shrub or tree usually shows complete recovery (Plate 3.2). Vegetation observations on grazing pressure were supplemented with consideration of the extent of faecal deposition by sheep, cattle, rabbits and horses before grazing intensity was assigned on a rising scale of 0 to 5. No account was taken of invertebrate contribution to grazing pressure.

3.4 RESULTS FROM THE 1996 FIELD SURVEY

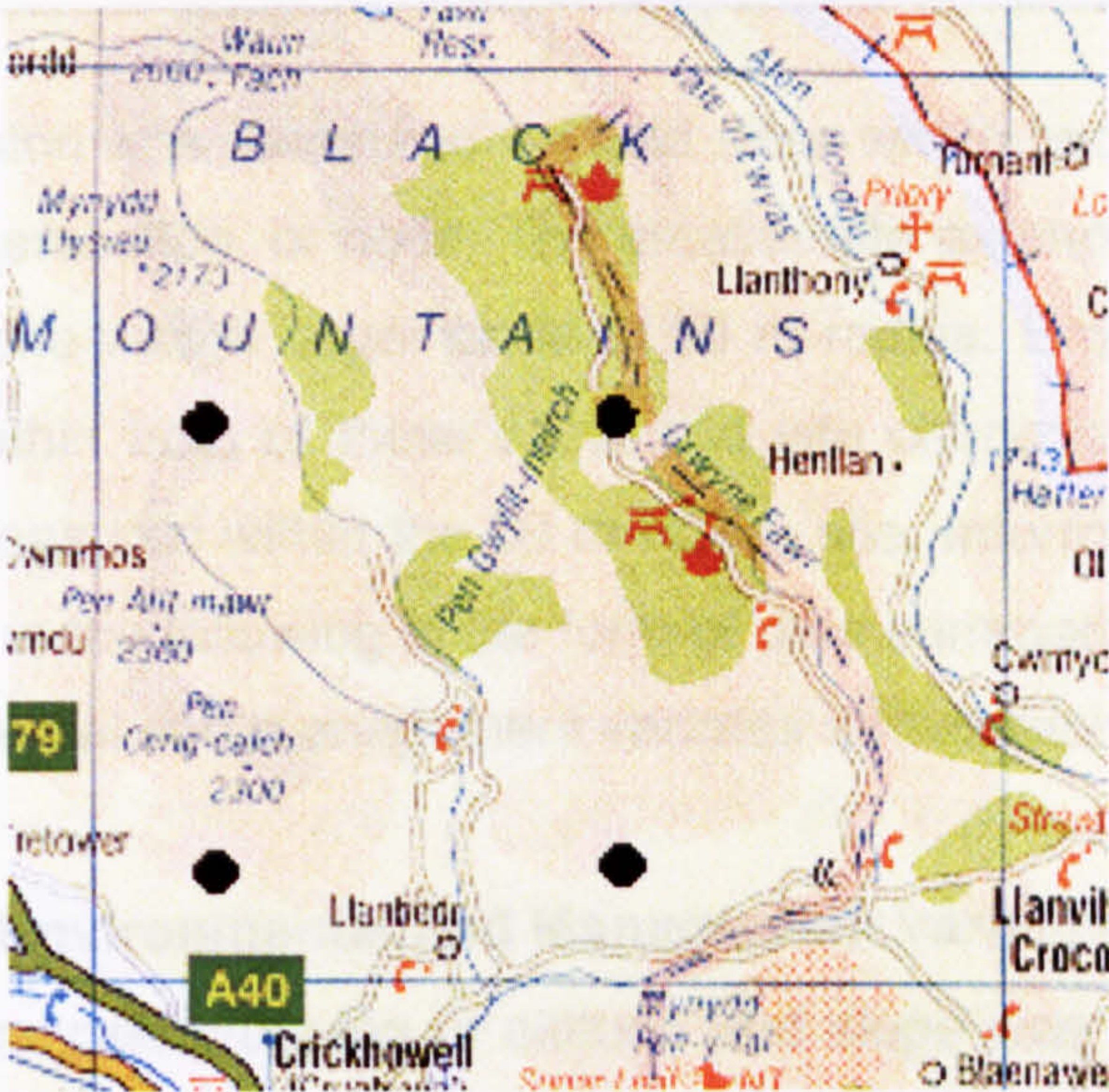


Plate 3.1 Location of field sites within 100 km² square SN22 (Abergavenny). Reproduced from Ordnance Survey maps by permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office. © Crown Copyright NC/00/590.



Plate 3.2 The intense grazing pressure exerted by sheep on this *Crataegus* has resulted in advanced topiary up to the maximum sheep reach: above this, the bush recovers well.

3.4 RESULTS FROM THE 1999 FIELD SURVEY

The extent of erosion was measured on field sites within two circular sites centred on the NSI grid intersection, or node. The smaller site extended to a radius of 10 m while the second site was a larger circle of 50 m radius. Erosion area and volume were calculated within both of these sites, and site characteristics, including slope and relief, were measured within the 50 m radius site. Information from the two site sizes is presented in the following in the form of data summaries and of relationships between environmental and management variates and erosion.

3.4.1 Analysis of Environmental and Management variates

In the following analysis, grouping of altitude and slope was necessary because of the variability within the dataset, caused by the large number of individual observations and the wide range of erosion extents recorded on field sites (Table 3.1). The environmental factors were recorded in groups (Table 3.2).

Table 3.1 Subdivisions of continuous variables measured on field sites

Altitude (O.D.)	Slope
≤200 m	≤3°
201-300 m	4-7°
301-400 m	8-11°
401-500 m	12-15°
501-600 m	16-24°
601-700 m	≥25°
701-800 m	

Table 3.2 Grouped environmental variates measured on 50 m sites: soil subgroups are in classes.

Aspect	Morphology	Vegetation	Soil subgroups (in classes)				Grazing Pressure
			Dry mineral	Wet mineral	Wet peaty mineral	Peat	
Level	Concave	Scrub	3.13	6.41	7.21	3.11	1 Low
NE	Linear	Bracken	3.14	6.42	8.71	10.11	2 Low -
E	Convex	Upland Grass	5.42	6.43		10.13	medium
SE		Grass/Heath	5.47	6.51		10.23	3 Medium
S		Upland Heath	6.11	6.52			4 Medium -
SW		Heath/Bog	6.12	6.54			high
W		Bog	6.21	7.13			5 High
NW			6.31	7.15			
N			6.32				
			9.2				

3.4.2 Statistical analysis of data

Evidence of relationships between the environmental variates and field site erosion, as well as the statistical significance of those relationships, was tested using Genstat (Version 5, Release 4.1). The individual relationships between erosion and each variable or factor were assessed, before the effects of interactions between variables and factors on erosion were established. A description of all statistical tests is provided in Appendix 4.

Frequency distribution histograms show that erosion measured within both 10 m and 50 m field sites was not distributed normally and had a large positive skew (Figure 3.1). As all parametric statistical applications require normally distributed data, the area and volume of erosion were log transformed, resulting in near-normal distribution curves (Figure 3.1). The summary statistics in Tables 3.3 and 3.4 also show that agreement between mean and median is greater for transformed, and hence normal, data.

In total, 74 field sites were eroded within 10 m of the node: this number rose to 206 for eroded 50 m field sites. Respectively, these values represent 18.5% and 51.6% of the total number of field sites surveyed.

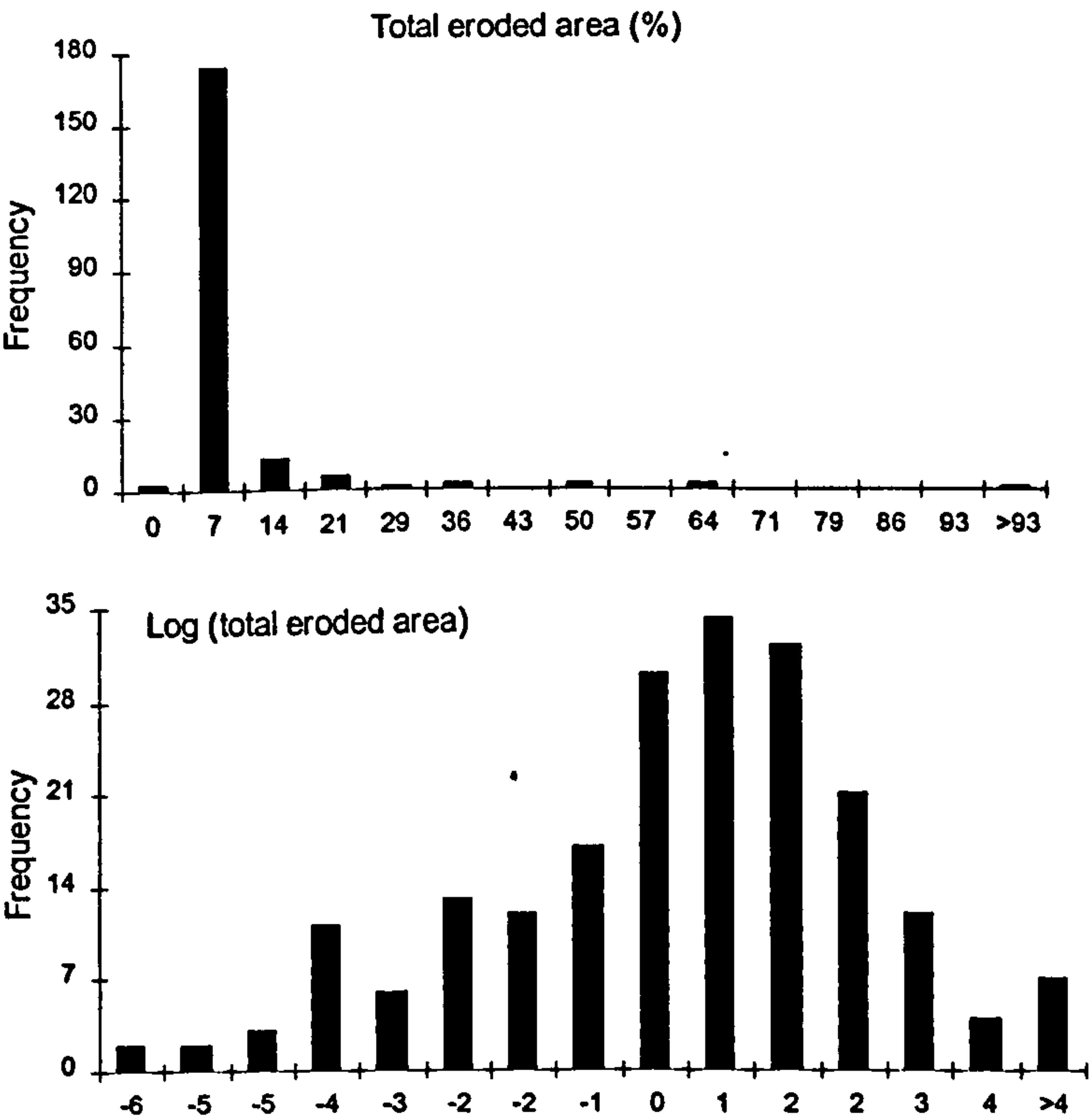


Figure 3.1 Frequency distributions of raw and transformed eroded area recorded on 50 m field sites.

The usual accepted level at which statistical significance is tested is 95%, or F probability (F pr) of 0.05. In the analyses presented here, however, the number of observations varied between 74 and 206 and, correspondingly, significance was based on a large number of degrees of freedom. Because of this, and the inherent high variability of field data, all relationships with statistical significance greater than 90% (F pr < 0.100) were considered.

Table 3.3 Summary details for eroded 10 m field sites: both raw and transformed data are presented.

	Total area %	Total volume (m ³)	Log (total area)	Log (total volume)
Mean	9.03	18.26	0.50	0.30
Standard Error	1.74	5.56	0.08	0.11
Median	2.85	1.40	0.45	0.15
Standard Deviation	14.94	47.80	0.68	0.96
Sum	668	1351	36.68	21.98
Count	74	74	74	74

Table 3.4 Summary statistics for both raw and transformed erosion area and volume, recorded within 50 m field sites.

	Total area (%)	Total volume (m ³)	Log (total area)	Log (total volume)
Mean	4.77	432	-0.08	1.27
Standard Error	0.81	98	0.07	0.09
Median	1	16.58	0	1.22
Standard Deviation	11.60	1408	0.96	1.27
Sum	983	88962	-17.24	263
Count	206	206	206	206

3.5 EROSION, THE ENVIRONMENT AND LAND MANAGEMENT PRACTICES

Results are presented from analysis of the 1999 field data, which provided the most complete and uniform data on soil erosion. Results from 10 m and 50 m sites are presented together because they frequently complement each other and also because the same environmental variates are used to describe their erosion. In addition, the juxtaposition of 10 m and 50 m data allows direct comparison between the extents of erosion measured on each field site.

3.5.1 Altitude and erosion

The high variability and wide range of erosion records made at different altitudes effectively masked any trends in the data (Figure 3.2). To compensate, the range of field site altitudes was subdivided into seven groups and mean erosion recorded within each altitude group was plotted, as in Figure 3.3. The variability of the dataset is still represented by standard error bars, but the overall relationship between erosion and altitude may be more clearly seen.

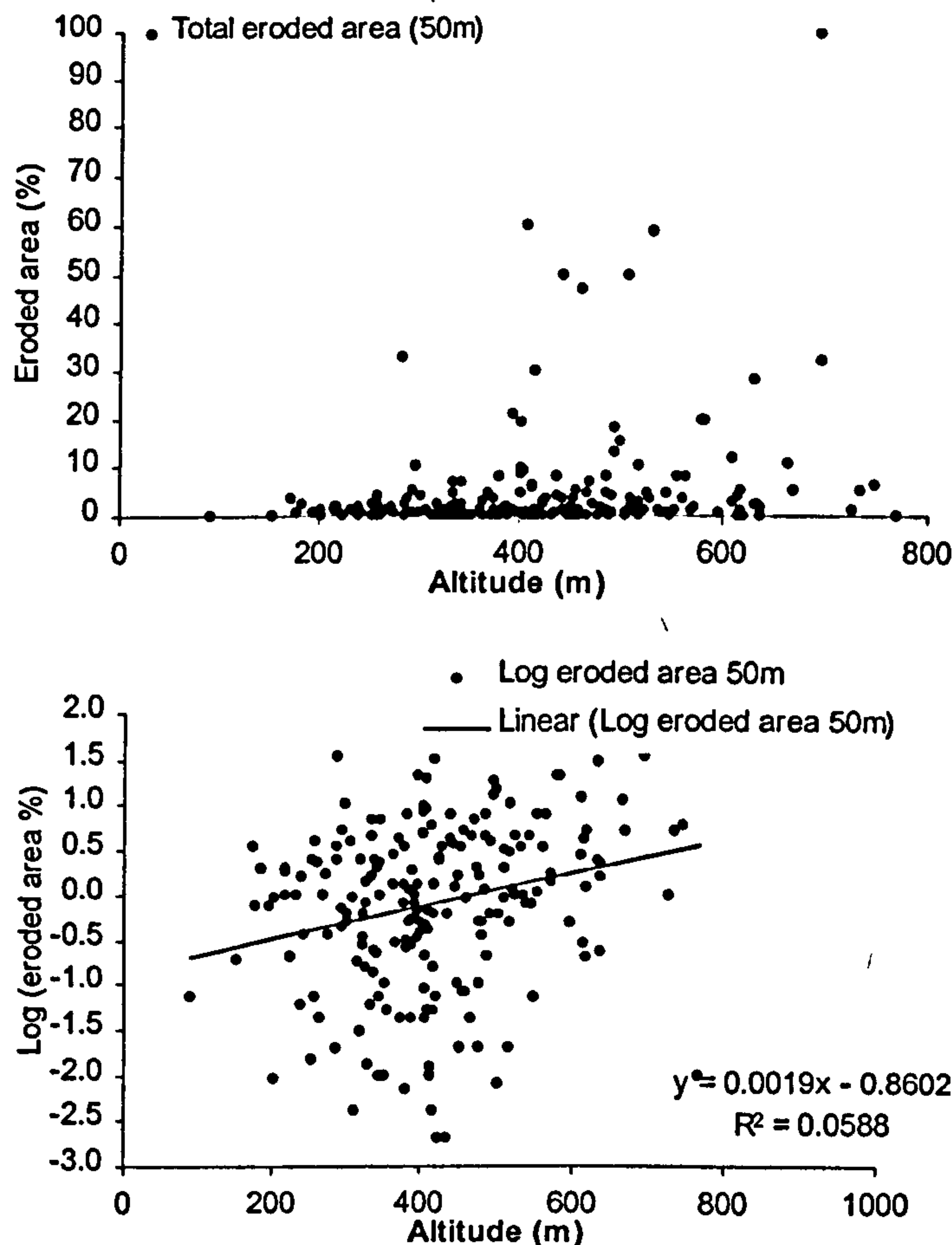


Figure 3.2 Eroded area recorded on 50 m field sites and plotted against field site altitude. The high variability of both raw and transformed data masks the relationship between altitude and erosion.

In Figure 3.3, the relationships between altitude and erosion measured on 10 m and 50 m field sites show that, overall, erosion extent increased with height above sea level. Eroded area remained steadily low below 400 m: above this, it increased sharply. Eroded area and volume on 50 m sites and 10 m erosion volume all declined in erosion extent above 700 m. This may be due to the distribution of field sites: 69% of 10 m field sites and 76% of 50 m field sites were at altitudes of less than 500 m, with fewer total and eroded sites at the highest altitudes (Table 3.5).

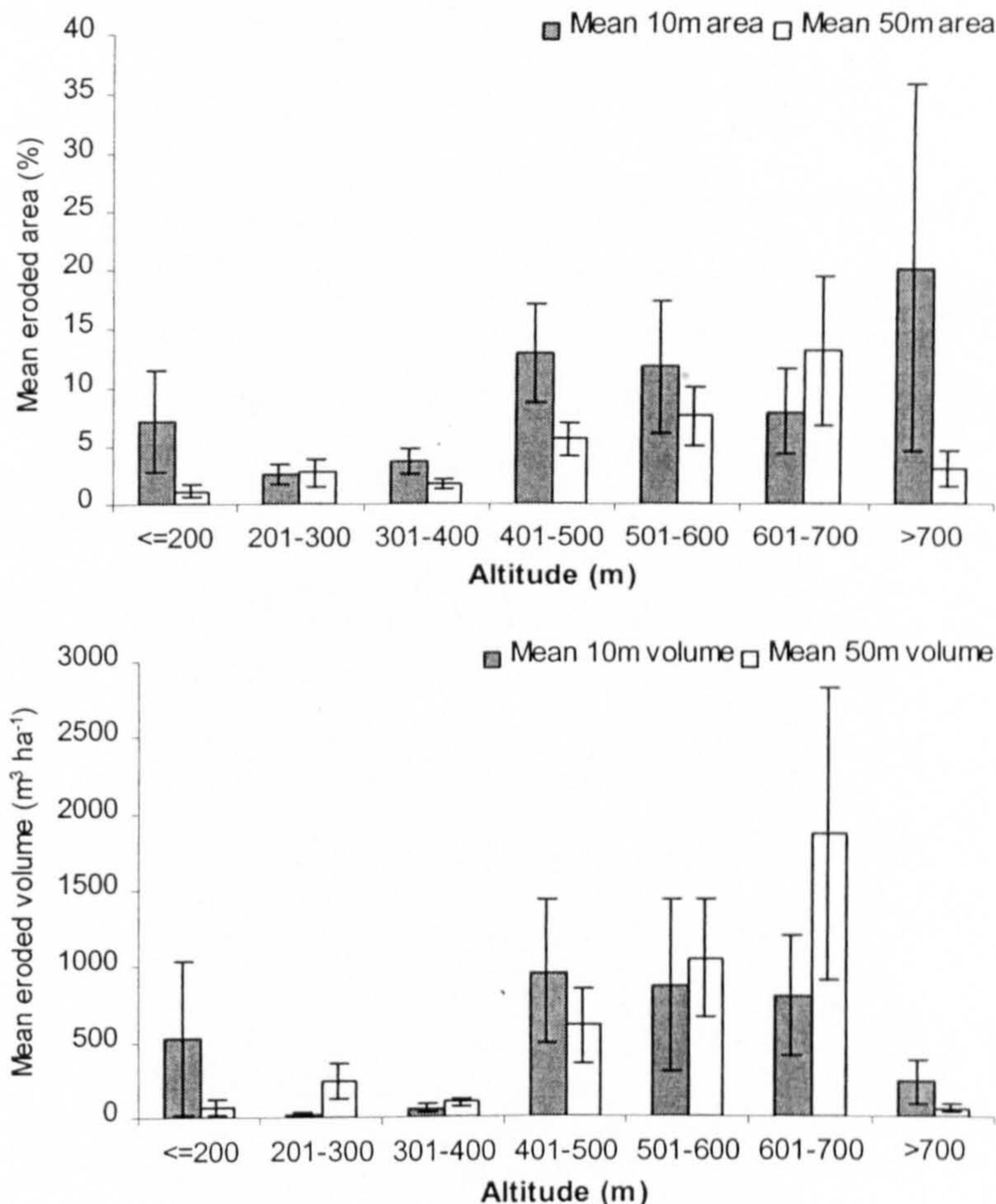


Figure 3.3 Changes in mean eroded area and volume recorded within 10 m and within 50 m, classified in altitude groups. Standard errors of the data are presented ($SE = SD/\sqrt{n}$).

The importance of different causes of erosion also varied with altitude (Table 3.5). At lower altitudes biotic erosion dominated while water-induced erosion was more frequent at higher altitudes, particularly above 400 m. The shift in erosion cause began at altitudes between 301 m and 400 m where biotic factors accounted for erosion on more field sites than water. By 401 m to 500 m, the emphasis had shifted towards water-caused erosion. At altitudes of over 500 m, water erosion was the dominant recorded cause of field site erosion (Table 3.5).

Statistical analysis of erosion and altitude revealed no relationship between 10 m eroded area and altitude. A significant and positive relationship was identified, however, between altitude and 10 m eroded volume (F pr 0.004), although the variance accounted for by that relationship was low at 9.7%. From that linear regression, an increase of $1.005 \text{ m}^3 \text{ ha}^{-1}$ of eroded soil was expected for every

single metre increment in altitude. All statistical tests are summarised in Appendix 4, Table I.

There were significant relationships between altitude and both eroded area and volume on 50 m field sites (F pr <0.001 and <0.001 ; R^2 5.7 and 10.2 respectively). The predicted increase in area with increasing altitude was $78.5 \text{ m}^2 \text{ m}^{-1}$. Similarly, the relationship between altitude and erosion volume predicted an increase of $1.007 \text{ m}^3 \text{ ha}^{-1}$ with each single metre increase in altitude. Analyses that examine the statistical significance of interactions between altitude and other environmental variates are discussed in Section 3.5.9 and summarised in Tables I and II (Appendix 4).

Table 3.5 The number of 10 m and 50 m field sites with erosion caused by biotic, water or wind factors.

Altitude (m)	10 m field sites			50 m field sites			
	Total	Biotic	Water	Total	Biotic	Water	Wind
<200	3	2	1	6	4	2	
201-300	6	4	2	28	20	8	
301-400	18	10	8	58	39	18	1
401-500	25	10	15	64	34	30	
501-600	9	2	7	30	6	23	1
601-700	10	2	8	16	3	13	
>700	3	2	1	4	2	2	
Total	74	32	42	206	108	96	2

3.5.2 The influence of slope angle on erosion

Overall, the erosion measured within both 10 m and 50 m field sites decreased with increasing slope angle, but only after an initial peak at low slopes (Figure 3.4). For both 10 m and 50 m erosion, this peak occurred at a threshold slope of 4-7°, after which the amount of erosion declined. The mean eroded area and volume increased again on slopes steeper than 16° for 50 m data, and steeper than 25° for 10 m data.

Table 3.6 summarises the causes of erosion in relation to slope. At slopes up to 7°, there was a higher incidence of water erosion than of biotic erosion. This ratio was reversed however on slopes of 8° and steeper where biotic erosion was responsible for greater numbers of eroded sites than water erosion. Within the steepest slope group ($\geq 25^\circ$), numbers of biotic- and water-eroded sites were almost equal.

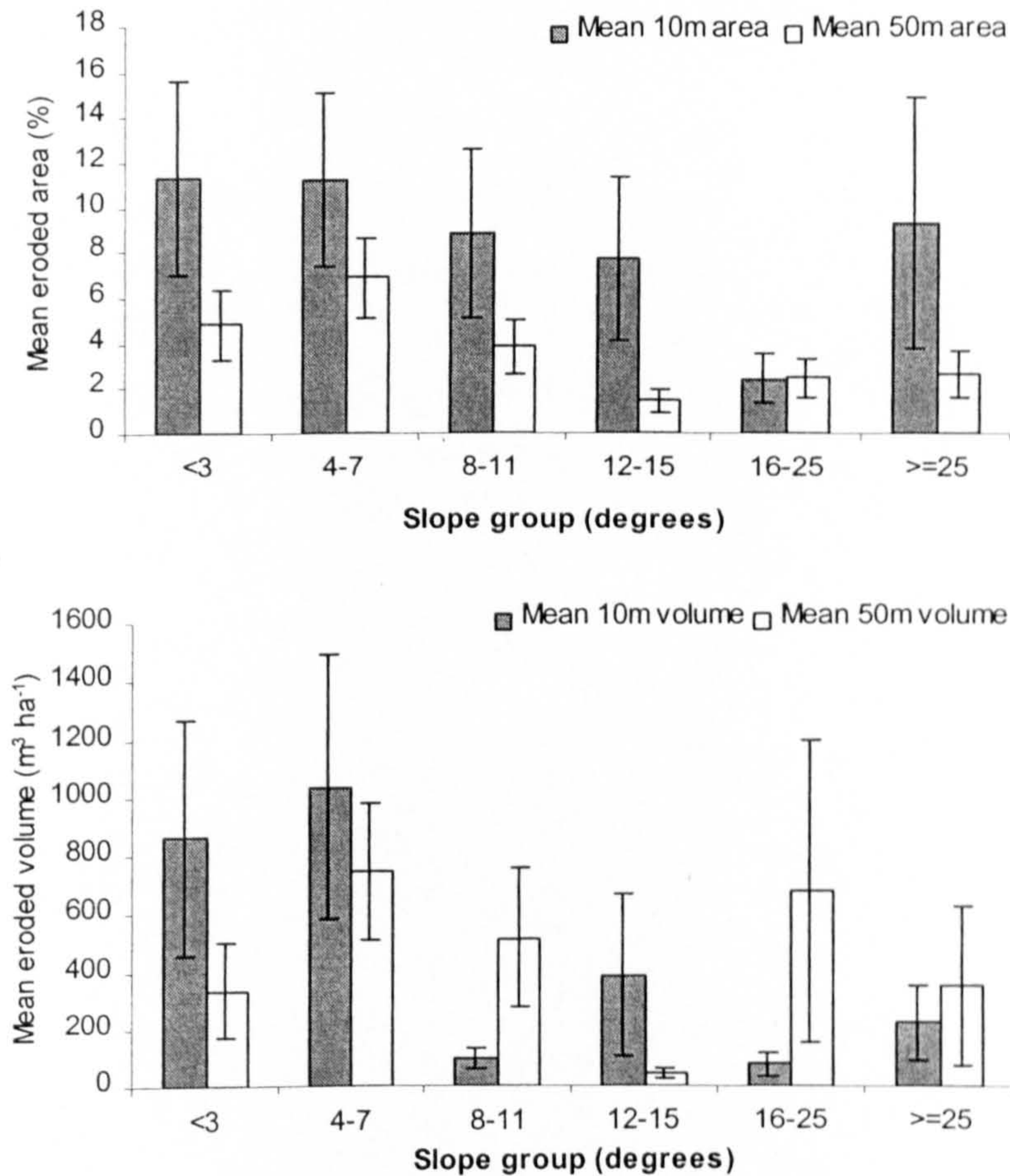


Figure 3.4 Changes in mean eroded area and volume with increasing slope angle. Standard errors of the data are presented ($SE = SD / \sqrt{n}$).

Table 3.6 Numbers of eroded 10 m and 50 m field sites categorised by erosion cause and slope.

Slope (°)	10 m field sites			50 m field sites			
	Total	Biotic	Water	Total	Biotic	Water	Wind
<3	11	3	8	28	12	14	
4-7	26	6	20	86	35	50	1
8-11	10	5	5	35	22	13	
12-15	7	4	3	19	13	5	1
16-24	11	10	1	24	18	6	
>=25	9	4	5	14	8	6	
Total	74	32	42	206	108	94	2

In the statistical analyses, there was a significant linear regression between slope and 10 m log erosion volume (F pr 0.079; $R^2 = 2.9$). With each single degree increase in slope eroded volume was predicted to decrease by $1.05 \text{ m}^3 \text{ ha}^{-1}$. The relationship between slope and 10 m eroded area was barely significant (F pr 0.101;

R^2 2.4). Eroded area was predicted to decrease by 1.03% (3 m²) with every degree increase in slope.

For 50 m data, linear regressions of slope and erosion were significant for both area and volume (F pr 0.073 and 0.033 respectively). In both cases however, the adjusted R^2 s, which accounted for the inherent variability of the dataset, were very low (R^2 1.1 and 1.7). Again, there was a predicted decrease in erosion with increasing slope: a decline of 1.04% was calculated in area while volume was predicted to decline by 1.05 m³ ha⁻¹ with every single degree increase in slope angle.

For eroded area recorded within both 10 m and 50 m, and for eroded volume recorded within 10 m field sites, a high degree of the data variance was explained by polynomial relationships between erosion and slope. The equations and R^2 values for these relationships are:

$y = 0.4127x^2 - 3.9644x + 16.075$	$R^2 = 0.4962$
$y = 0.1243x^2 - 1.6327x + 7.5034$	$R^2 = 0.5615$
$y = 42.719x^2 - 465.08x + 1426.7$	$R^2 = 0.6582$

In combination with the low significances and R^2 values obtained for linear regressions, the polynomial equations above suggest that erosion is not solely affected in its distribution or extent by slope. It is therefore necessary to investigate interactions between slope and other environmental variables, and their combined effects on erosion (Section 3.5.9).

3.5.3 Soil subgroups and erosion extent

As discussed in Section 3.3, the soil immediately around the NSI node was described and assigned to a specific soil subgroup (Avery, 1980). This soil information was treated in two different ways: firstly, the 20 different soil subgroups involved were related individually to erosion, as in Figure 3.5: soil subgroups for which there was only one representative site were omitted. In the second method, the twenty soil subgroups were further classified as in Section 3.5.4.

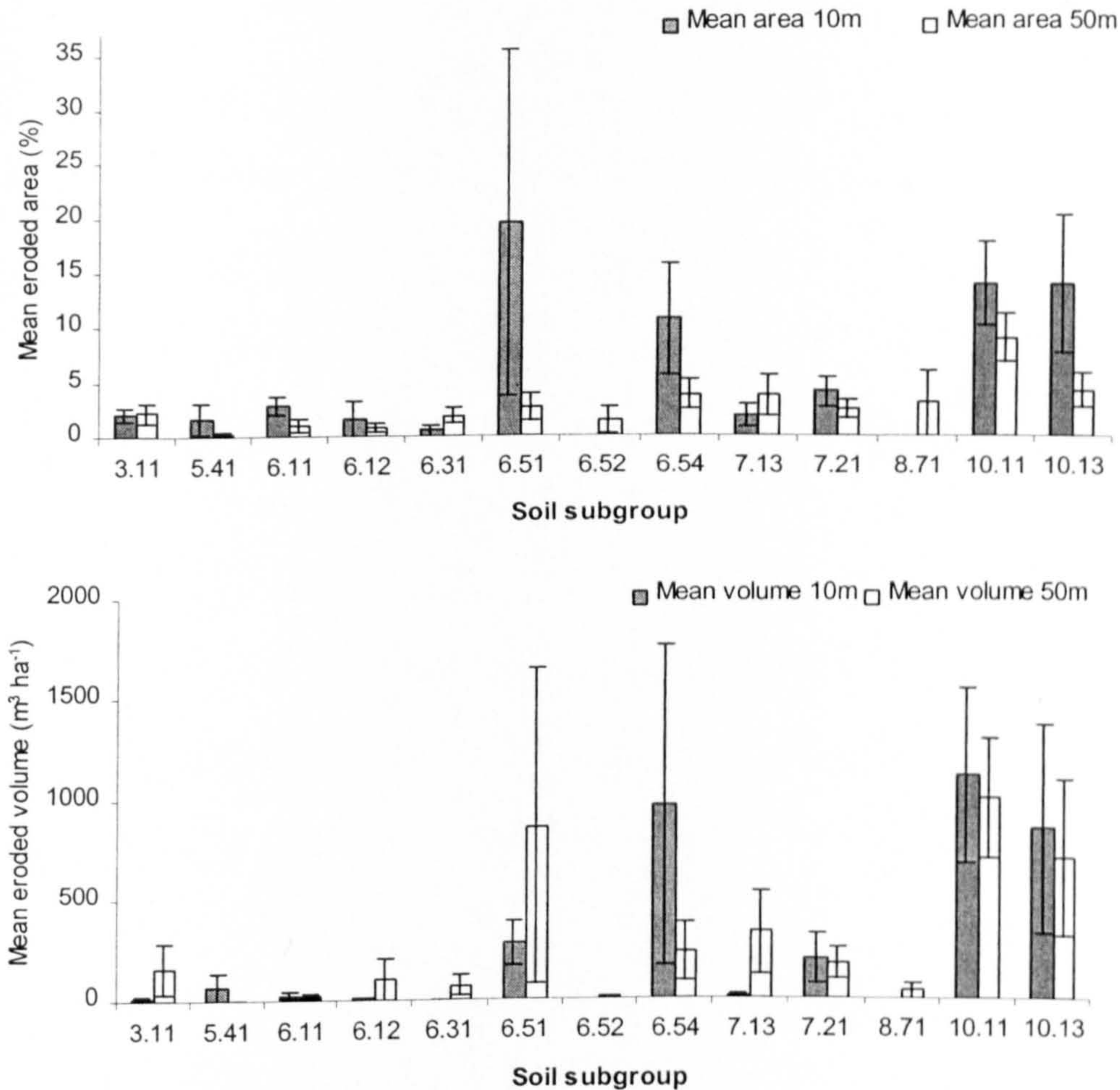


Figure 3.5 Mean eroded area and volume within 10 m and 50 m field sites, plotted against soil subgroup. Subgroups that occurred on only one field site are omitted. Standard errors of the data are presented ($SE = SD / \sqrt{n}$).

Analysis of variance was used to assess the relationship between soil subgroup, as a factor, and erosion. Significant relationships existed between 10 m eroded area and volume and soil subgroup (F pr 0.045 and 0.001 respectively). Mean erosion was greater on subgroups 10.13 and 10.11 than on 3.11, 6.12 or 6.31. Within 50 m, there were also significant relationships between eroded area and volume and soil subgroup (F pr 0.029 and 0.002 respectively). The only significant difference in eroded area was between subgroups 10.11 and 5.41, which, in Figure 3.5, represent the greatest and least mean eroded areas respectively. Eroded volume on 5.41 was also statistically different from that on soils subgroups 6.54, 7.13, 10.11 and 10.13.

Table 3.7 Eroded 10 m and 50 m field sites, distinguished by cause of erosion and soil subgroup.

Soil subgroup	10 m field sites			50 m field sites			
	<i>Count</i>	<i>Biotic</i>	<i>Water</i>	<i>Count</i>	<i>Biotic</i>	<i>Water</i>	<i>Wind</i>
3.11	4	3	1	9	8	1	
3.13	1	1	0	1	1	0	
5.41	2	2	0	6	5	1	
5.42	1	1	0	1	1	0	
6.11	3	2	1	9	7	2	
6.12	2	2	0	4	4	0	
6.21	0	0	0	1	1	0	
6.31	2	2	0	7	5	2	
6.32	0	0	0	1	1	0	
6.42	1	0	1	1	0	1	
6.43	1	1	0	1	1	0	
6.51	3	1	2	16	11	5	
6.52	0	0	0	3	3	0	
6.54	4	2	2	8	6	2	
7.13	2	1	1	5	3	2	
7.21	13	7	6	45	27	18	
8.71	1	0	1	3	2	1	
9.2	1	1	0	1	1	0	
10.11	27	5	22	70	17	51	2
10.13	6	1	5	14	4	10	
<i>Total</i>	<i>74</i>	<i>32</i>	<i>42</i>	<i>206</i>	<i>108</i>	<i>96</i>	<i>2</i>

3.5.4 Soil classes and erosion extent

The classification that follows divided the 20 soil subgroups into four soil classes based on a hydrological gradient between freely draining and permanently saturated soil conditions. Soil subgroups 6.54 and 7.13 were therefore placed in the seasonally waterlogged wet mineral class, while 10.11 and 10.13 were the principal components of the wettest peat class. Subgroup 5.41, meanwhile, was in the driest class (Table 3.2). It is logical that these soil subgroups, which are the principal components of different hydrological classes, were found significantly different in Section 3.5.3. The lack of statistical distinction of the other soil series within this classification may reflect soils for which a hydrological classification is not the optimal discerning characteristic. Other soil subgroups, such as 6.51 and 6.54 cover a range of hydrological conditions, depending on the thickness of their thin peaty or

peat-derived topsoils (Hogan and Harrod, 1982). Table 3.2 shows all soil subgroups in their respective classes.

In Figure 3.6 there are obvious similarities between the patterns of erosion recorded on 10 m and 50 m field sites. The mean areas of erosion were greatest in the wet mineral and peat classes, although the distinction was less marked for 50 m data. Eroded volume was also markedly greater in these two soil classes and was particularly low on dry mineral soils.

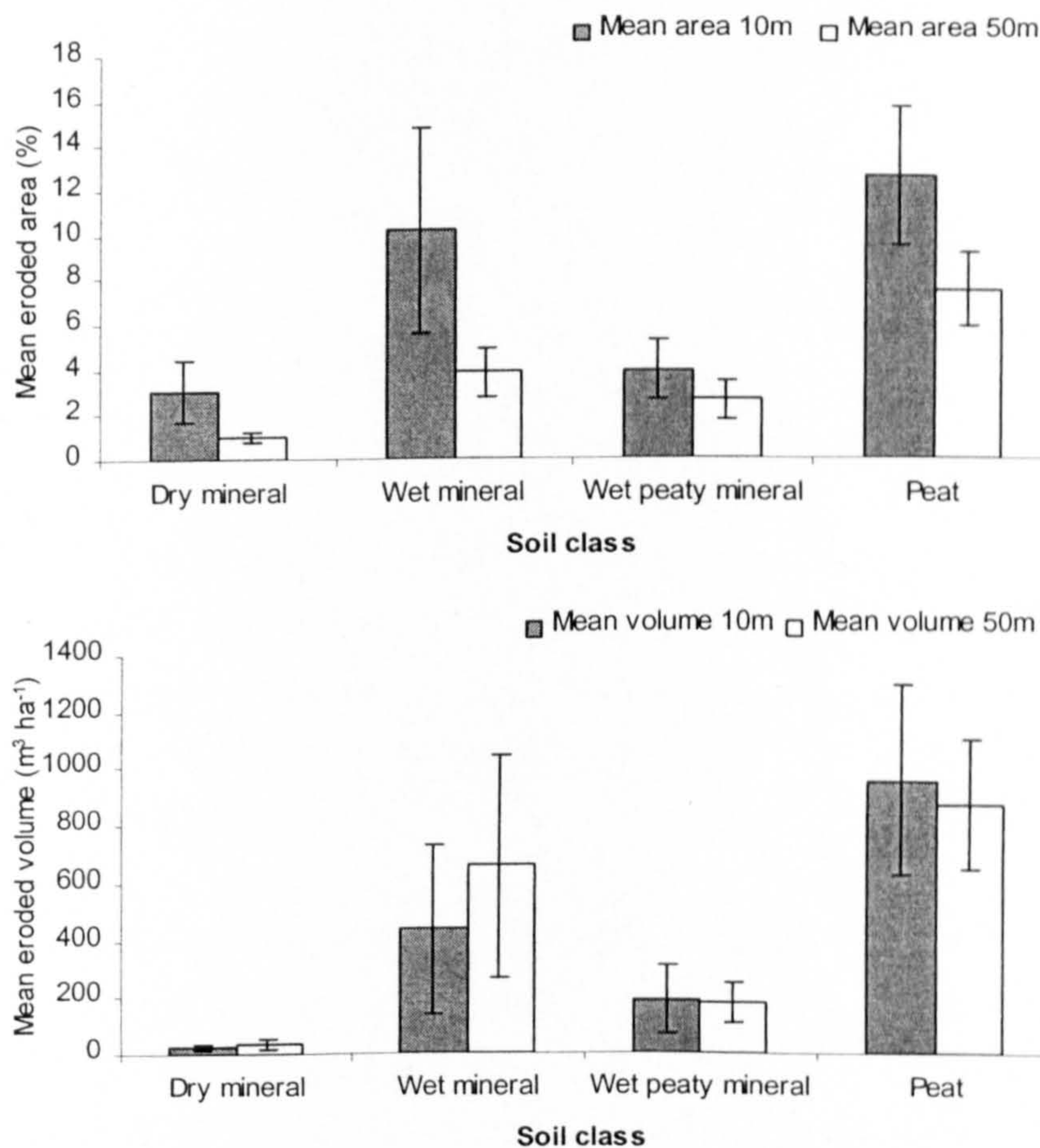


Figure 3.6 Mean area and volume of erosion recorded within 10 m and 50 m field sites and categorised in soil classes. Standard errors of the data are presented ($SE = SD / \sqrt{n}$).

Statistical analyses confirm the differences between soil classes: ANOVA identified significant relationships between both 10 m eroded area and volume and soil class (F pr 0.027 and <0.001 respectively). The mean area of erosion was significantly greater on sites in both wet mineral and peat classes than on dry mineral soils. Significant differences were also established between eroded volumes measured on

dry soils and on wet mineral soil groups, and between both dry and wet mineral soils and peat: again the highest mean erosion occurred on peat and wet mineral soils.

Within 50 m, the probabilities of significant relationships between soil class and eroded area and volume were 0.002 and <0.001 respectively. There was, again, significantly less erosion on dry soils than on either wet mineral or peaty soils. A significantly smaller area of erosion was also recorded on wet peaty mineral soils, when compared with peat soils.

Table 3.8 Eroded 10 m and 50 m field sites, distinguished by cause of erosion and soil class.

Soil Class	10 m field sites			50 m field sites			
	Total	Biotic	Water	Total	Biotic	Water	Wind
Dry mineral	12	11	1	31	26	5	
Wet mineral	11	5	6	34	24	10	
Wet peaty mineral	14	7	7	48	29	19	
Peat	37	9	28	93	29	62	2
Total	74	32	42	206	108	96	2

The causes of erosion within different soil classes are summarised in Table 3.8 by the numbers of eroded sites in each class. As expected, the number of water-eroded sites increased between dry mineral soils and peat soils. In contrast, the numbers of field sites with erosion caused by humans or grazing animals fluctuated little between soil classes.

3.5.5 The relationship between field site aspect and erosion

Figure 3.7 shows the relationship between field site aspect and erosion. There was little variation between sites with different orientations: within 10 m there was a decline in erosion on NE-facing slopes, with slightly higher mean eroded volume on E- and S-facing slopes. Within 50 m, there was also limited variation in the trend apart from a slight decline in mean erosion on westerly slopes. As suggested by these graphs, there was an absence of statistical significance between aspect and erosion within either 10 m or 50 m datasets.

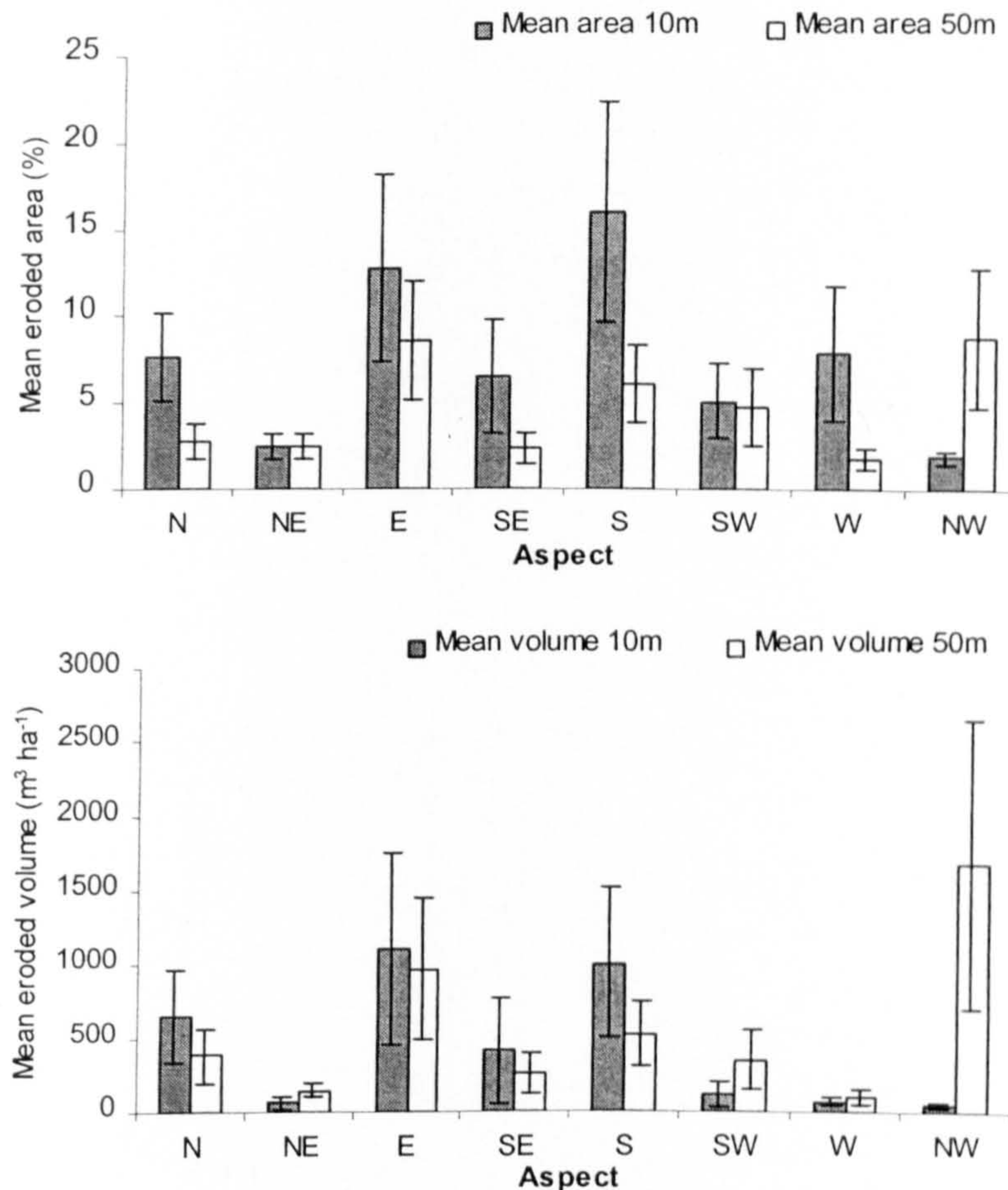


Figure 3.7 The relationship between aspect and mean extent of erosion, recorded on 10 and 50 m field sites. Standard errors of the data are presented ($SE = SD/\sqrt{n}$).

In order to determine whether the use of eight aspect groups accounted for the lack of a relationship with erosion, the number of aspect groups were reduced. All N, NE and NW-facing sites were combined into a single N class: the S class was formed similarly. Both E and W groups consisted of directly E or W-facing sites. In spite of the potential for under-representation of E and W sites, only the W group is significantly smaller (Table 3.10).

Figure 3.8 depicts the mean erosion on 10 m and 50 m field sites defined by these four aspect classes. Mean erosion on E-facing slopes was greater than that recorded on other aspects, and followed by erosion on S-facing slopes. The smallest mean eroded area and volume were recorded on W-facing slopes.

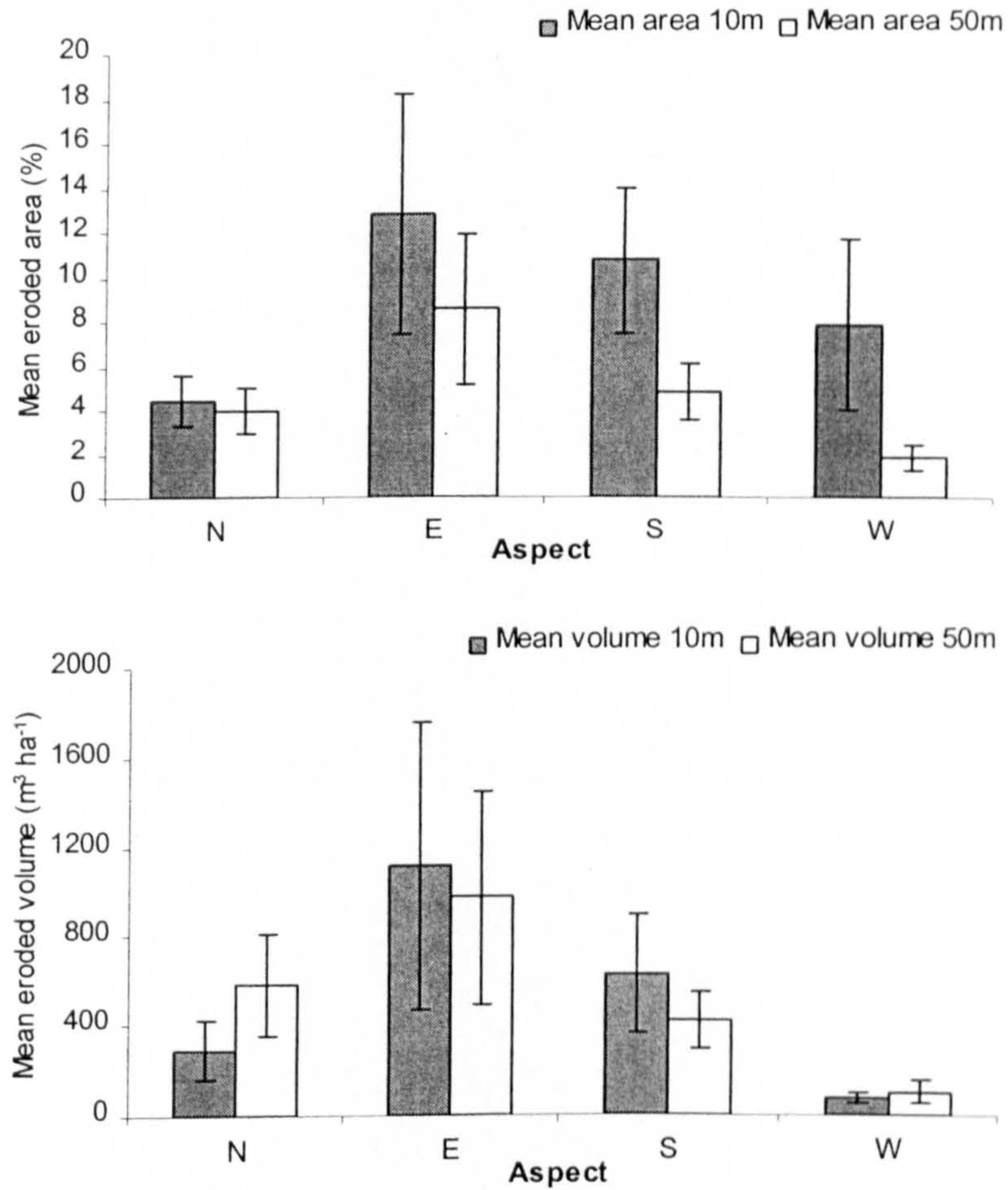


Figure 3.8 Mean eroded area and volume on 10 m and 50 m field sites, grouped according to aspect. Standard errors of the data are presented ($SE = SD/\sqrt{n}$).

Table 3.9 Water, wind and biotic erosion on field sites of different aspects (eight compass ordinals).

Aspect	10 m field sites			50 m field sites			
	Total	Biotic	Water	Total	Biotic	Water	Wind
N	9	4	5	33	22	10	1
NE	10	6	4	24	12	12	
E	17	8	9	35	18	16	1
SE	6	3	3	17	10	7	
S	10	6	4	34	20	14	
SW	5	0	5	17	6	11	
W	10	4	6	23	13	10	
NW	4	1	3	16	4	12	
Total	71	32	39	199	105	92	2

The causes of erosion on field sites of different aspects are presented in Tables 3.9 and 3.10. Where eight compass ordinals were used (Table 3.9), there was no clear

relationship between erosion cause and aspect. Aside from the lower incidence of biotic erosion on SW and NW-facing slopes, biotic and water erosion occurred to similar extents on all aspects. When only four compass points were used, high numbers of both biotic and water eroded sites occurred on both N-facing and S-facing slopes. Again, there was little or no discernible pattern of erosion based on site aspect.

Table 3.10 Water, wind and biotic erosion on field sites of different aspects (four compass ordinals).

Aspect	10 m field sites			50 m field sites			
	Total	Biotic	Water	Total	Biotic	Water	Wind
N	23	11	12	73	38	34	1
E	17	8	9	35	18	16	1
S	21	9	12	68	36	32	
W	10	4	6	23	13	10	
Total	71	32	39	199	105	92	2

3.5.6 Field site erosion and vegetation

Figure 3.9 shows the relationship between erosion and field site vegetation. Erosion on both 10 and 50 m field sites increased as the vegetation changed from bracken and upland grassland, before it peaked on heath and mixed heath/bog vegetation. Subsequently, mean erosion declined on bog vegetation.

The causes of erosion on different vegetation types are summarised in Table 3.11. On upland grassland vegetation, humans and animals dominated erosion processes, particularly on 50 m field sites. On heather-covered sites, meanwhile, erosion on a greater number of sites was due to water (10 m and 50 m) and wind (50 m). The little erosion on other vegetation communities was evenly divided between biotic and non-biotic causes.

Statistically, there were significantly important relationships between erosion and vegetation within 50 m ($F_{pr} < 0.001$ for both) and between eroded volume and 10 m vegetation ($F_{pr} 0.016$). Within 10 m, ANOVA identified differences between eroded volume on mixed grass/heath vegetation and that on mixed heath/bog vegetation. Within 50 m, significant differences existed between eroded area and volume on bracken and those on heath/bog sites. Finally, there was a significant distinction between eroded volume on bracken and bog vegetation, which represent the extremes, or near extremes, of upland vegetation in terms of hydrology.

Generally, erosion on heather/bog vegetation and on bog vegetation was significantly greater than that on bracken or grassland sites. Full details of the remaining statistical analyses, which investigate the interactions of environmental variates and their influence on erosion, are in Section 3.5.9.

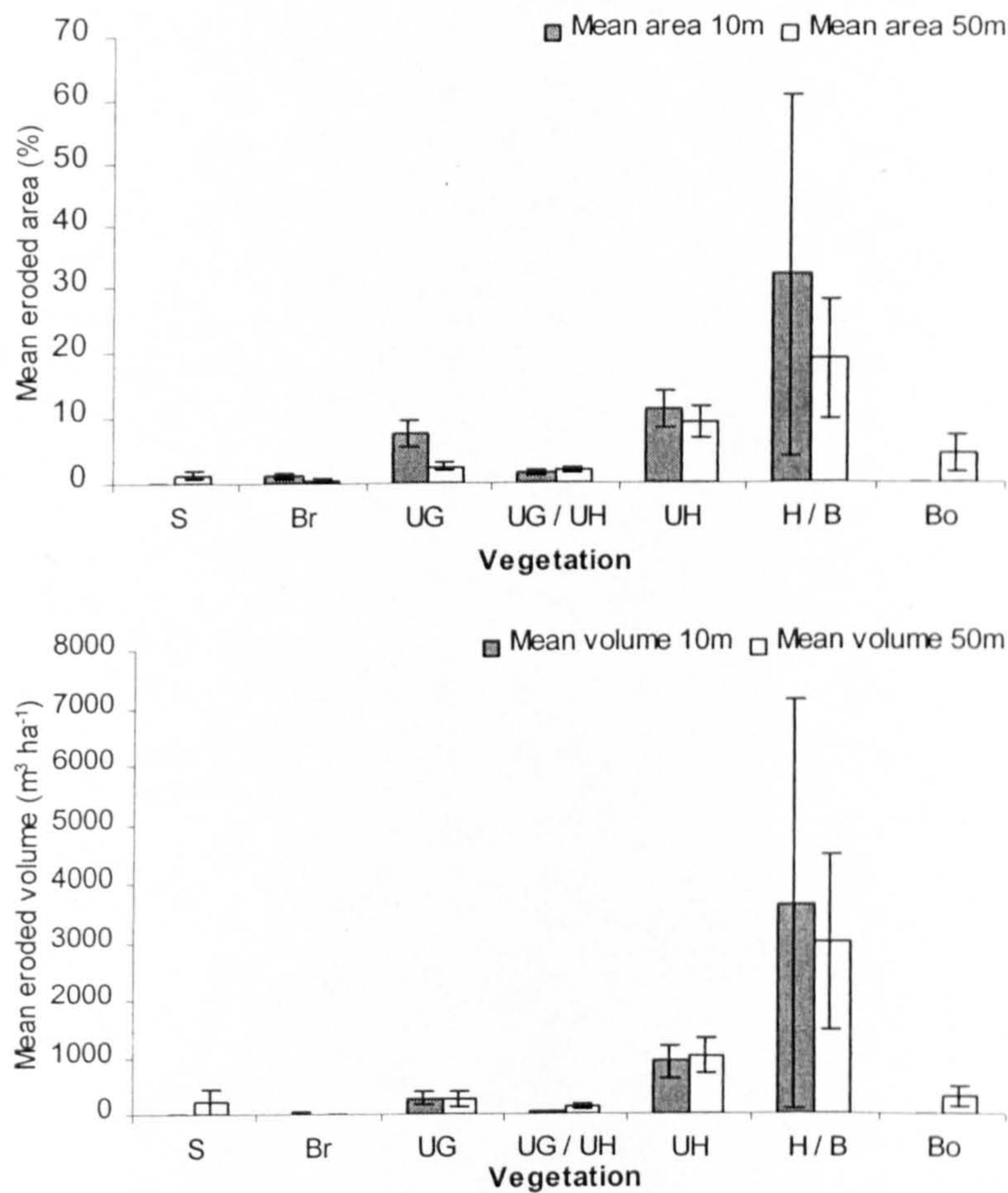


Figure 3.9 Erosion measured on 10 and 50 m field sites, plotted against site vegetation. (See Table 3.11 for key). Standard errors of the data are presented ($SE = SD / \sqrt{n}$).

Table 3.11 Erosion causes within vegetation groups, as measured on 10 m and 50 m field sites.

Vegetation (Abbreviation)	10 m field sites			50 m field sites			
	Total	Biotic	Water	Total	Biotic	Water	Wind
Scrub (S)	0	0	0	5	5	0	
Bracken (Br)	2	1	1	7	6	1	
Upland grassland (UG)	38	20	18	100	61	39	
Grassland / Heath (UG/UH)	8	5	3	27	15	12	
Upland heath (UH)	23	5	18	57	18	37	2
Heath / Bog (H/B)	3	1	2	7	2	5	
Bog (Bo)	0	0	0	3	1	2	
Total	74	32	42	206	108	96	2

3.5.7 Field site morphology and soil erosion

Erosion measured on field sites showed a consistent trend in terms of field site morphology. On both 10 m sites and 50 m sites, there was greater mean erosion on concave sites than on either linear or convex sites (Figure 3.10). From the statistical analyses, the differences between erosion on different site morphologies were significant, with confidence limits of 0.002 and 0.010 for area and volume respectively (50 m sites). Within 10 m, morphology did not significantly affect eroded area (F pr 0.214) although there was a significant relationship with eroded volume (F pr 0.096). In the latter, there was again statistically more erosion on concave sites than on convex sites.

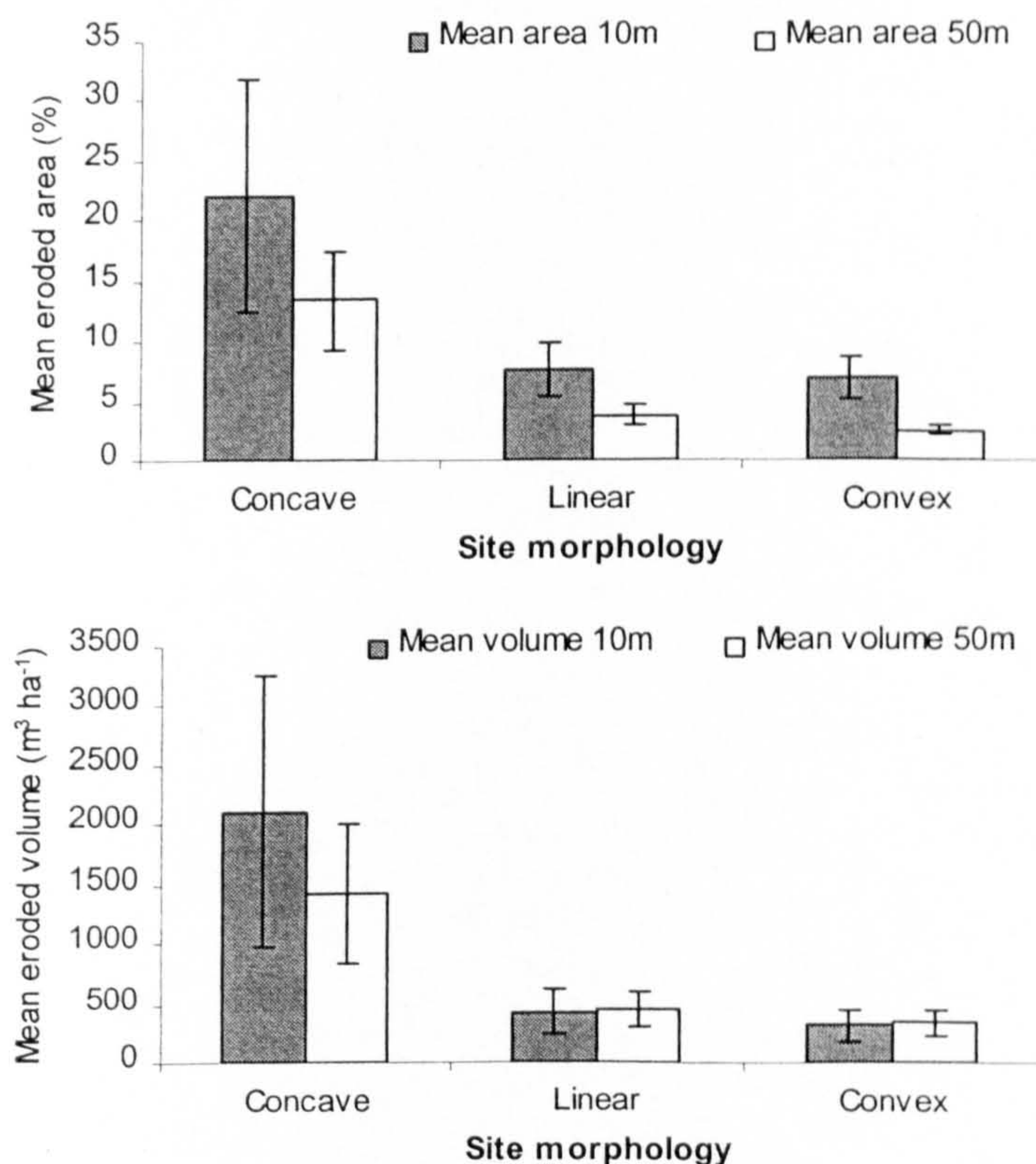


Figure 3.10 Mean soil erosion recorded on 10 m and 50 m field sites, plotted according to field site morphology. Standard errors of the data are presented ($SE = SD/\sqrt{n}$).

Information on the causes of erosion is presented in Table 3.12. There were many more eroded linear and convex field sites, in spite of the greater eroded area and volume measured on concave sites. Within 10 m, most linear and concave fieldsites were water eroded. Within 50 m field sites, meanwhile, erosion on linear and convex sites was predominately biotic. Water erosion occurred more frequently than biotic erosion on concave field sites only.

Table 3.12 Morphology of 10 m and 50 m eroded field sites, linked to the causes of erosion.

Field site morphology	10 m field sites			50 m field sites			
	Total	Biotic	Water	Total	Biotic	Water	Wind
Concave	9	2	7	32	13	19	
Linear	33	13	20	95	51	44	
Convex	32	17	15	79	44	33	2
Total	74	32	42	206	108	96	2

3.5.8 Grazing pressure and soil erosion

The effect of grazing pressure on erosion is presented graphically in Figure 3.11. Overall, both 10 m and 50 m data showed decreased erosion under conditions of higher grazing pressure, except for a high increase in 10 m eroded area recorded under the most intense grazing conditions. This increase was accompanied by very large standard errors, however, and may not represent reliably the trend between erosion and grazing pressure.

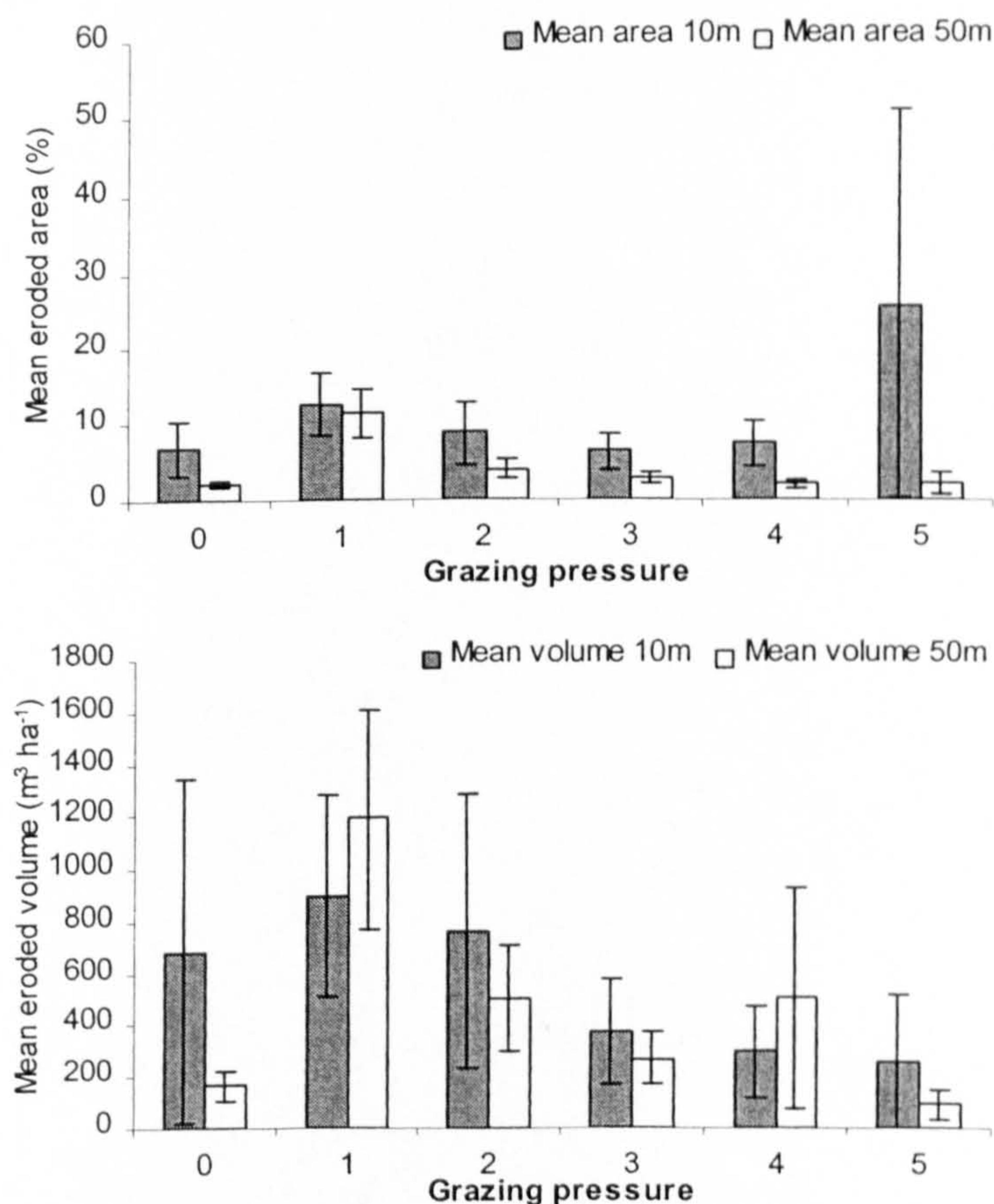


Figure 3.11 Eroded area and volume on 10 m and 50 m field sites, plotted against grazing pressure. Standard errors of the data are presented ($SE = SD/\sqrt{n}$).

Statistically, analysis of variance did not recognise significant differences between 10 m erosion under different grazing pressures. Erosion on 50 m field sites was significantly related to grazing pressure (F pr 0.018 area; 0.014 volume), although there were no significant differences between erosion extent measured under different grazing regimes.

The causes of erosion under conditions of increasing grazing pressure are presented in Table 3.13. Within both 10 m and 50 m, there were increases in the numbers of biotically-eroded field sites up to grazing level three, after which their numbers equalled or exceeded the numbers of water-eroded field sites.

Table 3.13 Erosion on 10 m and 50 m field sites measured under different grazing pressures and linked to erosion cause.

Grazing pressure	10 m field sites			50 m field sites			
	Count	Biotic	Water	Count	Biotic	Water	Wind
0	4	2	2	8	4	3	1
1	14	4	10	41	18	22	1
2	21	6	15	64	22	42	
3	19	12	7	59	42	17	
4	14	7	7	30	19	11	
5	2	1	1	4	3	1	
Total	74	32	42	206	108	96	2

3.5.9 Statistical analyses of interactions between variates

The preceding paragraphs have discussed individual relationships between the environmental variates and erosion recorded on field sites. To determine the existence of interactions between variates, and to quantify their effect on erosion, various statistical analyses were performed on the data, as summarised in Tables I and II (Appendix 4) and described here (Genstat 5 Committee, 1987).

3.5.9.1 Altitude and slope, individually regressed with environmental factors

Each of the five factors of aspect, grazing, vegetation, morphology and soil class were individually combined with altitude, to test their combined influence on erosion. Within 10 m, only grazing and altitude combined in a non-parallel regression to influence significantly both eroded area and volume (F pr 0.045 and 0.023 respectively). While the variances accounted for by these relationships were low at 7.4% and 20.3%, they were higher than those for individual relationships. Genstat

also distinguished that, in interaction with altitude, there was significantly greater eroded area and volume under grazing level 5.

The same analyses carried out on erosion within 50 m yielded significant parallel and non-parallel regressions between altitude, soil class and both eroded area and volume (Appendix 4, Table II). In both regressions, mean eroded area and susceptibility to erosion were greatest on peat soils.

Evidence of interaction between field site slope and the various environmental factors was sought also using simple linear regression with groups (SLRG; Appendix 4). Within 10 m data on eroded area, a significant non-parallel regression existed with field site morphology and slope: linear field sites were the most prone to erosion.

No other interactive regressions were found between slope and the environment using 10 m eroded volume or 50 m area or volume data. Parallel regressions with altitude identified greatest mean erosion on grazing level zero, on heather vegetation, on concave field sites and on peat soils.

3.5.9.2 Altitude and slope combined and regressed with environmental factors

In this test, the two variables altitude and slope were combined and their impact on erosion was established before the effect of adding a third dependent variable, such as soil class, was determined (MLR and MLRG; Appendix 4).

Within 10 m data, the multiple regression between altitude, slope and eroded volume was significant (F pr 0.006, R^2 11.2; Appendix 4, Table I). Genstat predicted a positive change in erosion of $1.05 \text{ m}^3 \text{ ha}^{-1}$ for every single metre increase in altitude, while, with a one degree increase in slope, erosion was predicted to decrease by $1.04 \text{ m}^3 \text{ ha}^{-1}$.

Within 50 m, the multiple regression resulted in a positive relationship between both eroded area and volume (F pr <0.001 for both). The low variances of these relationships (R^2 6.5 and 11.4) indicated the high variability in the dataset (205 degrees of freedom). The predicted changes in erosion were, for a single metre

increment in altitude, an increase of 1.004% and 1.006 m³ ha⁻¹, with decreases in area and volume of 1.03% and 1.05 m³ ha⁻¹ for each one degree increase in slope.

In MLRG, aspect combined with altitude and slope was significantly related in a non-parallel regression to 10 m eroded volume (F pr 0.085; R² 21.3). Sites facing S and SW were most susceptible to erosion. Other parallel regressions with both altitude and slope established that mean eroded area was greatest on wet mineral soils, and that eroded volume was greatest on peat soils and on mixed heath/bog vegetation.

Within 50 m, soil class interacted significantly with altitude and slope in a relationship with eroded volume (F pr 0.049; R² 17.5). In relation to altitude, peat soils were most susceptible to erosion while in combination with slope erosion change was greatest on wet peaty mineral soils.

3.6 SOIL DEPOSITION RECORDED ON 10 M AND 50 M FIELD SITES

In addition to the records of erosion extent made on each field sites, the length, width and depth of any areas of deposition were measured. As it derives from field site erosion, the extent of on-site deposition reflects the degree to which eroded material is transported further downslope.

3.6.1 Summary details for deposition recorded on field sites

In Table 3.14, the extent of field site deposition is summarised: as can be seen from the disparities between mean and median values, the data were heavily skewed. Soil deposition was measured on only 14 field sites out of the seventy-four 10 m sites that had eroded. Similarly, within 50 m field sites, deposited soil was measured on only 41 out of 206 eroded field sites (Table 3.14). On 80% of eroded field sites, therefore, none of the degraded soil was redeposited within the field site boundary in 1999.

In total, 0.05 ha of deposited soil was measured on 10 m field sites: the total volume of this soil was almost 58 m³. On 50 m field sites, meanwhile, 0.7 ha of redeposited soil, with a total volume of 625 m³, was measured.

Table 3.14 Summary details for soil deposition measured on 10 m and 50 m field sites.

	10 m field sites		50 m field sites	
	<i>Total area (%)</i>	<i>Total volume (m³)</i>	<i>Total area (%)</i>	<i>Total volume (m³)</i>
Mean	10.44	4.13	2.19	15.23
Standard Error	4.36	1.80	1.01	7.89
Median	2.75	0.93	0.32	1.10
Standard Deviation	16.31	6.75	6.45	50.55
Sum	146	57.88	89.64	625
Count	14	14	41	41

3.6.2 Deposition linked to environmental and management features

Field sites on which deposition occurred were subdivided into the variate groups mentioned in Section 3.5 to investigate links between the environment and soil deposition. Summary tables for the data are provided in Appendix 5. Most deposition was recorded on linear sites, on south-facing slopes and at higher altitudes. The number of deposited sites and the extent of soil deposition peaked at 4-7°, and again at slopes of greater than 25°. It therefore followed a trend similar to that of erosion.

In view of the high number of eroded sites located on peat soils, it was surprising that, within 50 m field sites, deposited area and volume was greatest on dry mineral soils. Yet, for both 10 m and 50 m, more field sites with deposition were located on peat. Some 65-90% of deposition on 50 m field sites, and 92-95% of that on 10 m field sites occurred on upland grassland vegetation.

Finally, while more sites with deposition were exposed to grazing level 3, the greatest areas and volumes of erosion occurred under more intense grazing at level 4 or 5. Although the relationships between soil deposition and the environment were not tested statistically, the relevance of the above results is discussed in Section 3.10.4.

3.7 FIELD EROSION ON 50 M SITES, EXCLUDING PEAT SOILS

The number of eroded field sites, and the areal and volumetric extent of erosion on peat soils far exceeded the degradation on dry mineral, wet mineral, or wet peaty mineral soils (Table 3.15). Peat soils may act, therefore, to suppress or mask evidence of links between erosion on other soils, and the environment. For this

reason, the eroded site database was reduced by excluding peat soils before searching for links between soil erosion and the environment. In this section, the data summaries already presented, including the statistical analyses, are repeated for the reduced dataset. Much of the following uses only 50 m field site data as the reduced size of the 10 m dataset affected the validity of its results. Statistical analysis was, however, carried out on both datasets, as discussed below and summarised in Tables III and IV (Appendix 4).

Table 3.15 Mean eroded area and volume recorded on 10 m and 50 m field sites within soil classes

Soil class	10 m field sites			50 m field sites		
	<i>N</i>	<i>Mean area (%)</i>	<i>Mean volume (m³)</i>	<i>N</i>	<i>Mean area (%)</i>	<i>Mean volume (m³)</i>
Dry mineral	12	3.2	0.84	31	1.1	30.79
Wet mineral	11	10.1	13.72	34	3.8	517
Wet peaty mineral	14	3.9	5.90	48	2.6	138
Peat	37	12.6	29.89	93	7.5	686
<i>Total</i>	<i>74</i>	<i>30</i>	<i>50.36</i>	<i>206</i>	<i>15</i>	<i>1372</i>

3.7.1 Data summary

The reduced dataset formed by the removal of field sites with peat soil is summarised in Table 3.16, juxtaposed by the summary statistics for all 50 m eroded field sites. Removal of peat soils has reduced the data by almost fifty percent, from 206 field sites to only 113. Similarly, both the mean area of erosion and the mean eroded volume have almost halved, indicating the contribution of erosion on peat soils to these values.

The total area and volume of erosion on non-peat soils are each less than one third of the equivalent values within the total dataset: this again emphasises the significance of erosion on peat soils. The difference between median and mean values highlight the skewed nature of the reduced dataset: statistical analyses are therefore carried out on log transformed data.

Table 3.16 Statistics for eroded 50 m field sites: data are provided for non-peat soils only.

Statistic	All 50 m field sites		50 m field sites minus peat soils	
	Total area (%)	Total volume (m ³)	Total area (%)	Total volume (m ³)
Mean	4.77	432	2.52	223
Standard Error	0.81	98.12	0.49	96.52
Median	1	16.58	0.80	7.4
Standard Deviation	11.60	1408	5.21	1026
Sum	983	88962	285	25202
Count	206	206	113	113

3.7.2 Relationships between erosion and the environment

In Figure 3.12, the relationships between erosion and the environment are plotted. Values of eroded volume have been divided by 100 to allow their comparison with data on eroded area. Mean eroded area and volume are highest at altitudes between 601 m and 700 m, due to a small number of highly eroded field sites. Apart from this peak, there is little variation within the graph: the steady increase in erosion with altitude shown in Figure 3.3 is not repeated here. Statistically, there were no significant relationships between altitude and either eroded area or eroded volume measured within 10 m or 50 m field sites (Tables III and IV, Appendix 4).

Mean erosion exhibits a clear trend when plotted against increasing slope: after an increase to a threshold inclination of about 11°, the extent of erosion falls before rising again on slopes steeper than 16°. Overall, this trend is similar to but more marked than when all eroded field sites were linked to slope (Figure 3.4). Erosion on peat soils is largely confined to low slopes and would therefore mask the contribution of other soil classes to the erosion quotient on steep slopes. Statistically, there was no clear relationship between erosion and slope angle (Tables III and IV, Appendix 4).

The relationship between mean erosion and field site vegetation revealed that erosion was not limited to mixed heath/bog communities as in Figure 3.9. In Figure 3.12, highest mean erosion occurred on heath and bog vegetation. There was also evidence of greater erosion on scrub, grassland and grass/heath vegetation.

In the statistical analyses, ANOVA recognised a significant relationship between 50 m eroded area and volume and field site vegetation (Appendix 4, Table IV), but there were no significant differences between erosion in different vegetation groups.

Figure 3.12 also related grazing pressure on 50 m sites to extent of degraded soil. Eroded extent clearly increased with grazing intensity to a threshold at grazing level three. At this level, evidence of grazing is abundant, with loss of flowering heads and some heather topiary. Dung deposition on the field site and signs of poaching are also indicators of grazing intensity. No significant relationships were identified between grazing and erosion using ANOVA using either 10 m or 50 m data.

In the graphs relating aspect, soil class and site morphology to erosion, there was little or no difference between entire-dataset and reduced-dataset results (Figures 3.6, 3.7, 3.10 and 3.12). No clear relationship existed between aspect and erosion in either case. Morphologically, concave field sites are consistently more prone to soil erosion, and, following the removal of the peat soil class, the greatest mean eroded area and volume occurred on wet mineral soils.

Statistically, ANOVA highlighted the soil class-eroded volume relationship: mean eroded volume within both 10 m and 50 m field sites was greatest on wet mineral soils, and significantly higher there than on dry mineral soils. There were, however, no significant differences between mean eroded volume on wet mineral and wet peaty mineral soils (Tables III and IV, Appendix 4).

Statistical interactions between site variates and their combined effects on mean field site erosion were also examined using Genstat. Within 10 m field sites, interaction was confined to parallel regressions of soil class with both altitude and slope individually, and with altitude and slope combined. In all cases, mean eroded volume was highest on wet mineral soils. Eroded area was not influenced by combination with either altitude or slope.

The same relationships were observed between 50 m eroded area and wet mineral soils, in regressions with altitude or slope. Significant parallel regressions were also isolated between both slope and altitude with vegetation and morphology (Appendix

4, Tables III and IV). No interactive (non-parallel) regressions were found between altitude or slope and any of the environmental factors recorded on field sites.

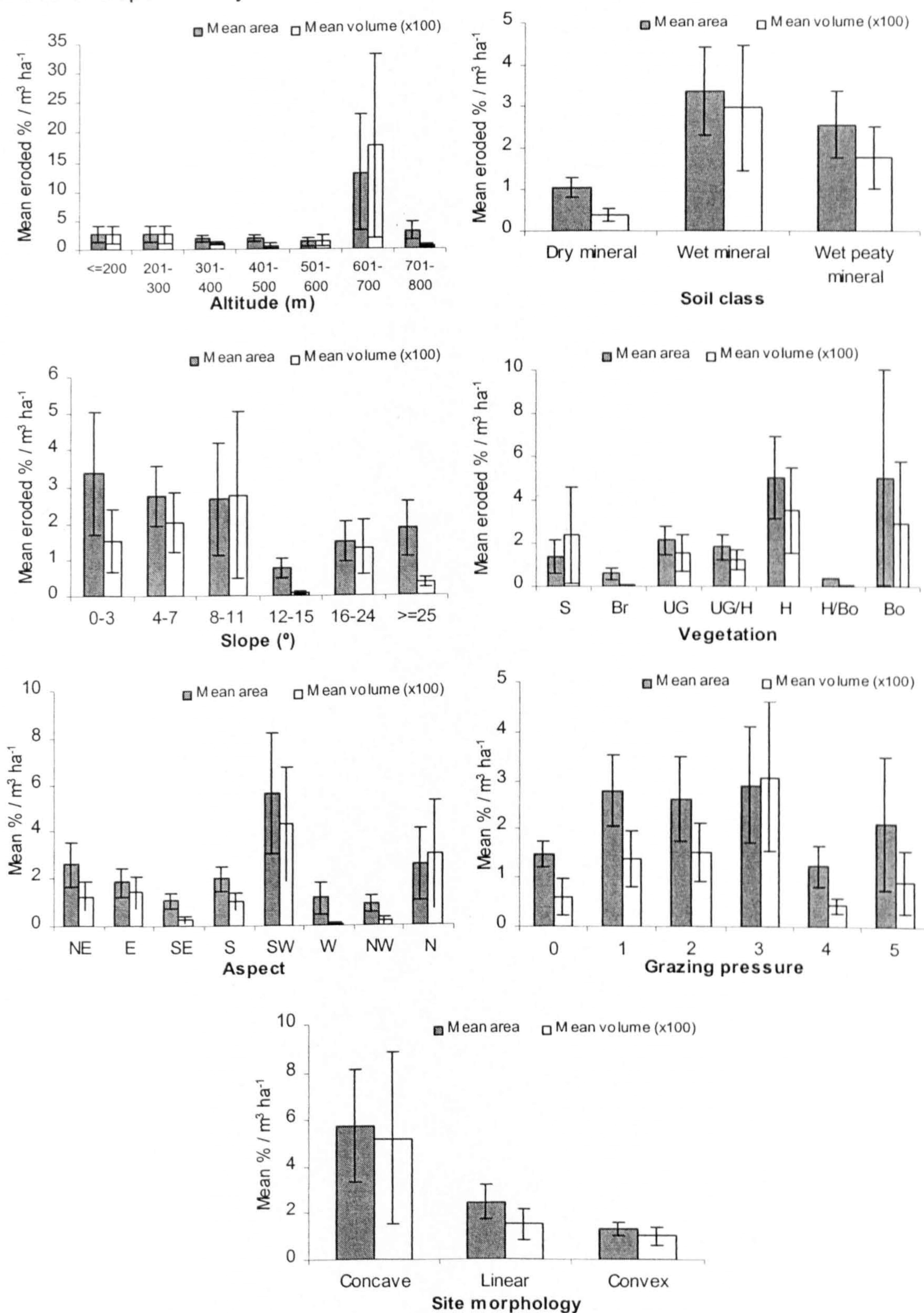


Figure 3.12 Eroded area and volume recorded on 50 m field sites: all eroded sites on peat soils are omitted. Standard errors of the data are shown (SE = SD/√n).

3.8 BARE AND VEGETATED ERODED GROUND

In addition to the dimensions of individual erosion features measured, the state of each erosion feature was assessed in terms of its degree of revegetation. Thus, erosion scars were classified as entirely bare and therefore prone to further degradation or as entirely revegetated, and therefore stable and not subject to further soil loss. The majority of scars were at some intermediate stage.

Here, data on the area of bare and vegetated eroded ground recorded within 50 m field sites are summarised. Following this, bare and vegetated eroded areas are related to field site characteristics.

3.8.1 Summary of bare and vegetated eroded ground on 50 m field sites

Table 3.17 summarises data on total, bare and vegetated erosion area, as recorded on 50 m field sites. The total eroded area of 7.72 ha is almost equally divided into bare and vegetated proportions: although there was slightly more bare than vegetated soil, the difference accounts for approximately 0.1 ha. On vegetated sites, the mean area of vegetated ground was more than twice the area of bare soil. In skewed data such as these, the median value or centre data point, is a more useful indicator of the data spread than the mean as it is not affected by outlying data. The median of vegetated soil area is greater than that for bare erosion (Table 3.17). Of 206 eroded field sites, bare soil was measured on all but nine in 1999. In contrast, only 82 field sites, or 40% of the total, contained vegetated eroded soil.

Table 3.17 Summary statistics for total, bare and vegetated areas of eroded soil recorded on 50 m field sites in 1999.

Statistic	Total area %	Bare area %	Vegetated area %
Mean	4.77	2.53	5.90
Standard Error	0.81	0.51	1.45
Median	1	0.64	1.64
Standard Deviation	11.6	7.09	13.11
Sum	983	499	484
Count	206	197	82

3.8.2 Bare and vegetated eroded area and field site altitude

Figure 3.13 shows the change in mean bare and vegetated eroded area recorded at different altitudes on 50 m field sites. The extent of vegetated soil clearly increased with height above sea level. While there were slightly greater areas of bare erosion at altitudes above 400 m, there was generally little variation in bare eroded extent with altitude. This result indicates that the rate of erosion recovery, represented here by the amount of erosion revegetation, is not limited by altitude. As with total erosion, the decline in both bare and vegetated eroded ground above 700 m may be due to the lower number of field sites at this altitude.

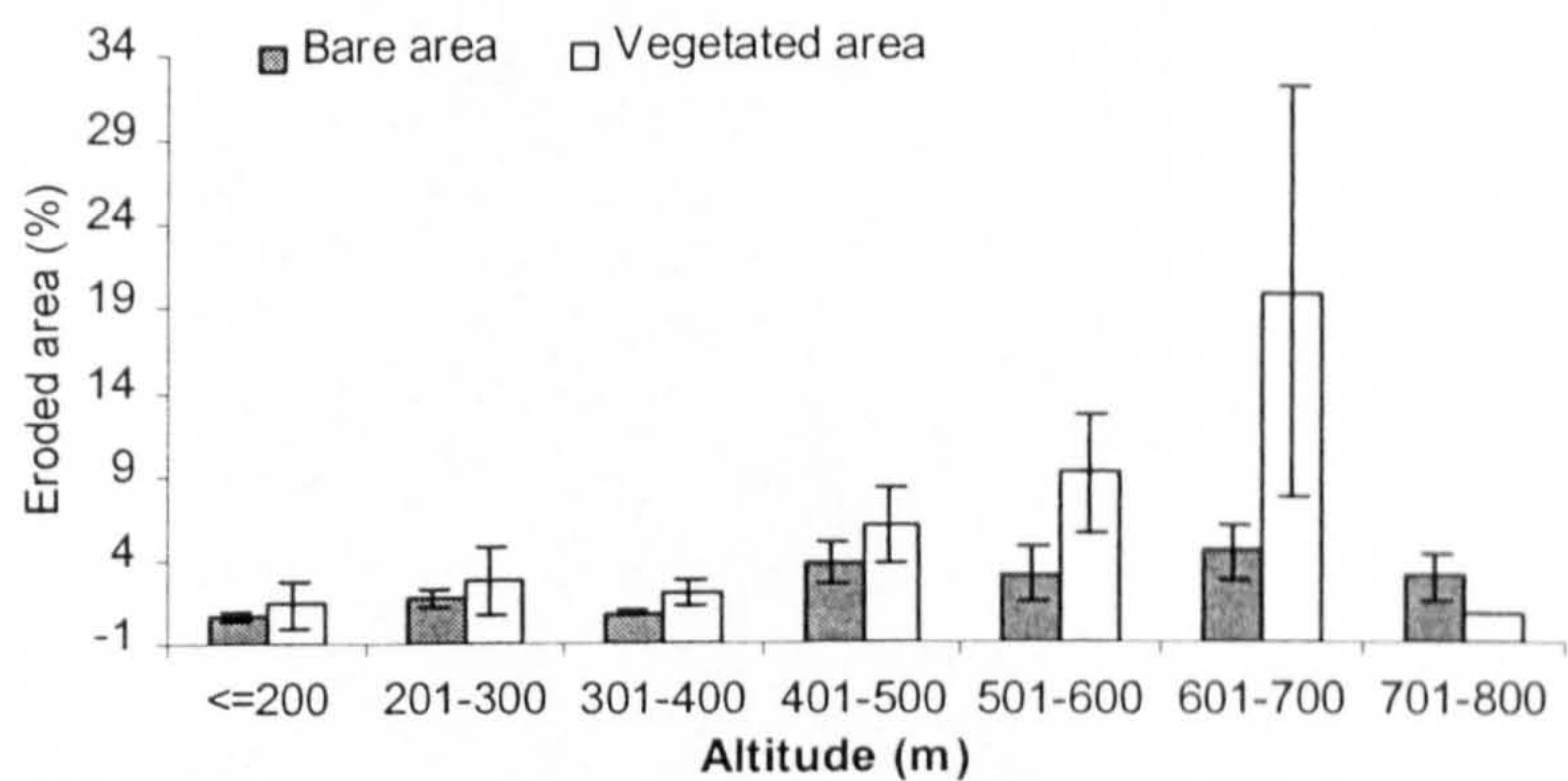


Figure 3.13 Bare and vegetated eroded ground recorded within 50 m of the node. Error bars represent standard error of the data ($SE = SD / \sqrt{n}$).

In the statistical analyses summarised in Table V (Appendix 4), altitude was significantly regressed with bare erosion area (F pr 0.004; R^2 3.7). The mean area of erosion was predicted to increase with altitude by just over 1.003% for every single metre increase in altitude. There was also a significant relationship between altitude and vegetated area: the extent of vegetated erosion was predicted to increase by 1.008% with every metre increase in altitude (F pr <0.001; R^2 12.8).

3.8.3 Field site slope related to bare and vegetated eroded ground

From Figure 3.14, the area of bare soil declines with increasing slope up to a slope of between 12 and 15°. Above this threshold, its area increased slightly, but there was little appreciable difference between 20° slopes and those greater than 25°.

Eroded ground that had revegetated showed a different relationship with slope. Initially, there was a constant increase in erosion from level sites up to 11°, after which the extent of vegetated eroded ground declined sharply. From this low

incidence on slopes between 12 and 15°, however, the mean vegetated area increased again, to approximately 3% on slopes steeper than 16°.

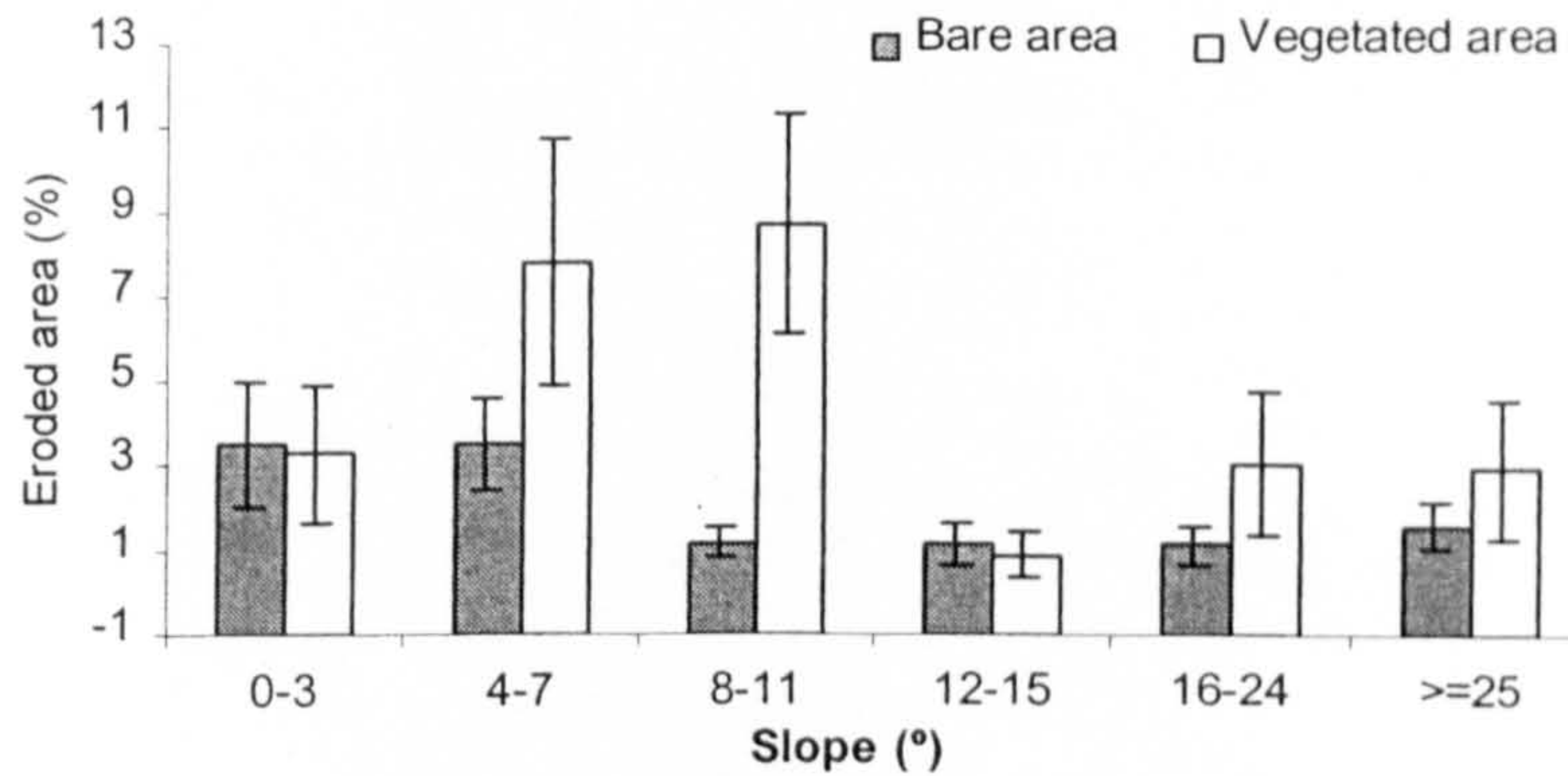


Figure 3.14 Change in bare and vegetated erosion extent with increasing slope, for 50 m field site data. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

Statistically, there was no significant relationship between slope and 50 m bare eroded area. The regression of slope and vegetated area was significant (F pr 0.048; R^2 3.6) and the mean area of revegetated ground was predicted to decline by 1.07% for every single degree increase in slope angle (Table V, Appendix 4).

3.8.4 Field site morphology related to bare and vegetated soil

Data for mean bare and vegetated eroded area recorded on different morphologies are shown in Figure 3.15. Both bare and vegetated area declined as morphology changes from concave, through linear, to convex. The only significant differences between bare and vegetated area occurred on convex sites, where the area of vegetated soil was significantly greater. The extents of both forms of erosion are significantly greater on concave sites than on other site morphologies.

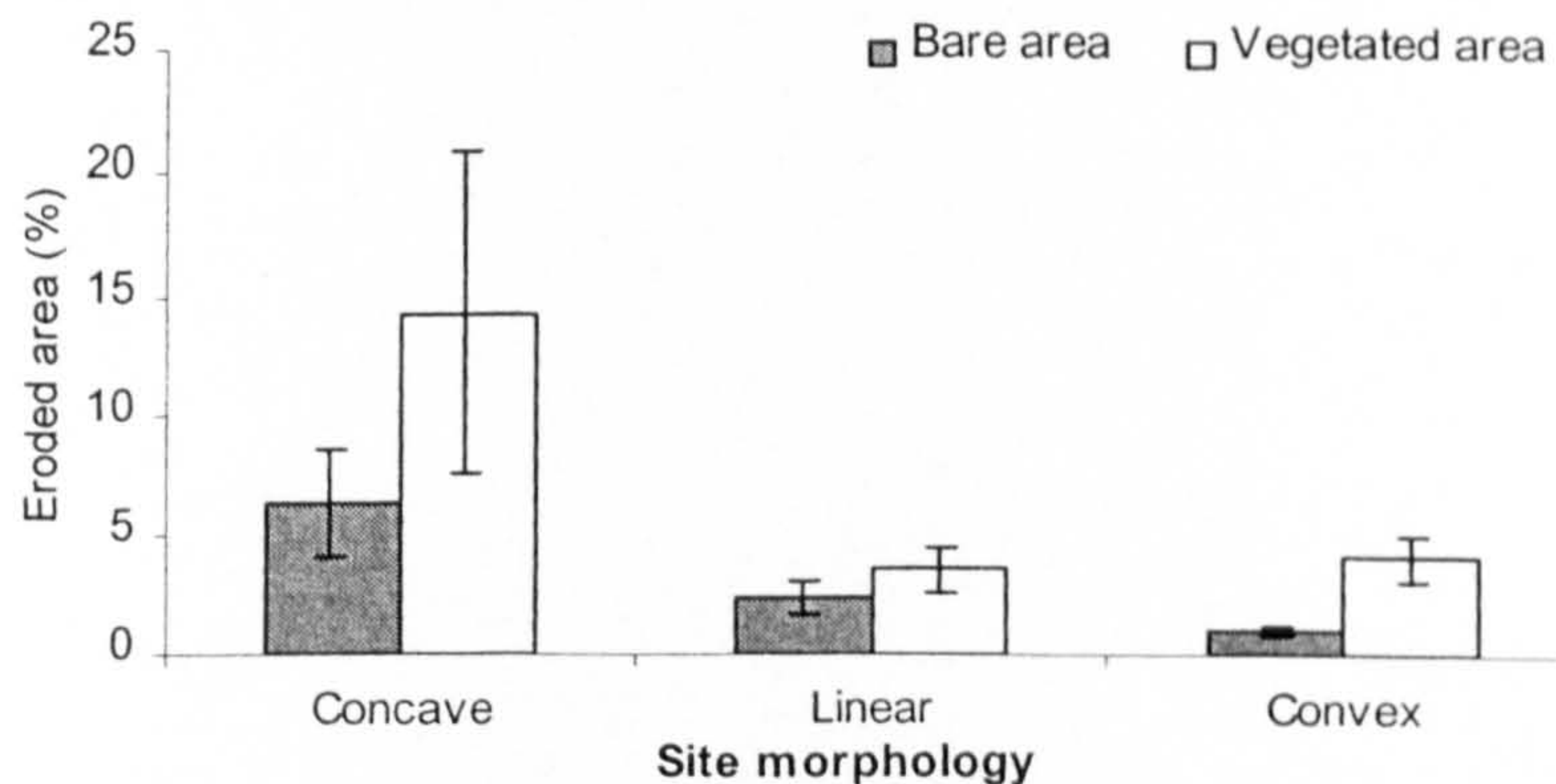


Figure 3.15 Mean eroded vegetated and bare area on 50 m field sites of different morphology. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

ANOVA highlighted the relationship between site morphology and bare eroded area (F pr <0.001), and distinguished between the area of bare soil on concave sites and that on both linear and convex sites. No significant relationship was identified between the extent of vegetated eroded ground and site morphology.

3.8.5 Bare and vegetated eroded area and soil class

Figure 3.16 illustrates the relationship between bare and vegetated eroded ground and the soil classes on which records were completed. The general erosion trend seen in Figure 3.6 is also reflected here; the greatest areas of both bare and vegetated eroded ground occurred on peat soils and on wet mineral soils.

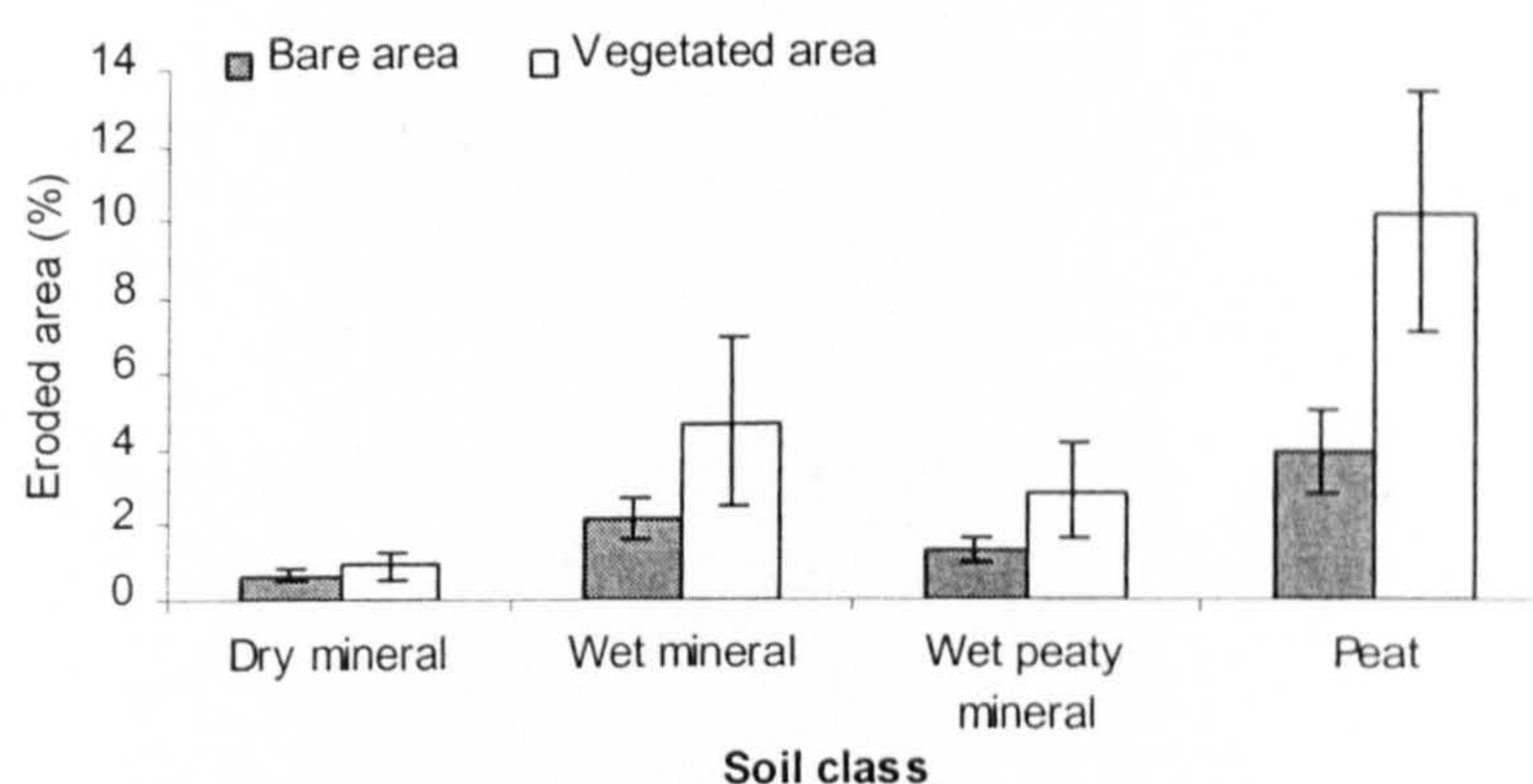


Figure 3.16 Area of bare and vegetated soil erosion on different soil types. Standard errors bars are shown ($SE = SD/\sqrt{n}$).

Statistical analysis of this dataset identified a significant relationship between soil type and bare eroded soil area (ANOVA; F pr 0.009). Significant differences were identified between the bare eroded area on all soil classes, with the greatest eroded areas on peat soils followed by wet mineral soils.

ANOVA also identified significant relationships between soil and vegetated erosion area (F pr 0.012): the eroded areas on dry mineral and wet mineral soils were significantly different.

3.8.6 Bare and vegetated eroded areas related to vegetation communities

The vegetation on which field sites were located, together with the area of bare and vegetated eroded soil, are presented in Figure 3.17. The most obvious feature of this graph is the high values of vegetated soil recorded on bog and on mixed

heath/bog vegetation. There is also a gradual increase in eroded ground along the approximate hydrological gradient that occurs between bracken-covered slopes, through grassland and heath-dominated sites, to sites with mixed heath/bog and bog vegetation.

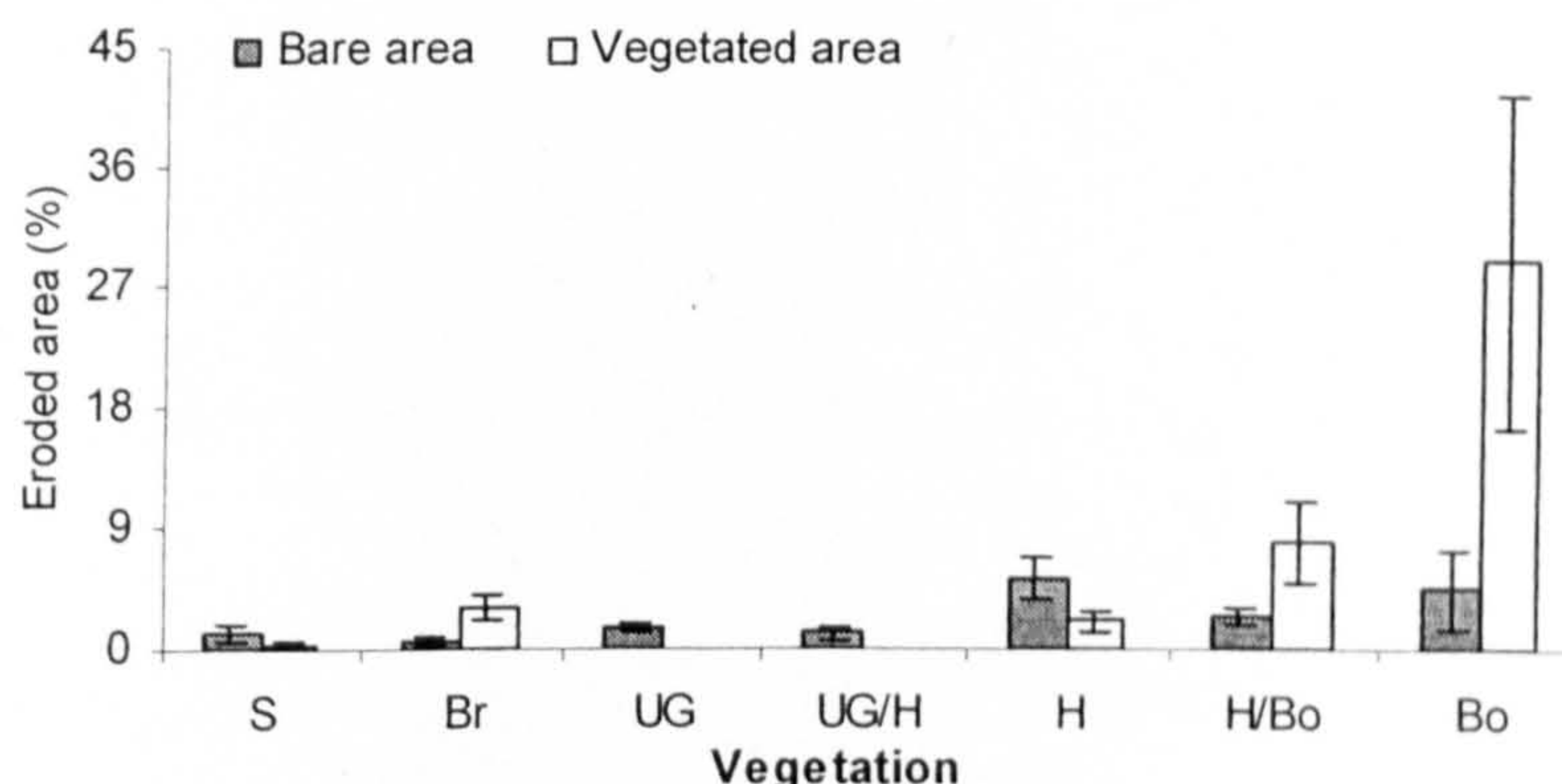


Figure 3.17 Bare and vegetated eroded area on 50 m field sites of different vegetation communities. Standard error of the data are presented, where $SE = SD/\sqrt{n}$.

Bare erosion scars dominate on upland grassland, mixed grass/heath, heather and scrub vegetation. Scrub vegetation consists of indeterminate vegetation with scattered *Ulex* and *Crataegus* as well as constituents of grass and heather communities. Excluding heather vegetation, eroded bare area was exceeded by vegetated ground area wherever revegetation was recorded.

Using 50 m bare eroded ground data, ANOVA identified significant relationships between vegetation and eroded area (F pr 0.015), although there were no discernible differences between the bare eroded areas recorded on different vegetation groups. Links were also established between vegetated area and vegetation type (ANOVA; F pr 0.033), with significant differences between the mean erosion recorded on scrub and that on mixed heath/bog vegetation.

3.8.7 Field site aspect related to bare and vegetated eroded area

Figure 3.18 illustrates the changes in mean eroded area recorded within 50 m field sites and linked to site aspect. There is little evidence of a trend: vegetated eroded area was highest on E, SW and NW sites, while bare eroded area appeared relatively evenly distributed between different aspects, with a slightly greater extent on S-facing slopes.

Statistically, there were no significant relationships with bare or vegetated eroded ground on 50 m field sites.

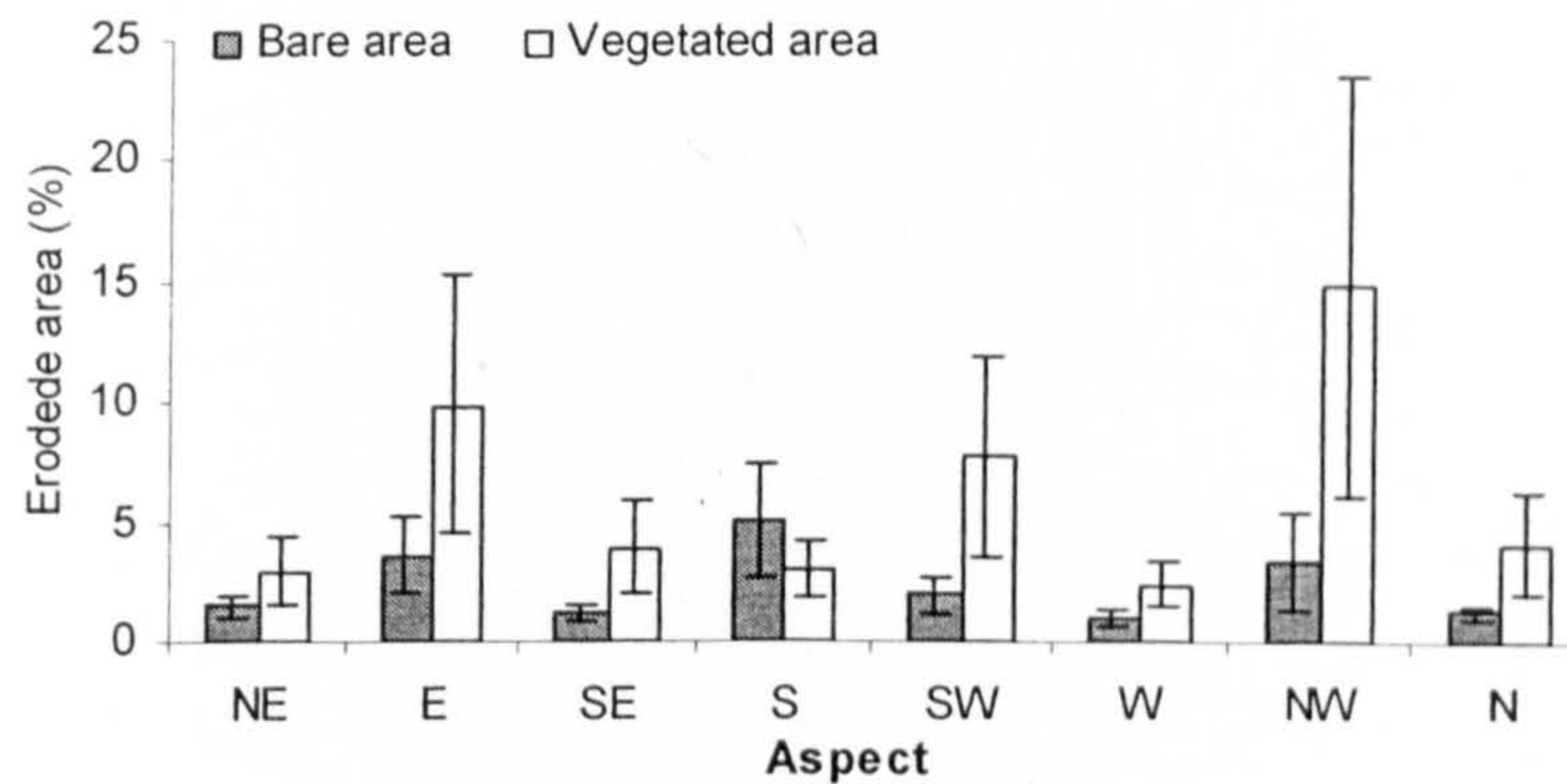


Figure 3.18 Bare and vegetated eroded area on field sites of different aspect. Standard error of the data are presented, where $SE = SD/\sqrt{n}$.

3.8.8 Grazing pressure and bare and vegetated eroded ground

In Figure 3.19, mean erosion is plotted according to the grazing pressure to which field sites were exposed. After an initial peak at grazing level 1 there is a steady decline in erosion extent with increasing pressure, until after level 4, when there is an increase in bare eroded soil only.

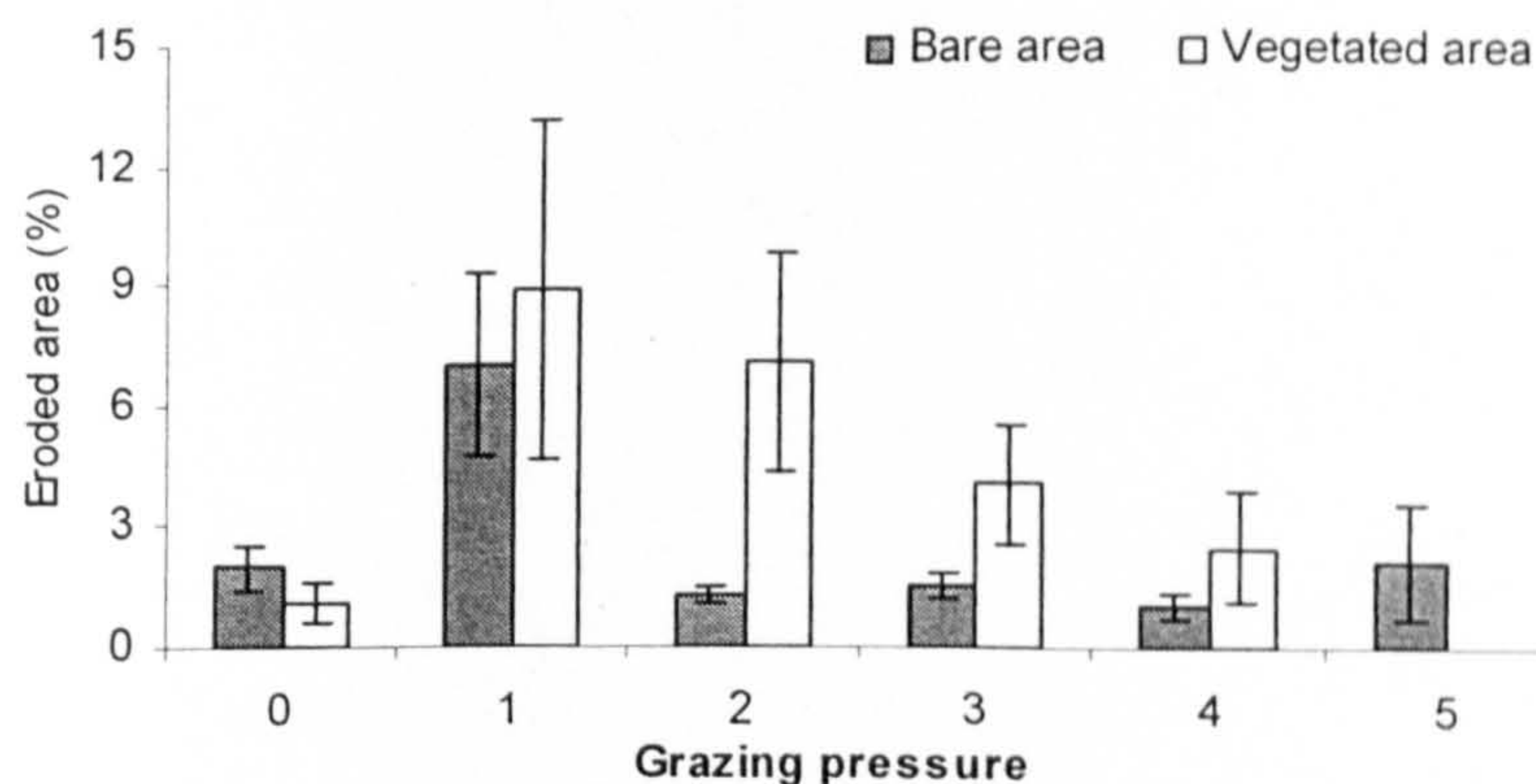


Figure 3.19 Bare and vegetated eroded area recorded on 50 m field sites and classified according to grazing pressure. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

Analysis of these data identified a significant relationship between grazing pressure and bare erosion area (F pr 0.068), although no significant differences were identified between the different grazing levels. There was no evidence of a significant relationship between grazing pressure and vegetated eroded ground.

3.8.9 Interactions between variables and factors

Significant interactions between altitude and grouped environmental factors, such as aspect and grazing pressure, were investigated using simple and multiple linear regressions with groups: these statistical tests are described in Appendix 4. For bare eroded area, the only significant relationships identified were parallel regressions between altitude and grazing pressure, vegetation, field site morphology and soil class (Table V, Appendix 4). The greatest areas of bare soil occurred on field sites subject to grazing level four, on sites with mixed heath/bog vegetation, on concave field sites and on peat soils. With altitude, vegetated eroded ground also interacted with soil class in a non-parallel regression (F pr 0.074; R^2 17.1): with increasing altitude, vegetated erosion was more likely to be found on peat soils.

In assessment of the interactions between slope, the environment and erosion, slope was positively linked with bare eroded area in parallel regressions with grazing, vegetation, site morphology and soil. The highest mean areas of bare ground occurred on grazing level 1, on heath/bog vegetation, on concave slopes and on peat soils. In addition, there was a single significant non-parallel regression between slope, soil and bare eroded area in which dry mineral soils on increasing slopes were more prone to bare eroded ground.

In interactions with altitude and slope, bare eroded soil was significantly regressed with vegetation and to field site morphology: the mean area of bare soil was higher on heath/bog vegetation and on concave field sites (F pr 0.062 and 0.002; R^2 6.9 and 9.2 respectively).

3.9 THE SIGNIFICANCE OF FIELD SITE SIZE ON EROSION MEASUREMENTS

For the analysis of the 1999 field survey dataset, results were first presented for erosion recorded within both 10 m and 50 m field sites. In subsequent analyses, the 10 m dataset was omitted as it had been reduced by elimination of data, such as field sites on peat soils (Section 3.4). In this section, a statistical interpretation is provided for the validity of the two field site sizes used, and an “ideal site size” for erosion field studies is proposed. The two different field sites sizes are also used to infer the pattern of erosion distribution within field sites.

3.9.1 Hypothesis

The hypothesis is that different field site sizes can be used to determine the distribution pattern and, hence the form, of the erosion being measured. From this, it may be possible to determine the suitability of 10 m and 50 m field sites to erosion surveys.

3.9.2 Method

The hypothesis was tested by comparing the results from eroded 10 m and 50 m field sites: 74 pairs of data were therefore available for interpretation. In the field surveys, eroded area was measured as a percentage of the field site area, while volume was assessed in cubic metres and converted to volume per unit area.

Firstly, the total eroded area measured on 10 m sites was divided by that measured on 50 m field sites. The natural logarithm of this 10 m: 50 m ratio was obtained and converted to an absolute value by disregarding its sign. In this way, the agreement between 10 m and 50 m results could be discerned by accessing a single absolute value, referred to in the following as the Distribution Score. Eroded volumes measured on 10 m and 50 m field sites were treated similarly.

A Distribution Score of zero represented complete agreement between the erosion extent measured on 10 m field sites and that measured on 50 m field sites and thus implied the even distribution of the measured erosion. Distribution Scores that were remote from zero, meanwhile, represented situations where erosion extents measured on 10 m and 50 m field sites were not comparable, and thus represented less evenly scattered erosion. Distribution Scores were limited only by the range of erosion extents recorded on field sites. For eroded area, the highest Distribution Score was 5.7 while that for eroded volume was 6.2.

For each of the 74 sites considered, erosion cause had been determined in the field as either biotic or water. Biotic erosion, caused by humans and grazing animals, included erosion such as sheep scars, tracks, footpaths and poached areas. Water erosion, meanwhile, included areas of degraded peat as well as seepage areas and gullies. By plotting the Distribution Scores for water and for biotic erosion, it was possible to assess the agreement between 10 m and 50 m data and to determine which field site size better represented the two principal causes of erosion.

3.9.3 Results

Distribution Scores were assessed to determine if both eroded area and eroded volume were suitable indicators of erosion distribution and of site size suitability. From Figure 3.20, it is clear that the Distribution Score for measures of non-biotic eroded area was significantly lower (99% confidence) than that for biotic eroded area. As a low Distribution Score corresponds to an evenly distributed erosion form equally well represented by 10 m and 50 m field sites, 10 m field sites may be used to measure non-biotic field erosion, but are less suited to the survey of biotic erosion.

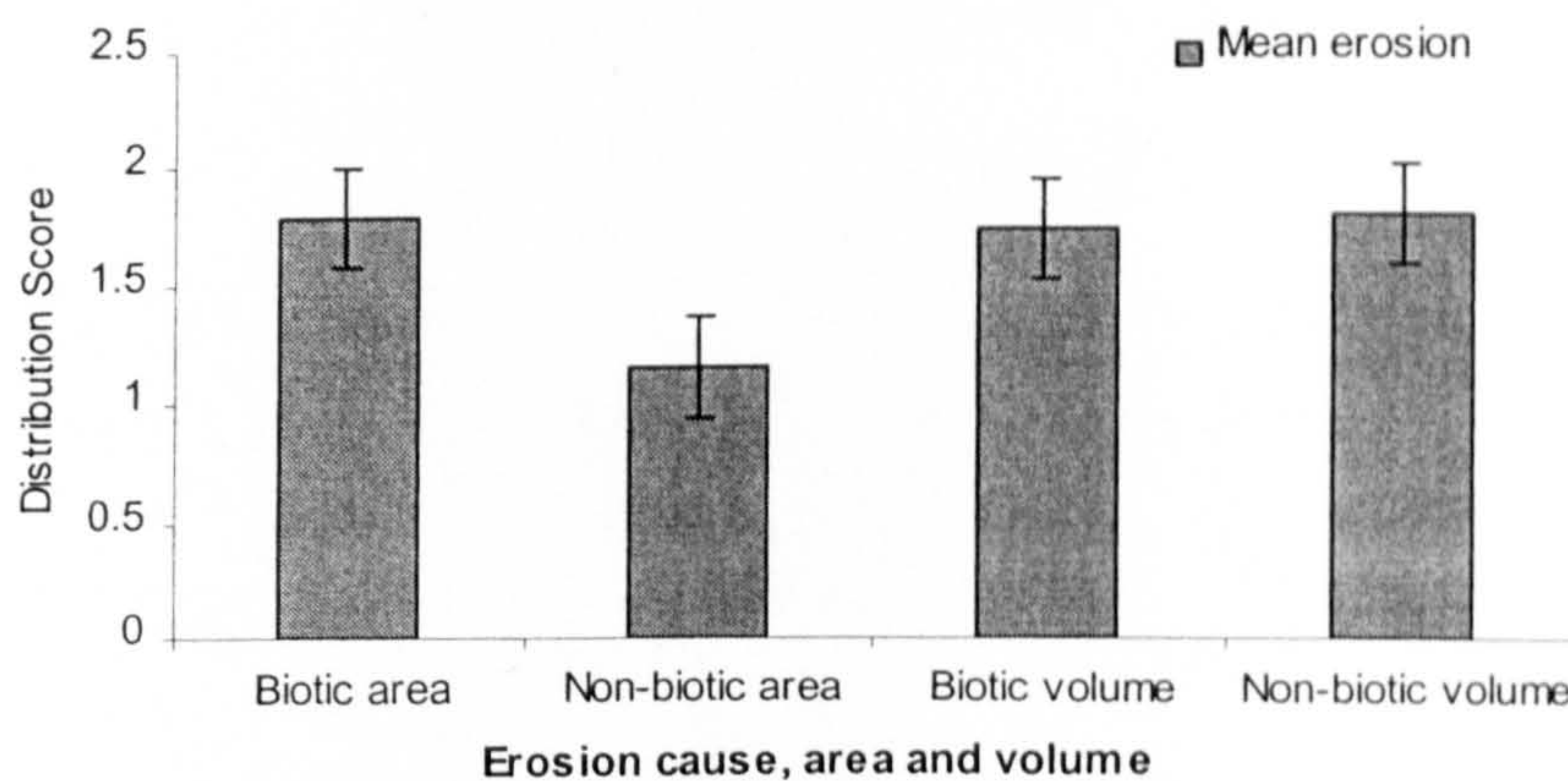


Figure 3.20 Distribution scores for eroded area and volume caused by biotic and non-biotic factors. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

There were no significant differences between Distribution Scores obtained from data on eroded volume. Consequently, neither 10 m nor 50 m field sites are more suited to the measurement of erosion volume, regardless of cause.

It is therefore clear that measurements of eroded area provide better estimations of the distribution patterns of the erosion measured, and that 10 m field sites are suitable for the measurement of water-eroded features. A larger field site is, however, required for the measurement of biotic erosion such as sheep scars and amenity footpaths. The reason for this distinction is obvious: biotic erosion is not even in its distribution. The presence of a single track of footpath in an area is not an indication that there will be similar tracks nearby. Similarly, while sheep scars may be clustered together on a sheltered slope, their presence does not indicate further collections of sheep scars evenly distributed across the slope. Water erosion, on the other hand, frequently takes the form of peat degradation, which may occur over

large areas of the immediate locality, or of regularly shaped linear gullies. Again, these forms of erosion do not imply that the same form of erosion occurs in the wider locality. Their regular form and the scale over which they develop mean, however, that they are as likely to be measured within a 10 m field site as within 50 m one. Of the two field site sizes used in this survey, 10 m sites are therefore adequate for the survey of water erosion only.

The Distribution Scores presented in the following are based upon measurements of eroded area. Scores were determined for each environmental and management factor measured in the field survey, to determine if field site sizes were suited to erosion in specific localities and, based on the above, to assess erosion form within different sections of the environment.

In Figure 3.21, Distribution Scores show that agreement between 10 m and 50 m data is at its highest for erosion measured at low altitudes, particularly at altitudes between 201 m and 300 m. At very high altitudes, however, the high Distribution Score implies that the erosion is disparate in nature and requires field sites of greater than 10 m radius.

Distribution Scores for erosion on different slopes, also shown in Figure 3.21, are lowest on very gentle and very steep slopes. Records of erosion from 10 m and 50 m sites are least alike between 8° and 15°: these were also the slope groups where the smallest mean eroded area and volume were recorded (Figure 3.4).

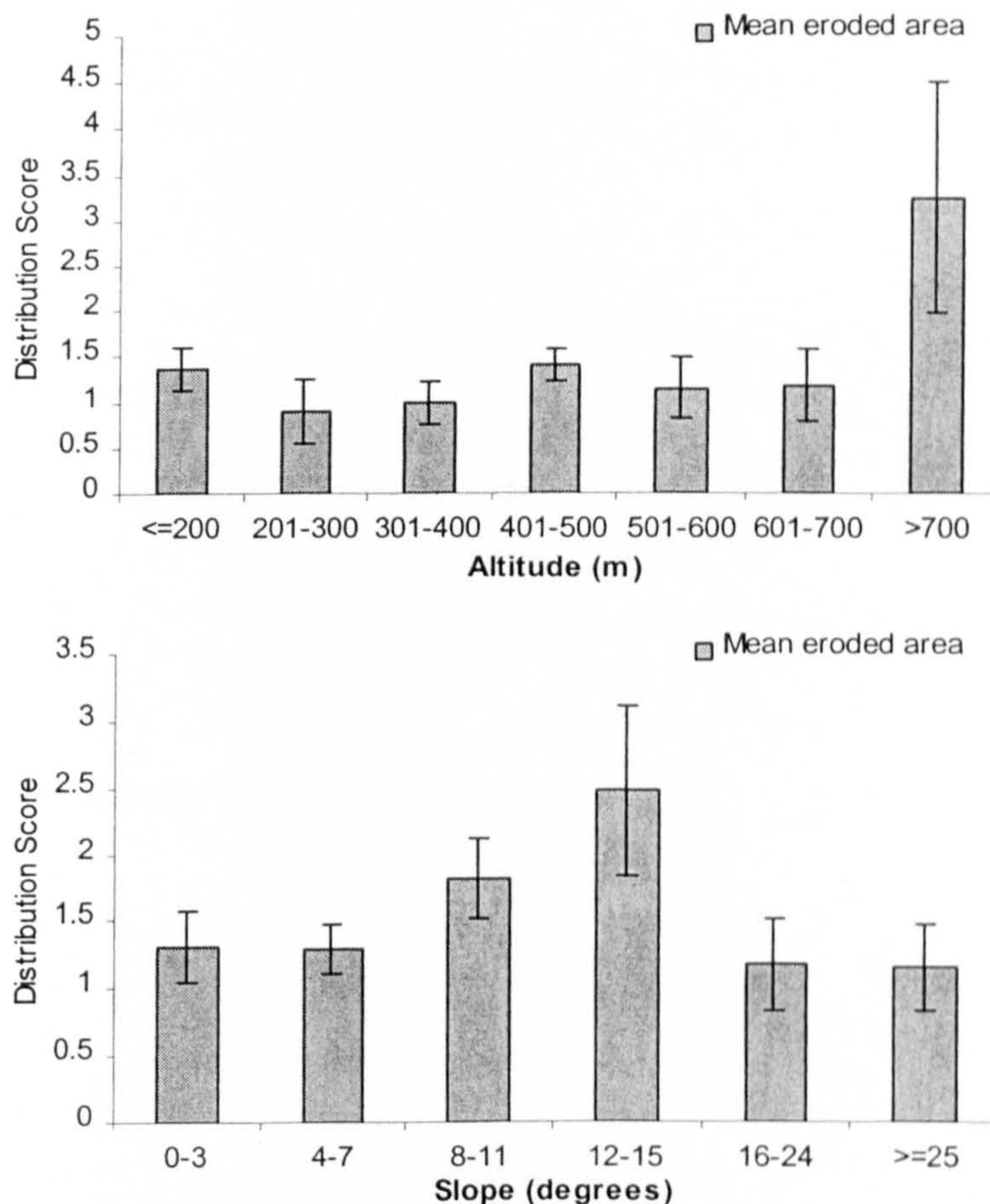


Figure 3.21 Distribution scores for eroded area measured within altitude and slope groups. Error bars represent standard error of the data ($SE = SD / \sqrt{n}$).

Figure 3.22 describes the changes in Distribution Score for eroded area measured at sublevels of the other environmental factors. It is obvious that it was not possible to distinguish between different erosion forms using field site morphology. For site aspect, the small variations in Distribution Scores are not significantly different and no clear trend associated Distribution Scores and erosion form. For grazing pressure, there were again no significant differences between Distribution Scores, but there was an obvious trend of lower scores at the lowest and the highest grazing pressures, with a marked increase in Distribution Score at intermediate grazing levels.

The Distribution Scores for different soil classes decrease along the hydrological gradient between dry mineral and peat soils (Figure 3.22). In the table on erosion cause within soil classes (Table 3.8), biotic erosion was greatest on dry mineral soils and water erosion dominated peat soils. This change in cause of erosion is reflected

in soil class Distribution Scores: highest scores reflect the scattered and uneven distribution of biotic erosion, while the lower scores for water erosion reflect its more regular distribution within field sites.

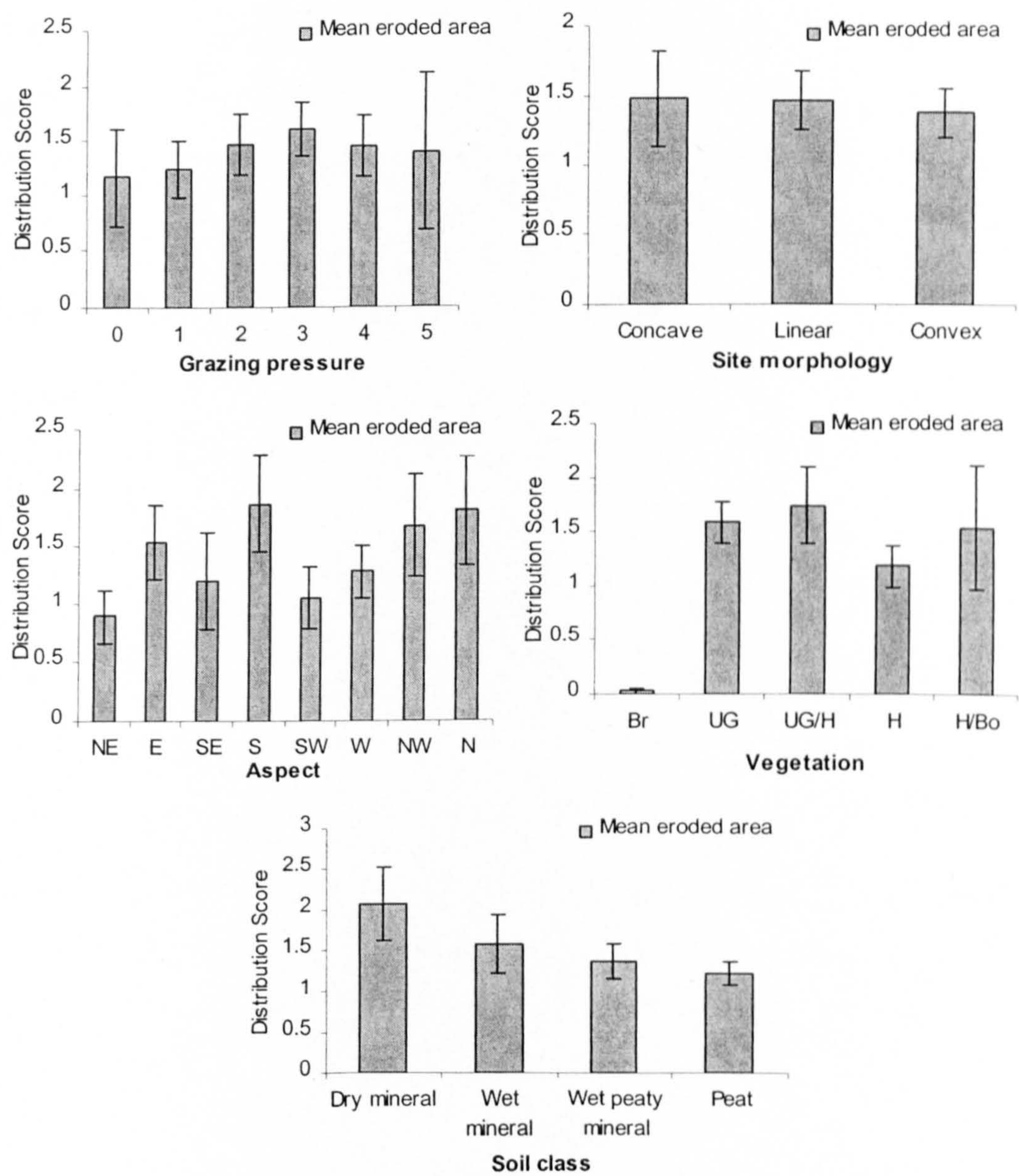


Figure 3.22 Distribution scores for eroded area, divided into environmental factors. Error bars represent standard error of the data (SE = SD/√n).

For eroded area measured on different vegetation types, there is close agreement between 10 m and 50 m data on bracken. This reflects both the nature of bracken and the form of erosion that develops under bracken. Usually, field sites were entirely dominated by *Pteridium* and understorey vegetation was restricted to

Trifolium species. Typically, the erosion that developed was approximately 0.1 m² in area, up to 5 cm deep, evenly distributed through the field sites and caused by sheep traffic through the vegetation. To measure the erosion, it was necessary to count the number of scars before using the mean dimensions to determine the eroded area and volume. The even distribution of the erosion explains the agreement between 10 m and 50 m eroded areas measured under bracken.

In contrast, distribution scores for all other vegetation types are high, although the score for heather is significantly lower than that for mixed grass/heather vegetation. As has already been seen, erosion on this vegetation is predominately water-caused: it is expected, therefore, that its distribution score should be low.

3.9.4 Summary

In the analysis of field site suitability, it was clear that eroded area was the more useful measurement of erosion. Eroded volume is calculated using the widely variable depth of erosion features, which range from shallow and extensive poaching, to deeper but areally-limited grip erosion. Depth therefore adds a further degree of complexity to the calculation of Distribution Scores that may explain why those based upon values of eroded area were the more useful.

It was also clear that, in erosion measurement, the usefulness of 10 m and 50 m field sites varied, and that this variation was influenced by erosion form. The low Distribution Scores obtained for water erosion, when compared with the higher Scores for biotic erosion reflect the suitability of 10 m field sites to surveys of water erosion. Human and animal erosion is difficult to measure adequately on small field sites because of its uneven distribution. Consequently, 50 m field sites were more suited to the measurement of biotic erosion.

Previously it had been considered that, as the 50 m data required little scaling up to unit area of one hectare, they were less likely to overestimate erosion extent. In comparison, values of erosion taken from 10 m field sites are more likely to overestimate erosion extent because of the large scaling-up required. Here, however, the usefulness of 10 m data in the measurement of water erosion was seen.

Using this information to determine where biotic and water erosion occurred within the environment confirmed the suitability of field sites to the measurement of different erosion forms. For example, agreement between 10 m and 50 m data was clearly better on peat soils and on heath, both of which are predominantly eroded by water. An obvious exception is the low Distribution Score for erosion under bracken: however, the unusually even distribution of this biotic erosion ensures coherency between 10 m and 50 m data.

3.10 DISCUSSION OF 1999 FIELD SURVEY RESULTS

Results from the 1999 field survey can be seen as stepping stones to further research as in most cases, the interactions between erosion and the environment are complex and require further investigation. In this discussion, the results are summarised and interpreted methodically to allow understanding of their complexities more easily.

3.10.1 Full and reduced (minus peat) 1999 field survey results

The following discussion summarises the interactions between environmental and management factors measured within both 10 m and 50 m field sites.

3.10.1.1 Altitude

Upland erosion area and volume both increased with altitude but this influence reflects changes in the upland environment associated with increasing altitude, however, rather than a direct altitudinal effect. Environmental changes associated with higher altitudes include lower temperatures, more frequent ground frosts and higher rainfall. Growing conditions are therefore compromised and result in less dense vegetation cover and reduced plant growth and germination rates. Consequently, exposed soil is less likely to revegetate than at lower altitudes. Bare soil may also be more mobile at higher altitude because of higher wind speeds and increased precipitation.

Another factor influenced by altitude is the development of soils: the greater area and depth of peat soil, coupled with its susceptibility to degradation, means more eroded soil is expected at higher altitudes. Finally, management conditions vary with altitude: human and animal use is expected to be more prevalent at lower altitudes

and to decrease in more remote regions, although recreational erosion is important at high altitudes. The increased erosion measured at higher altitudes in this survey may not, therefore, reflect altitude *per se* but the different environmental and management conditions experienced at higher altitudes.

3.10.1.2 Slope

In all analyses, there was a significant, negative relationship between erosion and increasing slope. This finding is supported by a number of previous works, most of which concentrated on plot scale studies (Morgan, 1995). Erosion on very low slopes may be due to large-scale peat erosion. Peat, which accounts for the greatest proportion of measured erosion, is confined to gently sloping hillsides or flat plateaux of reduced drainage. Because of the high susceptibility of peat to erosion, gullies form on gentle but extensive slopes once the vegetation cover is disturbed.

The increase in erosion seen on very steep slopes of greater than 16° may be due to gully erosion on mineral soils, landslides or pipe erosion, all processes that were omitted from the low slope-high erosion relationship mentioned above (Morgan, 1995).

Analyses of the survey data that excluded peat showed, however, that lower angled slopes continued to be dominated by erosion, which decreased at intermediate slopes of 12-15° before increasing to original levels. This negative slope-erosion relationship may be attributed to both the incidence of peat erosion on low slopes, but also to the inevitably greater landuse pressures in these areas. Soil on steep slopes, conversely, may not be exposed to intensive use by humans or grazing animals, but is subject to additional environmental forces, including gravity, that enhances its susceptibility to erosion. Sites of intermediate slope experience low rates of erosion, perhaps reflecting a balance of low use and high potential for erosion recovery.

The processes of erosion also change with slope angle: soils on low slopes, particularly silty and sandy loams, are more prone to crusting that reduces infiltration and increases runoff, while water moving faster through the soil on steeper slopes reduces surface runoff. On steep slopes, infiltration rates are often greater because the rate of erosion prevents surface sealing and crusting (Poesen, 1984). Sub-

surface pipe systems in blanket peat may also be an important determinant of erosion on gentle slopes. Although their extent remains unknown (Burt *et al.*, 1998), pipe systems make considerable contributions to peat drainage (Jones, 1979; Jones and Crane, 1984) and may represent a significant erosional mechanism (McCaig, 1979).

The resistance of steeply sloping areas to erosion may be due in part to bracken growth: *Pteridium aquilinum* is an indicator of porous, freely draining soils found on steep slopes. Up to 50% of field sites on slopes greater than 25° were bracken-covered: this value decreased steadily until there was no bracken on slopes of less than 3°. With its impenetrable vegetation that persists from late spring until October, and which is succeeded by a dense layer of dead vegetation, bracken is an aggressive invader that restricts understorey growth for much of the year (Tansley, 1949). While bracken is not grazed by sheep, is no longer widely used as winter bedding for cattle and also fails to present attractive or accessible amenity ground, it does, nonetheless, provide a highly effective soil cover that limits erosion to small scale poaching by sheep.

These results could be misinterpreted or negated if steeply sloping ground was not adequately sampled during this survey. The grid-based nature of the sampling strategy, however, ensured that all upland areas were thoroughly and objectively sampled. In total 107 field sites were on slopes greater than 11°: 69 of these had slopes greater than 16°. Only one field site was located on an incline that was too hazardous to survey (NSI grid reference NY31/6010).

3.10.1.3 Vegetation

From field survey results, mean erosion was lowest under bracken and highest on heather, mixed heather/bog and bog vegetation. These results occur in spite of the disparity in vegetation community extent: half of all eroded sites occurred on upland grassland communities.

The susceptibility of plant communities to erosion may be attributed to the soils on which they develop. Bog vegetation favours blanket peat while heather grows on highly organic, podzolised soils. Peat is distinguished from podzolic soils by the depth of its organic horizon which, in podzols, is less than 40 cm deep (Avery, 1980)

and by its year-round waterlogging, compared to the seasonal waterlogging of podzols. Both, however, are susceptible to erosion because of their high organic matter and water content. Accordingly, the low rates of erosion on grassland may be a reflection of the greater resistance of grassland, and the soils on which it grows, to erosive pressures.

The greater extent of erosion on heath-covered sites may also reflect the changes in hydrology and vegetation that occur once blanket bogs erode. Upon dissection, saturated peat masses lose a significant proportion of their water content (Ratcliffe and Oswald, 1988). This compromises the unique assemblage of blanket bog plants that depend upon the high water content and largely anaerobic state of peat. Once aerobic soil conditions are no longer limiting, vascular plants such as *Eriophorum* invade and are quickly followed by *Polytrichum* and *Juncus*. *Nardus* may be found as it can colonise loose peat around blanket peat edges (Tansley, 1949) and *Calluna* may eventually colonise the dry peat surface. This change in vegetation from a bryophyte-dominated flora to heath/grass may explain the communities on which erosion was measured. As heather vegetation also represents appealing and safe grazing ground for sheep, cattle and ponies, and drier walking conditions for humans, it is subject to greater intensity of use than blanket bog.

3.10.1.4 Soil

Upland soil erosion was consistently greatest on peat soils, followed by wet mineral soils. In Figure 3.23, the percentage of peat soils increases with altitude up to 700m, after which there is a sharp decline that corresponds to the overall decline in mean erosion extent in Figure 3.3. The dominance of this graph by peat soils reinforced the need to re-analyse the data without the peat soil class.

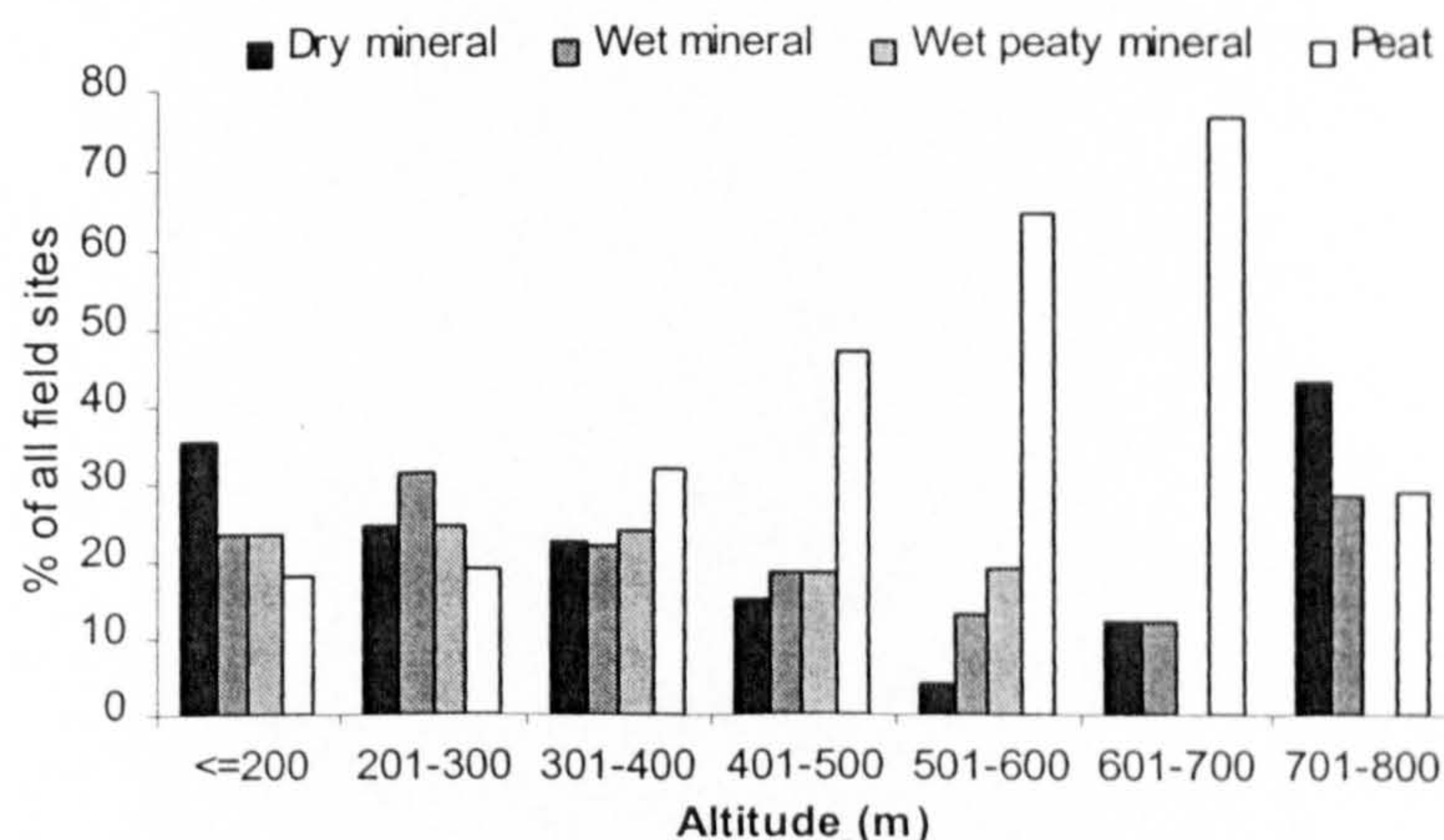


Figure 3.23 Changes in the numbers of field sites in the four soil classes with altitude.

As most erosion was recorded on peat soils, it was expected that relationships between erosion and the environment would reflect this dominance. With analyses of the minus-peat dataset, however, it was apparent that erosion on wet mineral soils was significantly greater than that recorded on other soil classes but, otherwise, the relationships between soil classes and the environment remained unchanged.

3.10.1.5 Grazing

Statistical analysis revealed that, while grazing pressure was significantly related to erosion extent, there were no significant differences between erosion measured at different grazing levels. In addition, analysis of the interactions between altitude and slope with grazing pressure revealed that the most susceptible field sites were exposed to a variety of grazing pressures.

A possible explanation of this variety of results is provided by the predominance of water erosion within the dataset, which may act to suppress the relationships between erosion and grazing pressure. However, in analysis of the dataset that excluded peat soils, no significant relationships were identified between erosion and grazing pressure.

This absence of a grazing-erosion relationship contradicts research that has emphatically linked soil degradation with grazing animals. Overgrazing by sheep alone is considered to be the greatest current threat to the upland habitat (Evans, 1977, 1997; Hodgson, 1985; Marsden, 1990). Much research linking erosion and grazing animals has been limited preferentially to severely eroded areas, such as the Peak District (Phillips *et al.*, 1981) and the Lake District (Loxham, 1997). As this study objectively assessed erosion over both England and Wales, the erosional effects of overgrazing may be more realistically represented as important, but of limited significance when considered with other erosion forms, including water erosion.

Alternatively, the lack of grazing pressure-erosion link may reflect the way in which grazing pressure was assessed. Logistically, a quick and easy method of grazing pressure assessment was required. A modified version of the English Nature

Grazing Index (English Nature, 1995), which assesses grazing by plant stem loss and topiary on heather only, was used. A more detailed procedure, capable of assessing grazing pressure on the range of vegetation communities surveyed, is required. Previous successful methods include assessments of the percentage cover of graminoids and ericoids (Welch and Scott, 1995), heather height (Welch, 1984b), rates of dung deposition (Welch, 1984a), and grazing animal numbers (Evans, 1996).

It is necessary, however, to distinguish between the lack of evidence linking erosion to grazing pressure as assessed during the field survey, and the evidence of erosion caused by grazing animals, as described in Chapter 7. There, it is confirmed that grazing animals are responsible for considerable amounts of upland erosion and are an important cause of upland degradation. In view of this, it is reasonable to assume that the assessment of field site grazing pressure used here was insufficient, and that conclusions regarding the influence of grazing animals on upland erosion should be drawn from direct evidence of erosion scars.

3.10.1.6 Aspect

The role of aspect in determining where and how much erosion occurs has not been clarified by this work. Both graphical and statistical interpretation of the full and reduced datasets failed to reveal a consistent trend in erosion caused by aspect.

The preferred aspect of upland field sites was not taken into account in this analysis. In England and Wales, and particularly in the Pennines, the uplands are commonly represented by many E-facing gradual slopes and relatively few steep and W-facing slopes. This may explain the high incidence of erosion on E-facing slopes, especially when taken into account with the elevated erosion measured on gentle slopes. However, in the absence of weighting against preferred slope orientations, it is difficult to appreciate any true relationship between aspect and upland erosion.

The lack of an erosion-aspect relationship may also reflect the record of aspect as the general orientation of the field site area. The aspect of the general location in which field sites are located may be more informative. In Chapter 5, aspect recorded as a function of the field site sub-catchment may provide evidence of a definite relationship, if any, between site aspect and soil erosion.

3.10.1.7 Field site morphology

Throughout this chapter, erosion has been consistently linked with concave field sites rather than either linear or convex sites. Water flow, an important erosive agent, is also greater over focussing concave slopes than on linear or convex sites (Soil Survey Staff, 1960). George and Conacher (1993) reported that concave hillslope sections accumulated soil moisture due to both saturated and unsaturated lateral flow processes. As well as detaching and transporting soil particles to the nearest watercourse, saturated concave sites are more susceptible to vegetation and soil disruption from human or animal traffic. In spite of the areas of bare ground prominent below convexities and attributed to sheep (Evans, 1996), the evidence here suggests that, across England and Wales, concave slopes are more susceptible to pronounced soil loss.

In addition, and because of their geomorphology, channelled water erosion is expected more frequently on concave slopes than on linear or convex slopes because of the focussing of water flow. As channelled flow is more erosive than overland flow, this may explain the higher extents of erosion on concave slopes.

3.10.2 Bare and vegetated eroded ground

Generally, relationships between areas of bare and vegetated eroded ground and the environment closely resembled those identified for the 1999 field survey data. However, the proportional differences in bare and vegetated eroded area may provide evidence of different forms of erosion.

The predominance of vegetated eroded area on mixed heath/bog and bog vegetation suggests that substantial areas of water erosion, which dominates these vegetation communities, were inactive. It may be assumed from this that bare soil, which is the greater condition of erosion on other vegetation types, is biotic-induced.

The extent of vegetated eroded ground exceeded bare eroded area on all soil classes. The extensiveness of water erosion may mask, however, the vegetated or bare condition of biotic erosion in different soil classes. Vegetated erosion was also dominant at all altitudes except for field sites located above 700 m: again, it is possible that, at that altitude, the most likely causes of erosion are recreational.

The total area and volume of erosion recorded on 50 m field sites was approximately equally divided into bare and vegetated portions. In spite of this, many more field sites contained bare eroded ground in 1999 than vegetated eroded ground (197 sites compared with 82). This difference suggests that currently active (bare) erosion in upland England and Wales is composed of smaller individual erosion features that are more widely distributed throughout the uplands and hence occur on many more field sites. Biotic erosion, which consists of linear tracks and paths, poached and rutted areas and sheep scars, fulfils these criteria, and its designation as the greater contributor to bare eroded ground supports the assumptions made above.

3.10.3 Optimal field site sizes for measurements of erosion

In total, 92 statistical investigations were made on the full 1999 field survey dataset. Some 55% of statistically significant relationships were on data collected within 50 m field sites. In comparison, 72% of statistical tests made on 10 m data were insignificant. Of the two measures of erosion extent made, significant relationships of eroded volume approximately equalled those for erosion area.

The higher statistical significance of the 50 m dataset may be a consequence of its larger observational area, which increased the relevance of the environmental variables recorded. The likelihood of overestimating eroded extent was also smaller in the 50 m field site, as translation of the data to unit erosion per hectare required scaling up by a factor of only 1.27 while 10 m data required scaling up by 31.8. Thus 2 m³ of erosion measured within 10 m converted to 64 m³ ha⁻¹, while 2 m³ of erosion recorded on a 50 m field site equalled 2.5 m³ ha⁻¹. Obviously the 10 m value may more readily represent over-estimation of erosion.

While the 50 m field sites provided more statistically significant relationships, 64 percent of relationships on 50 m field sites were repeated on 10 m field sites. Graphically, the trends in 50 m erosion were also reflected in the 10 m dataset. Both 10 m and 50 m field sites therefore provide suitable field sites for determination of the environmental and land management factors that influence erosion. However, because of the scaling required to convert erosion to unit values, it is advisable to

base summaries of mean erosion, and predictions of erosion change, on the 50 m dataset only.

The tests of site size made in Section 3.9 confirmed the applicability of 10 m field sites in the survey of water erosion. Water eroded features are evenly distributed within degraded areas, although the distribution of the eroded areas themselves may not be any more frequent or regular than those of small-scale biotic erosion, and therefore lend themselves to survey within a small field site.

In contrast, individual biotic erosion features usually cover limited ground, although they may occur more frequently than water erosion, or collectively, they may account for significant upland areas. Larger field sites, such as the 50 m site, are therefore required to survey adequately for biotic erosion. Further research on this topic is required to determine the ideal site size for erosion surveys.

3.10.4 Soil deposition within field sites

Redeposited soil was measured on only 20 percent of eroded field sites. In total, the volume of deposition measured on 50 m field sites represented 0.7 percent of the total volume of eroded soil recorded in 1999. The total area of deposition was 9.1 percent of the eroded area measured. Although these figures are low, particularly that for the volumetric proportion of soil that remained on-site, it is important to acknowledge that the assessment of erosion accounted for both current and historical erosion. Measurements of deposition, meanwhile, could only assess the contemporary extent of obviously redeposited soil and could not account for previously redeposited soil. Accounts of both present-day and historical soil loss may be more readily obtained from analysis of lake sediment cores, wherein the depositional history of the catchment is recorded.

However, it is still necessary to determine how much of the soil disturbed by ongoing erosion processes remains on-site in the uplands. To do this, larger field sites that encompass both erosional and depositional processes are required. The extents of deposition recorded in 1999 may also be examined in light of the change in erosion extent that occurred on upland field sites between 1997 and 1999, as in Chapter 7.

3.11 CONCLUSIONS

This field survey has successfully identified key environmental variables that influence where erosion occurs. The most important of these is soil: relationships between erosion and altitude, slope or vegetation can be explained in terms of the soils that develop in different environmental conditions.

A crucial result has identified the important role of peat soils in erosion: degradation at high altitudes, low slopes and on heath and bog vegetation is related to the dominance of peat in these areas. Chapter 7, which details where erosion occurs, further highlights that the majority of eroded area and volume within the uplands is due to large-scale erosion of peat. Information on the influence of the environment on peat erosion is an important step in rehabilitating eroded peats and preventing further degradation. Equally however, the vast scale of peat erosion effectively reduces the significance of erosion on any other soils type, and consequently, the influence of environmental variables on that erosion. While necessarily on a smaller scale, erosion on other soils is important in terms of area and volume. It may also prove to be the more important constituent of upland erosion if its rate of development exceeds that of peat (Chapter 7).

Importantly however, there is evidence of significant interactions between variables that may prove to be greater than the sum of their individual influences. Erosion is predicted to be greater on heath/bog vegetation, on low slopes and at high altitude. It is probable then that areas where these conditions are all fulfilled will be more susceptible to erosion initiation and less likely to promote recovery of degradation. Similarly, total erosion was predicted to increase by $1.005 \text{ m}^3 \text{ ha}^{-1}$ with altitude and to decrease by $1.04 \text{ m}^3 \text{ ha}^{-1}$ with slope. It may be concluded, therefore, that flat slopes at high altitudes are more susceptible to erosion than steep slopes at lower altitudes. In addition, as the effect of slope is relatively stronger, it is expected that gentle slopes at any altitude will experience more erosion than steep slopes at the same altitude.

As well as the importance of peat soils to erosion, this chapter has highlighted the contribution of humans and animals to erosion. While the overall extent of bare

eroded sites equals that of vegetated eroded sites, there is evidence that erosion in the latter was water-caused while much current erosion on bare sites is caused by humans and animals and is more widespread. These results have implications for future upland management aimed at protection of the upland environment (Chapter 8).

Finally, the assessment of field site size validity has supported the use of both 10 m and 50 m field sites in erosion studies. While the 50 m field site was statistically more useful, 10 m field sites also provided useful and relevant information on erosion and its causes. It has also been shown that 10 m field sites are adequate for the assessment of water erosion, but that 50 m field sites are more suitable for surveys on biotic erosion. Further information would determine the ideal site size for all erosion studies, as well as for research into specific forms of erosion and is therefore an important next step in erosion research.

Chapter 4

Soil loss within linear erosion gullies

4.1 INTRODUCTION

Erosion gullies are linear channels cut into the soil by the action of running water that cannot be removed by cultivation (Evans, 1996). In upland England and Wales, gully erosion occurs on both hillslopes and within blanket peat. On hills, gullies are induced by stream activity at the base of the slope or on the midslope by hydrological conditions on the slope itself (Harvey, 1996). The most widespread form of gully erosion, however, is the dissection of blanket bog by gullies incised into peat. Collapses of sub-peat pipe drainage systems and mass movements on steep slopes also allow gully development. On sloping ground, gullies run parallel to each other and branch infrequently, while on flat or nearly flat ground they become intricately branched and form a close-set reticulum with intervening residual blocks of peat (haggs) (Bower, 1961; Burt and Labadz, 1990; Tallis, 1997).

Although the temperate environment of Britain is not usually associated with high rates of gully erosion (Harvey, 1974), gullies act as runoff conduits and are important sources of runoff and sediment: individual gullies can exhibit high rates of soil loss (Harvey, 1974; Labadz *et al.*, 1991; Morgan, 1995). Estimates of soil losses from within gullies have been attained using rain gauges and peat traps (Tallis, 1972), but are usually inferred from measurements of suspended sediment loads made within drainage systems (Labadz *et al.*, 1991). Gross morphological changes within gullies have been determined using photographs, erosion pins and through constant resurvey (Harvey, 1974).

This chapter presents research into upland gully erosion based upon cross-sectional traverses of linear erosion gullies. Rates of soil loss and changes in gully morphology were measured over a two-year period. Both the theoretical and the practical aspects of the traverse procedure and the results obtained from data analyses are presented.

4.2 TRAVERSE METHODOLOGY

The practical considerations involved in the traverse procedure are described here. As the protocol was developed specifically for this research, the theoretical details of its development are also provided.

4.2.1 Site selection

The field survey described in Chapter 3 was completed in 1997 and again in 1999 using 399 accessible NSI and CS2000 field sites. A full description of field sites, including the means by which they were selected, is given in Chapter 3. The traverse procedure was applied to the small number of the sites that contained a non-vegetated erosion gully within the 50 m field site boundary. At each suitable site, and in addition to the environmental assessment and erosion quantification already completed, three separate traverses were completed using the protocol described in Section 4.2.5.

In total, 131 traverses were completed on 42 field sites: the locations of these field sites are shown on Plate 4.1 and their grid references are given in Appendix 1 (Table III).



Plate 4.1 Distribution of upland field sites at which gully traverses were completed.

4.2.2 Traverse equipment

The equipment required for field traverses was selected to fulfil several important criteria. Field materials needed to be

- *Portable*: lightweight equipment was particularly important for remote field sites.
- *Robust*: as the materials were used in all weather conditions distortions due to frequent re-wetting and drying or to wind were undesirable.
- *Unobtrusive*: this criterion was particularly applicable to any materials that were left in the field between visits as visible markers of any kind are prone to disturbance by both humans and animals.

The equipment used to complete field traverses therefore consisted of:

- A steel measuring tape
- One 20 m length of nylon twine, marked with indelible marker and with waterproof tags at 25 cm intervals
- Bamboo canes and bulldog clips; used to secure the measuring tape in high winds
- Metal detector and 65 mm nails; used in relocation of traverses.

4.2.3 Traverse relocation

Relocation of the precise start and end points of gully traverses was fundamental to the traverse procedure. Several measures were taken, therefore, to facilitate traverse recovery. The most important of these was the use of 65 mm galvanised nails as concealed metal ground markers.

As well as being lightweight and economical, the nails had the advantage of being unobtrusive and largely invisible when buried to full depth in the soil. This feature ensured that, throughout the field study, most of the nails remained undisturbed.

As it was crucial that the nails should be relocated, they were arranged with one centre nail surrounded by four corner nails: this layout covered an area of approximately 25 cm² and consistently provided sufficient charge to activate a standard metal detector. The wide heads of the nails (0.6 cm radius) both aided retrieval with a metal detector and allowed easy insertion and removal. Plate 4.2 is a photograph of traverse nails following relocation two years after placement.

A further measure taken to aid return to the precise location of traverses included using stereoscopic photographs of each traverse. These were taken as a pair of photos differing only in a slight lateral movement of the camera position of approximately 20 cm. When viewed in a stereo-pair, the photos provide a three dimensional image that was particularly useful for identifying key plants or gully features within the traverse.

All photographs were taken at a distance of 2-5 m from the traverse although the position varied between field sites according to the width of the traverse and the condition of the surrounding gully. In the majority of cases, the stereoscopic photographs were taken from the centre of the gully, facing the direction that afforded the greatest number of features, such as exposed rocks, that could later be use for relocation. Photos were also taken from the bank of the gully, and from directly behind the traverse start or end point.

Once a reliable system for the measurement and the relocation of gully traverses was established, the traverse procedure was included in the standard field survey protocol, as described in Section 3.2. The full protocols for completion of both initial and follow-up gully traverses are described below.

4.2.4 Traverse positioning

A standard and objective method for location of the traverses was required to minimise bias within the process and to ensure traverse relocation. For these reasons, random positioning of traverses was avoided and instead the gully nearest to the field site node was consistently used as the primary location for gully measurements. The shortest distance between the node and the gully also signified the starting position for the first traverse at all field sites.

Once the site of the first gully traverse was established, the distance between the traverse and the node and the orientation of the traverse itself were recorded before the traverse was carried out.

4.2.5 Traverse procedure

- The nylon tape, marked at 25 cm intervals, was secured at ground level on the side of the gully nearest to the node, at a point approximately 20 cm back from the gully edge. In this way, overhanging gully edges that may have degraded with the consequent loss of a traverse section were avoided.
- The nylon traverse tape was extended across the longest axis of the gully and secured at ground level on the opposite gully bank. Again, any overhanging edges were avoided by placing the endpoint approximately 20 cm from the gully edge.
- Moving along the traverse tape, the measuring tape was used to record the vertical depth of the gully every 25 cm. At each interval, the gully floor substrate or vegetation was also recorded: a list of the substrata encountered and their abbreviations is provided in Table 4.1.
- A stereoscopic pair of photographs was taken of the traverse. The position of the gully and its traverse were marked on the survey sheet map.
- The traverse tape was then removed, and two arrangements of five 65 mm galvanised nails were placed in and around the holes marking the origin and end of the traverse.
- Following an identical protocol, two further traverses were located and completed 5 m either side of the first traverse. The positions of these traverses were also recorded using stereoscopic photographs and by positioning nails at both ends of the traverse.

Figure 4.1 illustrates a hypothetical traverse and shows some of the principal features of both the gully and the method in which the traverse was completed. A gully pictured in Plate 4.3 highlights the applicability of the traverse procedure to the wide range of gully forms that occur in the uplands.



Plate 4.2 Arrangement of nails in ground two years after placement. Part of the metal detector used to relocate nails is also shown (Yorkshire Dales).



Plate 4.3 Traverse tape stretched across shallow erosion gully. The observation points at 25 cm intervals on the traverse tape can be seen as a series of coloured markers (Peak District).

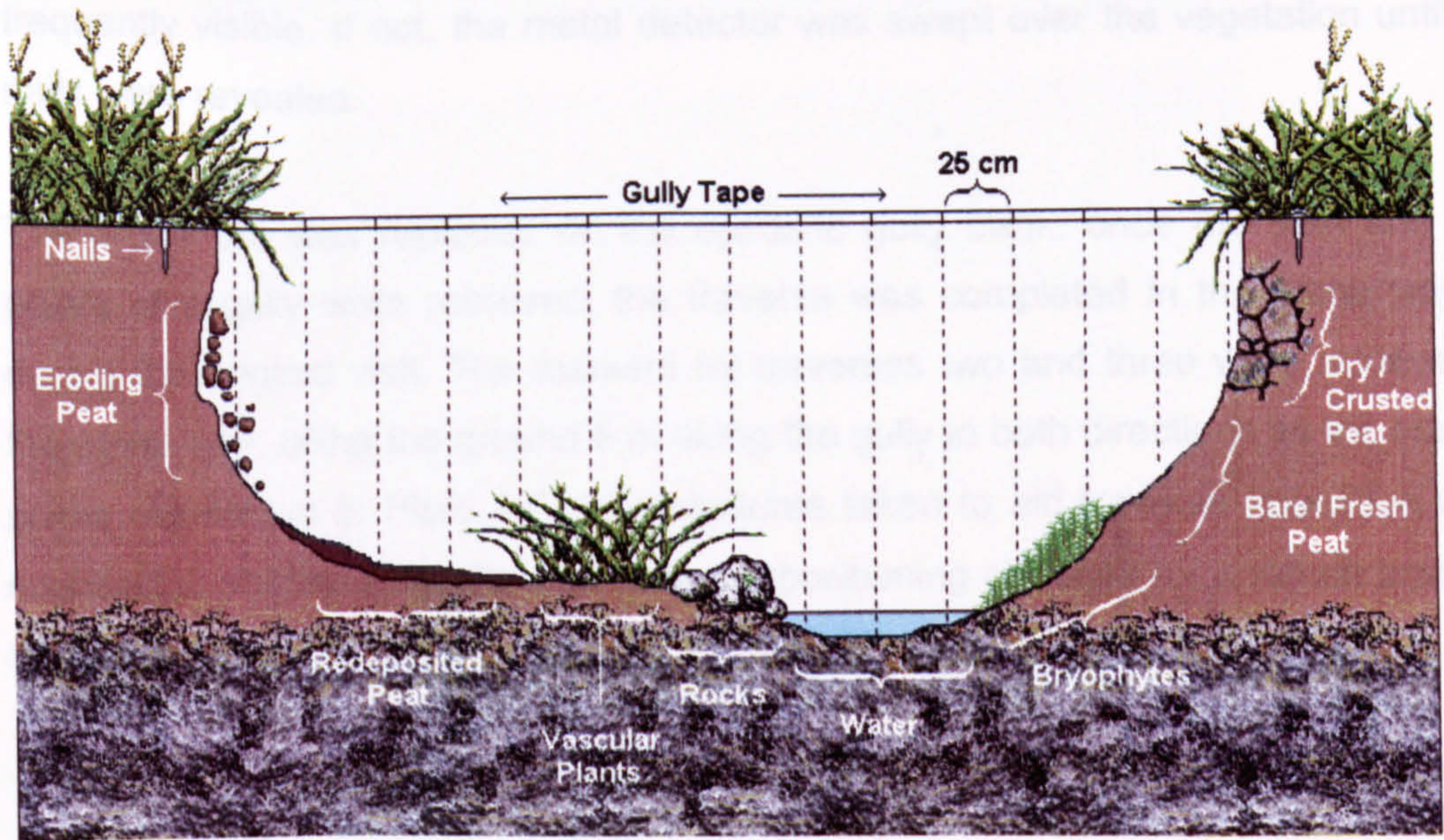


Figure 4.1 Illustration of a typical gully traverse: the principal ground features that occur in gullies are shown, as are the positions of the traverse tape and the ground markers (65 mm galvanised nails).

Occasionally, it was necessary to modify the traverse protocol when the cross-sectional gully width was greater than the extent of the traverse tape or when the gully depth was too great to be accurately measured. At other field sites, erosion was represented by a single eroding face, such as that of margin erosion (Plate 4.4). In those cases, it was considered advantageous to adapt the traverse protocol, rather than to neglect detailed measurements of the erosion feature. Traverses were completed, therefore, on these gullies, but the end point was located on the 'gully' floor, instead of on an opposite gully wall (Plate 4.5). These 'half-traverses' were alike in all other respects to full traverses, and as such, are treated with them in all statistical analyses (Section 4.3).

4.2.6 Completion of secondary traverses

In field site revisits completed in the summer of 1999, all gully traverses were remeasured using a similar protocol to that described above. Differences in procedure were associated with the retrieval of traverse markers.

Once the location of the field site was established, the original survey form was used to identify the erosion gully within which the traverses had been completed. As the point of this gully nearest to the node was the location of the first traverse, the search for erosion markers began here: the photographs of the first traverse were also used to minimise the area of interest. Once the search was limited to an area of less than 1 m², the heads of the marker nails embedded in the ground were frequently visible. If not, the metal detector was swept over the vegetation until the nails were revealed.

The procedure was repeated on the opposite gully bank: once the start and end points of a gully were retrieved, the traverse was completed in the same way as during the original visit. The markers for traverses two and three were retrieved in the same way, using the ground 5 m along the gully in both directions as the starting points. As shown in Plate 4.5, the measures taken to aid traverse relocation were successful: photographs show the exact repositioning obtained for a repeat traverse in the Yorkshire Dales.



Plate 4.4 Margin erosion, on which half-traverses were used to quantify erosion (Powys).



Plate 4.5 'Half-traverses' completed in 1997 (upper frame) and 1999 (lower frame). These photos highlight the success of the traverse relocation measures.

Table 4.1. Definitions used to describe gully floor substrata.

Name	Abbreviation used	Substrata
Peat soil	BF	Bare peat, recently exposed
	BC	Bare peat, with a dry, weathered surface layer
	R	Redeposited peat aggregates
Other soils	FE	Redeposited fine earth, usually <2 mm diameter
	M	Redeposited mineral material (coarse sand, stones, rocks)
Vegetation	V	Vascular plants (grasses, heather etc.)
	L	Lichens
	Bry	Bryophytes
	OE	Overhanging gully edge, usually lichen-covered
Water	W	Water

4.2.7 Missing traverse nails

Occasionally, the metal detector failed to identify the position of buried nails. In these cases, vegetation was removed from the immediate area in which the nails were buried and the metal detector was used again. If the nails were still not retrieved, a thin layer of the topsoil no greater than 1 cm deep was removed. If the nails remained undetected, as happened in a small number of cases, a number of alternative strategies were adopted.

The traverse photographs were used to pinpoint the start or end of the traverse as precisely as possible. The traverse tape was then fixed in position without the aid of the missing nails. By repeatedly comparing the original stereoscopic photographs of the traverse with the view from the same point, and adjusting the position of the tape accordingly, it was usually possible to arrive at a satisfactory location for the missing nails and hence the start or end of the traverse.

When nails went missing, only a single set of either start or end nails were mislaid. In these cases, a further check for the position of the missing nails was obtained from the length and orientation of the traverse recorded in the initial field survey. This information, combined with the photos, helped to compensate for the loss of the marker nails.

On a single field site, the traverse nails were lost because the gully wall in which they had been placed eroded away in the period between field surveys. On one

other occasion, the nails were buried beneath redeposited peat: in spite of the removal of 15 cm of material, the nails were still not retrieved. The reasons for the remainder of the missing traverse markers are unknown: occasionally, the nails had been removed from the soil, possibly by grazing animals. The nails were usually found lying on the ground close to where they had been buried.

4.3 TRAVERSE RESULTS

Of 131 traverses initially completed, 125 were successfully remeasured in 1999 and results from these are presented here. Section 4.4 discusses the differences in gully depth recorded at individual gully points 25 cm apart while the net changes recorded within traverses are described in Section 4.5. Section 4.6 assesses changes in different gully sections recorded between 1997 and 1999. The ways in which traverse data were manipulated for analysis are described here.

Although original gully traverses were completed in both 1997 and 1998, no distinction was made in the following between these traverses. Because of the very small changes in gully depth that were measured over the survey period, no attempt was made to discuss rates of soil loss from gullies. Instead, trends of soil loss and accumulation were sought and it was felt that information on these would not benefit from a sub-division of traverse data into that conducted over two years and that conducted over a single year. In any future work in which rates of soil loss are considered such a division is necessary.

4.3.1 Data processing

Each gully traverse recorded the depth and substrata of the gully at 25 cm intervals (Table 4.2; columns A-F). To obtain the change in gully depth over time, each original depth measurement was subtracted from the depth recorded at the same point in the subsequent survey. This led to a positive or negative value for each 25 cm point along the traverse, depending on whether the depth of the gully at that point had increased or decreased over the survey period (Table 4.2: columns D-A, E-B, F-C). These *Point Changes* were then examined for changes in gully erosion associated with vegetation and gully substrata (Section 4.4).

The individual depth measurements recorded in each traverse were also summed to provide a positive or negative *Net Change* in gully depth for each traverse (Table

4.2; Net Change). Where the net change was positive, the overall depth of the gully had increased between 1997 and 1999 and this was taken to indicate further soil detachment and loss from the gully. In contrast, a net negative change indicated a mean decrease in the depth of the gully resulting from soil deposition or increased vegetation cover within the gully. Results obtained using net gully change are presented in Section 4.5.

In all analyses, full and half-traverses (Section 4.2.5) were treated equally as depth measurements were made perpendicular to the traverse tape rather than to the gully floor (Figure 4.1). As the traverse tape was replaced in the same position in the second site visit, real changes in depth, unaffected by gully morphology, were recorded.

4.3.2 Changes recorded between 1997 and 1999

Figure 4.2 provides an example of gully traverse depths measured in 1997 and 1999. As for the majority of traverses, the changes that occurred over this two-year period were small. Students t-test failed to identify any significant differences between the point change records of any traverses (Appendix 6; Table I).

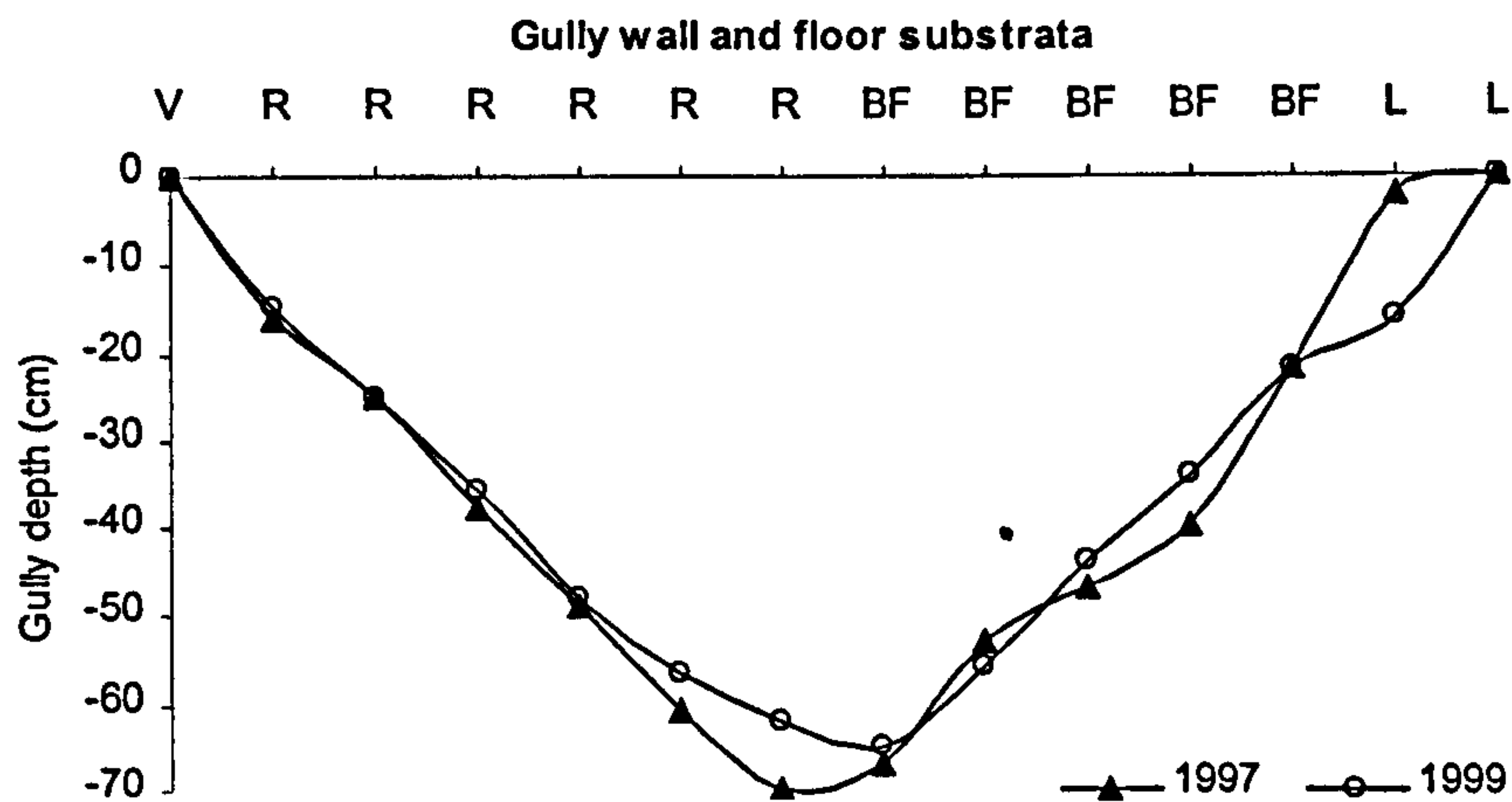


Figure 4.2 Gully traverse illustration highlighting the typical differences in gully depth recorded in 1997 and 1999. Data are presented as a continuum to illustrate the changes in gully structure.

In Sections 4.4, 4.5 and 4.6, the changes that occurred within gullies are presented despite their lack of statistical significance. It is necessary, however, to point out that in the absence of such significance, the relevance of the results is diminished. Nonetheless, the information presented is still a useful indicator of erosional trends

within linear gullies, provides a measure of the success of the traverse procedure and may be used to recommend further research, as in Chapter 8.

The error associated with traverse measurements is largely associated with the physical measurement of gully depth. The extent of this error was tested by repeating traverses at certain sites, immediately after their initial completion. As can be seen in Appendix 6 (Table II), the mean difference between records was less than 1 cm. As traverses were repeated in two separate years, the error was doubled to 2 cm. Differences in gully depth that are less than 2 cm, therefore, may be within the experimental error of the technique and should be treated with caution.

Table 4.2 Details of three traverses measured in 1997 (Column A, B and C) and in 1999 (Columns D, E and F). Point and Net changes are also presented.

<i>Individual depth measurements (cm)</i>						<i>Point changes (cm)</i>		
A (1997)	D (1999)	B (1997)	E (1999)	C (1997)	F (1999)	D-A	E-B	F-C
0	0	0	0	0	0	0	0	0
6	6	5	4	11	8	0	-1	-3
8	9	61	61	56	62	1	0	6
51	46	61	53	79	74	-5	-8	-5
54	50	58	52.5	82	77	-4	-5.5	-5
58	57	80	56	85	79	-1	-24	-6
75	62	77	76	93	90	-13	-1	-3
67	62.5	78	76	92	97	-4.5	-2	5
54	62.5	76	75	66	73	8.5	-1	7
49	52	50	60	58	63	3	10	5
47	47	17	33	55	53	0	16	-2
5	7	9	7	8	9	2	-2	1
0	0	0	0	0	0	0	0	0
<i>Net change (cm)→</i>						-1	-1.42	0

4.4 POINT CHANGES IN EROSION AND VEGETATION

In total, 125 gully traverses of varying width were measured in both 1997 and in 1999. The gully depth and substrate records made at each 25 cm interval of those traverses resulted in 2 033 individual pairs of depth and substrata records. Here, information from those pairs was analysed to determine the mean change in gully depth associated with different gully substrata.

4.4.1 Data transformation

From the distribution patterns in Figure 4.3, it was clear that the dataset of all point changes was normally distributed while those for positive and negative point changes were heavily skewed. Log-transformation was completed to correct the data skew: the presence of negative point changes, however, required that data were squared before transformation. The effect of transformation can be seen in Table 4.3 where mean and median values concur for all point changes and for transformed positive and negative point changes.

Table 4.3 also contains other summary details for point changes in gully depth. While the number of negative point changes is slightly greater than the number of positive changes, both mean and median values for both datasets agree.

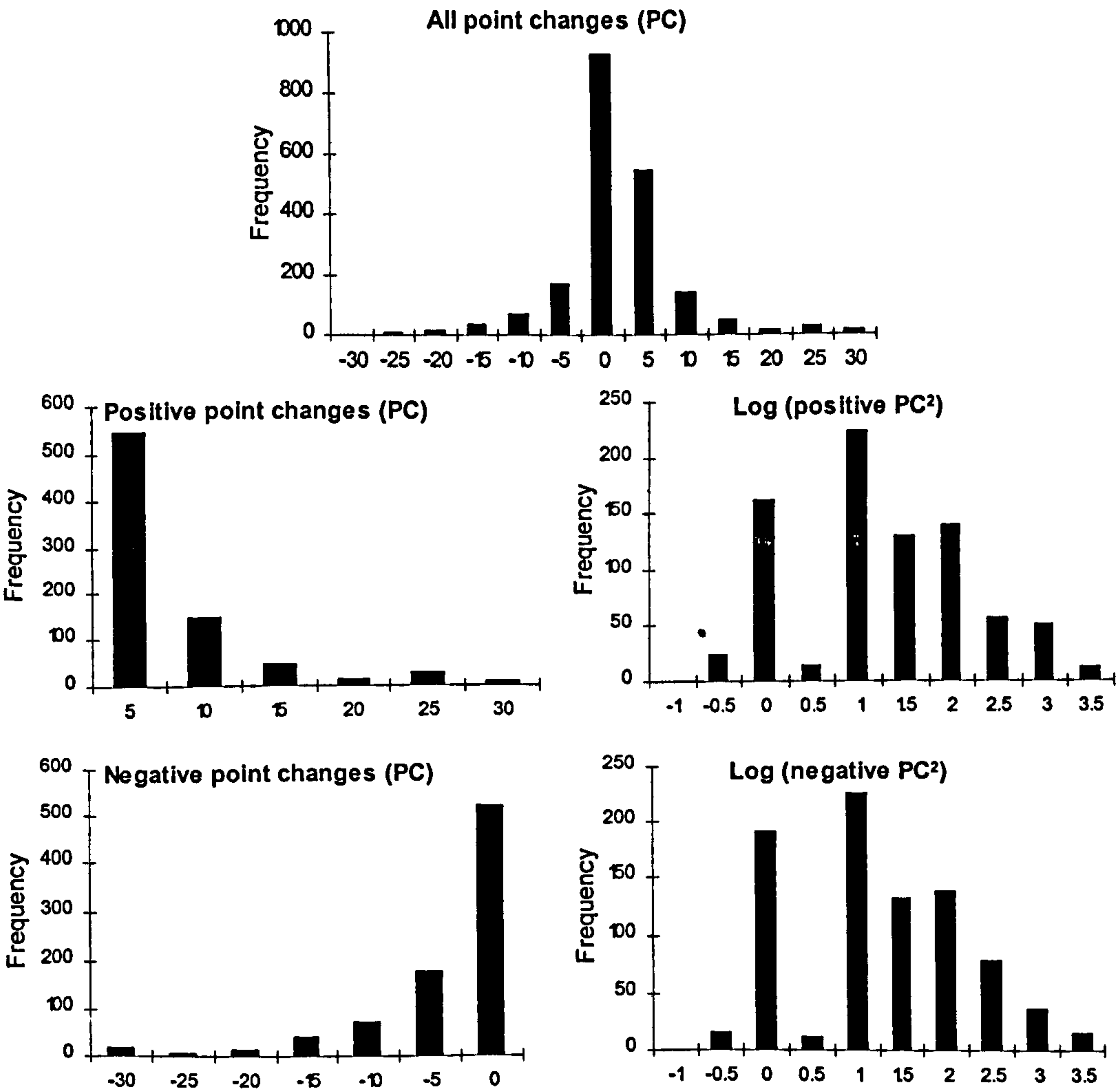


Figure 4.3 Frequency histograms of raw and transformed point change data: point changes refer to the difference between individual measurements of gully depths made in 1997 and in 1999.

Table 4.3 Summary statistics for point changes (PC) in gully depth.

Statistic	All	Positive PC	Log (positive PC ²)	Negative PC	Log(negative PC ²)
Mean	-0.01	5.81	1.07	-5.78	1.07
Standard Error	0.15	0.25	0.03	0.24	0.03
Median	0	3	0.95	-3	0.95
Standard Deviation	6.75	7.03	0.88	7.06	0.87
Sum	-21	4691	864.82	-4869	900.96
Count	2033	807	807	843	843

4.4.2 All point changes on different substrata

The numbers of positive and negative point changes that occurred on different substrata are presented in Figure 4.4. On bare fresh peat, bryophyte, mineral, fine earth and vascular substrata, defined in Table 4.1, the numbers of positive and negative point changes are almost equal. The greatest numbers of records were made on vascular vegetation and on bare fresh peat. On water, fine earth and redeposited peat substrata and on bryophyte and vascular vegetation the number of positive point changes exceeded the number of negative changes (Figure 4.4).

Of all point changes made on substrata, the highest percentage of positive changes occurred on overhanging gully edges: there, gully depth increased between 1997 and 1999 in 82% of cases. The highest percentages of negative change occurred under water and on areas of redeposited peat (79 and 61% respectively).

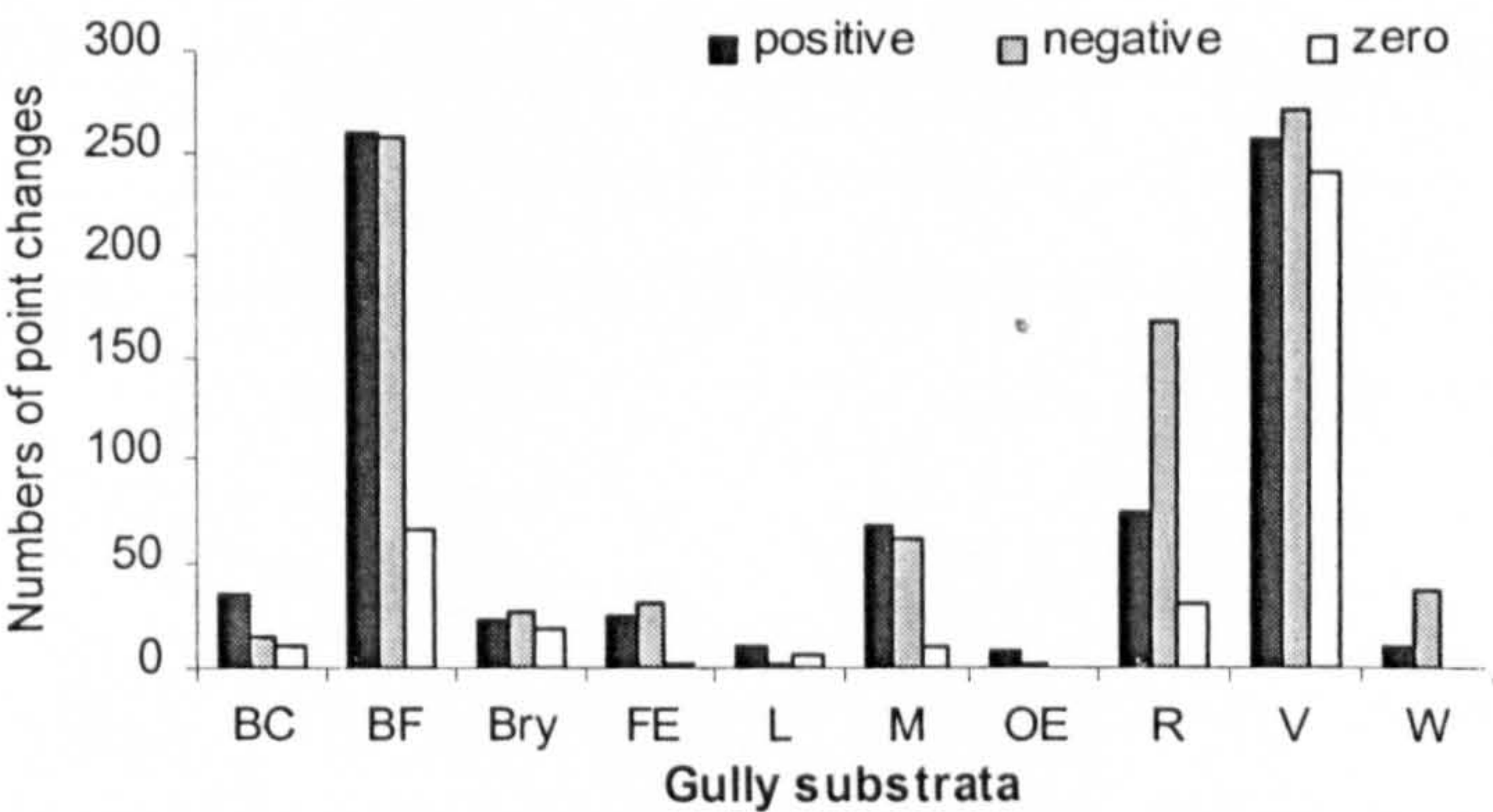


Figure 4.4 Positive, negative and zero point changes in gully depth recorded on different substrata. Substrata are described in Table 4.1.

The point changes in depth recorded on different substrata between 1997 and 1999 are shown in Figure 4.5: the greatest mean change in depth was positive and occurred on overhanging gully edges, where the mean increase in gully depth was

greater than 16 cm. The next highest increase in depth, of almost 6 cm, was recorded on lichen-covered sections of the gullies.

A mean decrease in gully depth was measured on four of the ten substrata, namely on bare fresh peat, redeposited peat and fine earth and under water. The remaining substrata showed mean increases in gully depth of less than 1.2 cm.

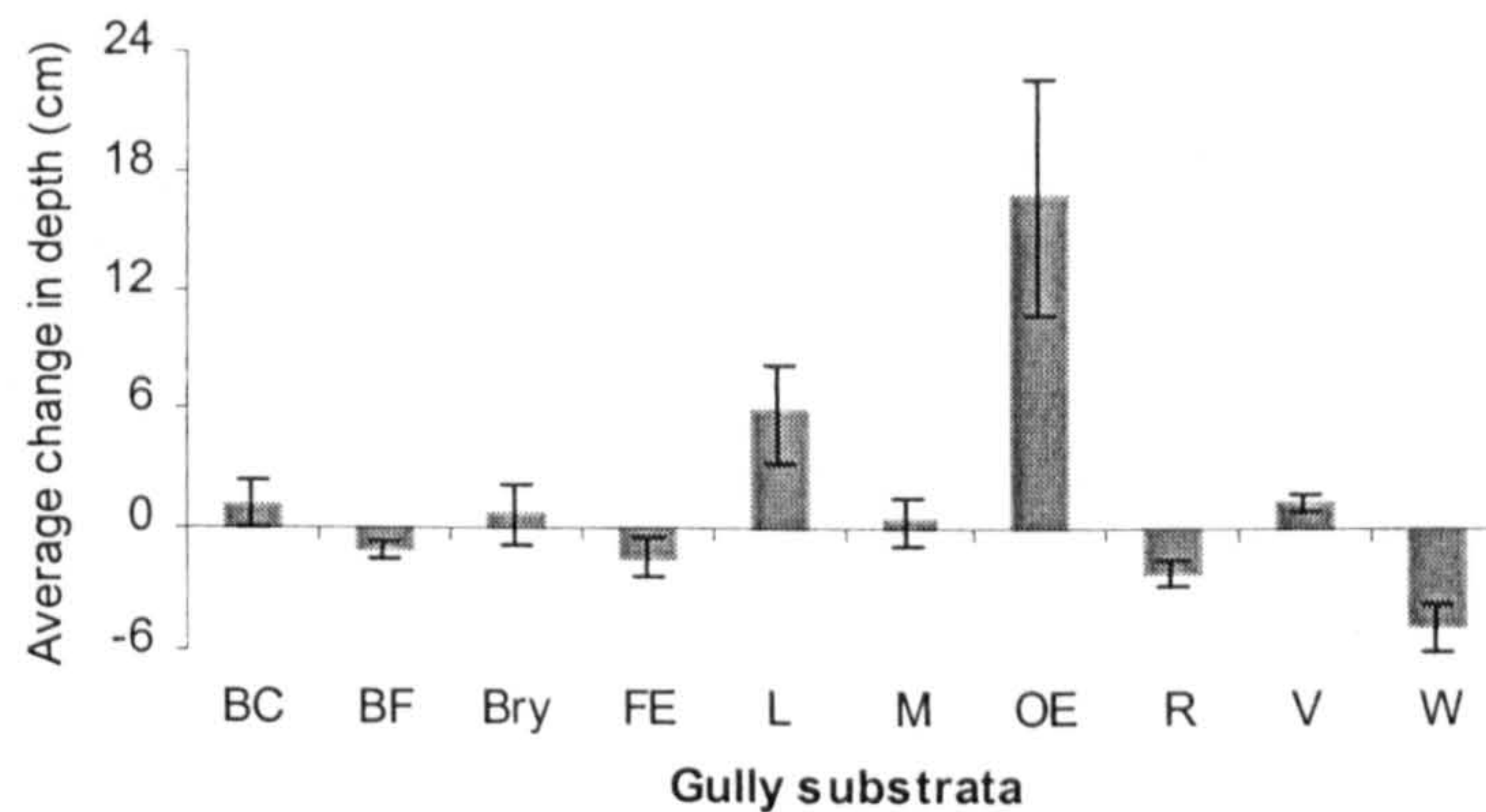


Figure 4.5 Mean change in gully depth recorded on traverse substrata between 1997 and 1999. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$). Substrata are described in Table 4.1.

4.4.3 Positive point changes on different substrata

The mean increases in gully depth measured on different substrata between 1997 and 1999 are shown in Figure 4.6. On fine earth (FE), the increase was limited to a mean of 5 cm: in contrast, measurements made on the gully overhanging edge (OE) experienced a mean increase of over 21 cm. This section of the gully is usually unvegetated but may be colonised by lichens. Its principal feature is the absence of underlying soil material, which explains its classification as a distinct substrate class. Usually, this material has been eroded away by water or animal traffic, resulting in an unsupported vegetation-root mat.

Gully depth increases were also substantial on bryophyte, lichen, mineral and vascular plant substrata while mean increases in gully depth were lowest on bare fresh peat, bare crusted peat and on fine earth.

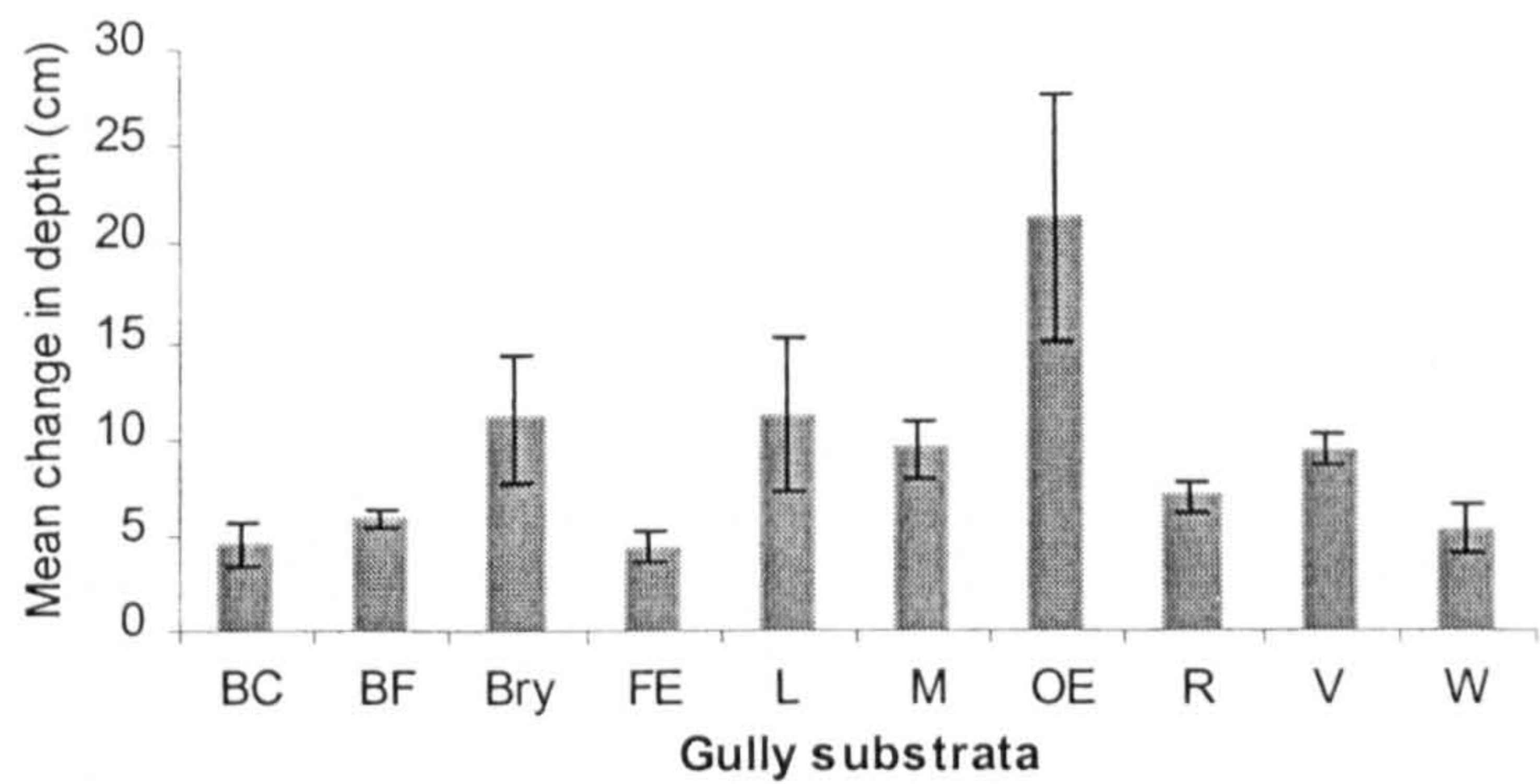


Figure 4.6 Positive point changes in gully depth as recorded on different gully substrata. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$). Substrata are described in Table 4.1.

4.4.4 Negative point changes measured on different substrata

Figure 4.7 shows the mean decreases in gully depth recorded from traverses between 1997 and 1999. These decreases are due to deposition of eroded material or to the establishment of vegetation within the gully. By covering the soil surface with litter and with its own root stock, encroaching vegetation can effectively reduce gully depth. As with positive changes, decreases in depth occur on all substrata. The greatest decreases occur on sections of the gully covered partially or wholly by coarse sand, stones and rocks (M). Decreases in depth of 6-9 cm also occurred on bare fresh peat, crusted peat, bryophyte, fine earth, water and redeposited peat substrata.

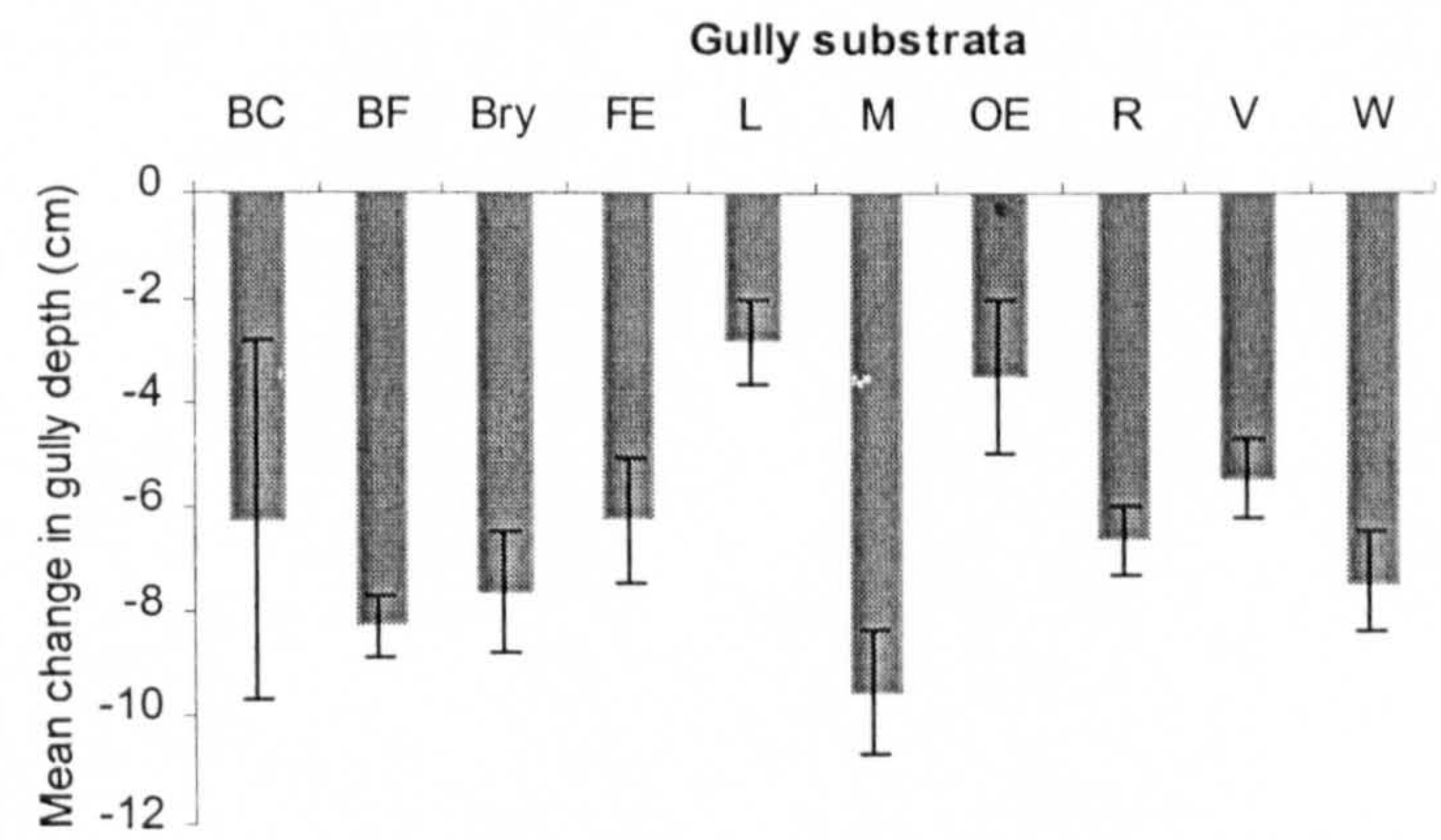


Figure 4.7 The mean decreases recorded in gully depth between 1997 and 1999 on different substrata. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$). Substrata are described in Table 4.1.

The smallest decreases in depth occurred on lichen-covered surfaces and on the overhanging edge of the gully. These surfaces have already been seen to experience large increases in gully depth.

Table 4.4 compares the mean net, positive and negative changes in gully depth for different substrata. On mineral material (M) and on redeposited peat (R), the positive and negative changes are almost equal. On bare fresh peat and fine earth and on measurements made under water, the mean negative change was greater than the mean positive change.

On bare crusted peat, bryophyte and vascular substrata, the mean increase in gully depth exceeded the mean depth decreases. Similarly, on the overhanging gully edge (OE), the mean increase of 21 cm far exceeded the mean decrease of 3.5 cm. On redeposited peat the overall change was negative even though the mean positive change exceeded the mean negative change.

Table 4.4 Mean fluctuations in gully depth for all, positive only and negative only point changes, as recorded on different substrata. Standard error (SE) = SD / \sqrt{n} . Substrata are described in Table 4.1.

	Net point change	Positive point change	Negative point change
<i>Substrata</i>	<i>Mean (SE)</i>	<i>Mean (SE)</i>	<i>Mean (SE)</i>
BC	1.15 (1.19)	4.44 (1.14)	-6.25 (3.45)
BF	-1 (0.4)	5.96 (0.45)	-8.28 (0.6)
Bry	0.67 (1.49)	10.96 (3.22)	-7.63 (1.14)
FE	-1.45 (0.99)	4.36 (0.82)	-6.27 (1.2)
L	5.7 (2.5)	11.14 (3.95)	-2.83 (0.83)
M	0.33 (1.15)	9.43 (1.45)	-9.59 (1.14)
OE	16.7 (5.9)	21.22 (6.28)	-3.5 (1.5)
R	-2.14 (0.59)	6.89 (0.85)	-6.66 (0.66)
V	1.21 (0.46)	9.34 (0.85)	-5.46 (0.79)
W	-4.8 (1.1)	5.3 (1.23)	-7.46 (0.96)

4.5 NET CHANGES IN GULLY DEPTH

Net changes in gully depth were calculated as the sum of all the positive and negative point changes measured within a single traverse. Summary statistics for net changes are provided in Table 4.5. Details are provided for all traverses, whether their net changes were positive or negative (*All*), for positive net changes in

gully depth only (*Positive*) and for net decreases in gully depth (*Negative*). Of 125 gully traverses, a single traverse showed no overall change in gully depth over time: this was disregarded in the analyses in this section.

As with the data on traverse point changes (Section 4.4), the data were squared and then logged to overcome the lack of normal distribution of the data. In Table 4.5 the differences between median and mean values are smaller for transformed data.

A net positive change in gully depth was measured on just over half (53%) of all traverses over the survey period. Overall, there is similarity in the statistics for this dataset: values for standard error and median are almost identical in the positive and negative columns (Table 4.5), as are the total changes in gully depth. The mean increase in depth however, at 1.73 cm, is less than the mean decrease in depth of 1.99 cm: both means are within the range of experimental error (Section 4.3.2).

Table 4.5 Summary statistics for the net change recorded on gully traverses completed between 1997 and 1999.

Statistic	Net changes in gully depth				
	<i>All</i>	<i>Positive</i>	<i>Negative</i>	<i>Log (positive²)</i>	<i>Log (negative²)</i>
Mean	-0.01	1.73	-1.99	0.10	0.12
Standard Error	0.23	0.21	0.27	0.11	0.13
Median	0.29	1.2	-1.26	0.15	0.20
Standard Deviation	2.62	1.67	2.07	0.89	1.02
Sum	-0.86	114.34	-115.2	6.30	7.25
Count	125	66	58	66	58

4.5.1 Relationships between net changes in gully depth and the environment

In this section, the environmental and management variates recorded on each field site are related to the net changes in gully depth. A full description of each variate and the way in which it was recorded has been provided in Section 3.3.3. A variety of parametric tests, completed using Genstat 5 (Release 4.1), were also completed to investigate the statistical significance of the relationships.

With increasing altitude, the change in gully depth switches from a mean decrease in depth to a mean increase. With slope, however, the mean change in gully depth switches from negative to positive at slopes between 4° and 7°. On steeper slopes, mean gully depth continues to increase, although there is no discernible trend.

The graph of aspect and mean changes in gully depth reveals a pronounced move from negative to positive gully depth changes between field sites on N and NE-facing slopes and those on S and SW-facing slopes. Intermediate levels of change occur on slopes facing E and SE.

Erosion gullies on upland grass, heather/bog and bog vegetation communities all exhibited continued gully erosion, which resulted in increased gully depth, between 1997 and 1999.

Changes in net gully depth were also related to field site morphology (Figure 4.8). There, a marked mean decrease in gully depth was recorded on linear field sites while gullies on concave field sites experienced a small increase in gully depth, corresponding to increased erosion. This change was much more slight than that experienced on convex field sites, however, where gully depth increased by a mean of 0.25 cm between 1997 and 1999.

Mean changes in gully depth also varied according to the field site soil class. Between 1997 and 1999, there were slight increases in gully depth on wet mineral and peat soil classes, while traverses on dry mineral and wet peaty mineral soils showed a mean decrease in gully depth.

The graph relating changes in gully depth to field sites under different grazing pressures indicates a threshold effect of grazing on gully erosion. Below grazing level 3, there was a steady increase in gully depth, which corresponds to continued erosion within the gullies. At grazing level 3, the mean change in gully depth became negative again. Following this, on sites where grazing pressure was very high, a mean increase in gully depth of 0.6 cm was measured.

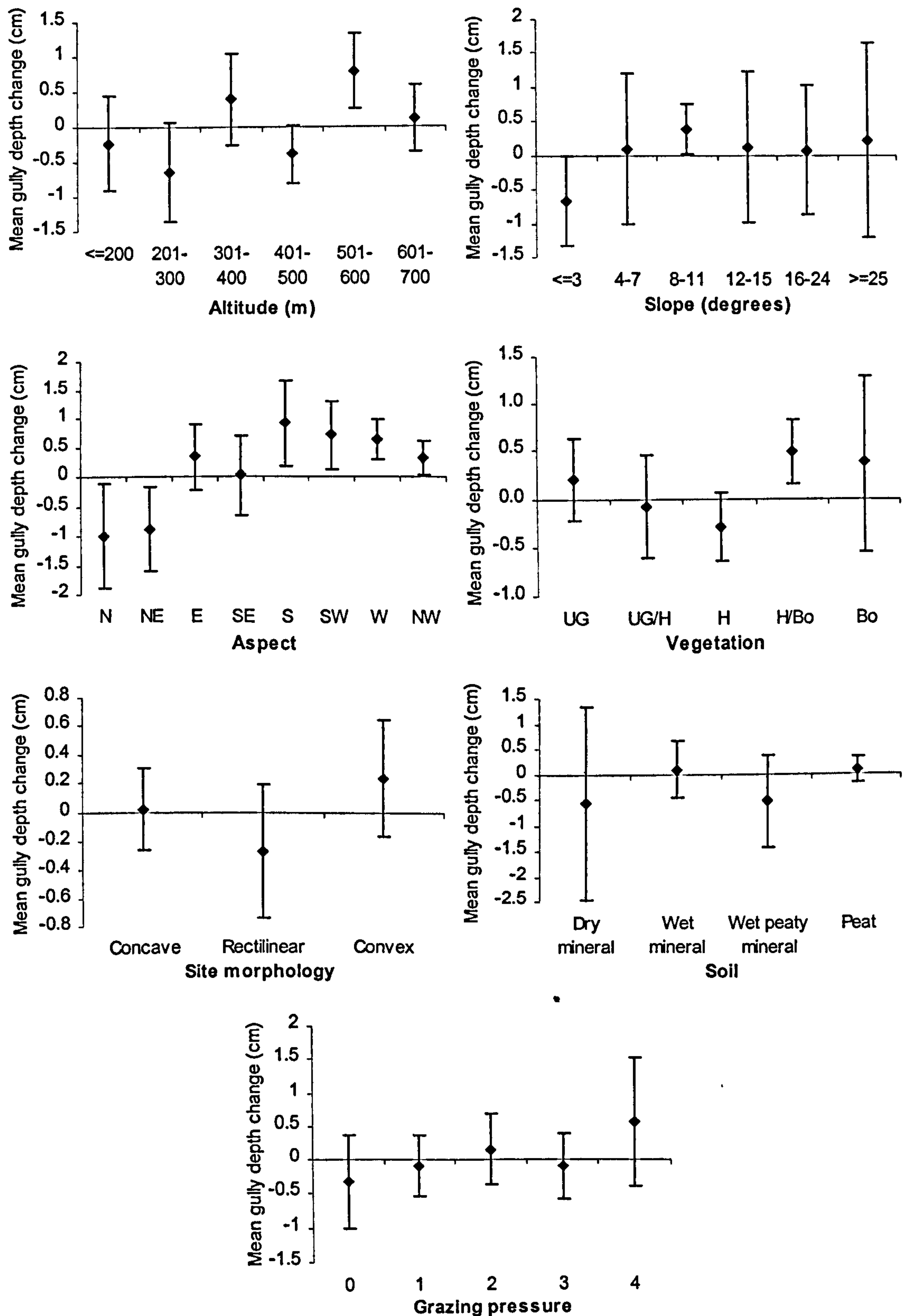


Figure 4.8 Mean changes in gully depth, recorded between 1997 and 1999, and related to environmental and management variates. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

The statistical tests used to investigate the significance of the above relationships and to assess the degree of interaction between variates included regressions and correlations. Linear regressions related gully change to the variables altitude and slope, and combined environmental factors with variables in multiple linear regressions. ANOVA, meanwhile, related each of the grouped factors aspect, soil, grazing pressure, landuse and landform to net gully change. Full descriptions of all statistical tests are provided in Appendix 4.

The statistical analyses were completed using datasets for all changes in gully depth, positive changes only and negative changes only. The total data and positive data analyses revealed no significant relationships between any of the environmental or management variates and gully erosion.

Data on negative changes in gully depth were significantly related to soil (F pr 0.041). The mean decrease in gully depth was significantly greater on dry mineral soils than within other soil classes. In parallel regressions with altitude, slope and with altitude and slope combined, mean decreases in gully depth were greatest on dry mineral soils (F pr 0.052, 0.038, 0.05 respectively).

A non-parallel significant relationship was also found when altitude and slope were combined and regressed with grazing pressure (F pr 0.041). With increasing altitude, decreases in gully depth were greatest under level 4 grazing pressure. With increasing slope meanwhile decreased gully depth occurred under lower grazing pressure (grazing level 1). In this, as in the above relationships, the variance accounted for by the relationships was low, at less than ten percent.

4.6 EROSION WITHIN DISTINCT GULLY SECTIONS

The previous section reported on the overall changes that occurred in erosion gullies over time and on the influence of gully substrata and of the environment on erosion or recovery within erosion gullies. Here, the erosional activity of specific gully sections is examined.

4.6.1 Hypothesis

In Figure 4.1, it was seen that bare fresh peat, redeposited peat and vegetation were prone to positive or negative changes in gully depth. As these substrata are frequently confined to distinct sections of the gully, the hypothesis was that it may be possible to distinguish between, and to estimate rates of soil loss or accumulation for, these sections.

Changes in gully depth recorded in different gully parts may be explained by water flow or by vegetation growth. Water flow along a linear gully will erode the gully floor (Harvey, 1974) and, until the bedrock is exposed, erosion rates may be higher here than elsewhere in the gully. Vegetation that encroaches onto the gully floor, however, will effectively prevent further soil loss, decrease gully depth by covering bare soil with a layer of vegetation and encourage deposition of eroded material. Tallis (1972) reported that frost action rarely affected the gully floor, but that drying out of bare peat on the gully floor occurred in summer and resulted in removal of superficial peat layers by runoff.

Water flow is not frequently directed over the lateral gully wall, however, and soil loss here may be less advanced than elsewhere in the gully. This part of the gully is, however, prone to desiccation, which not only weathers and shrinks the soil surface, but also encourages ablation. In winter, frost particularly affects the gully wall and loosens soil particles which, on thawing, are easily removed by runoff (Harvey, 1974; Tallis, 1972). Finally, because of its steepness, the gully wall is susceptible to the detachment of weathered material.

Finally, it is uncertain whether the base of the gully side slopes is prone to continued soil loss or to the accumulation of deposited soil. It is expected that at least a proportion of the material detached from the gully wall will be deposited here and that, consequently, gully depth will decrease. As Bower (1960) reported that redeposited peat did not experience frost and thaw cycles, it may be supposed that ablation and removal of material by runoff in this region are minimised. In contrast, however, the erosive power of any water flow down the gully wall may concentrate on and at the footslope (Morgan, 1995) and so there may be continued erosion within this region.

To determine where erosion is concentrated within the gully cross-section, each traverse was subdivided into distinct sections of wall, footslope and floor, as pictured in Figure 4.9. The particular patterns of erosion or deposition were then determined for each component. The same regions were located within half-traverses, where the very last depth measurements represented the gully floor.

4.6.2 Results: gully wall

The gully wall was the gully facet that, due to its position and susceptibility to detachment and erosion, was subject to the greatest changes in depth. It is the most nearly vertical facet of the gully, and is the linear section between the upper convexity of the overhanging edge and the lower concavity represented by the gully footslope. From the field survey, the region was known to be covered by traverse intervals two three and four, and by the second-, third- and fourth-last point measurements (Figure 4.9). The gully wall of half-traverses was also of interest, but here it was represented only by the second, third and fourth depth intervals. In total, 217 sets of data points covered the gully wall.

For measurements of erosion depth made at the gully wall, there was little difference between the number of sites with positive changes and the number with negative changes (108 sites compared with 103: Table 4.6). On six occasions, no overall change in depth was recorded at the gully wall.

The total increased depth at the gully wall was one metre greater than the total decrease in depth, although mean positive and negative changes were approximately equal. Overall, the mean change in depth at the gully wall section was an increase of less than half a centimetre while the total increase in gully wall depth, as measured in 217 locations, was almost one metre.

Table 4.6 Summary statistics for all, positive and negative changes in gully wall depth.

Statistic	Changes in gully depth (cm)		
	All	Increases	Decreases
Mean	0.45	5.86	-5.19
Standard Error	0.60	0.74	0.62
Median	0	3.17	-3
Standard Deviation	8.83	7.70	6.32
Sum	97.50	633	-535
Count	217	108	103

4.6.3 Results: Gully footslope

The gully footslope is defined here as the concave component immediately below the near-vertical gully wall and adjacent to the horizontal gully floor (Figure 4.9). In this section, reduced gravitational forces and water flow result in a diminished rate of soil loss and the deposition of soil detached from the gully wall. From the field survey, it was known that the footslope was best described by the 5th, 6th and 7th gully depth measurements and, on the opposite side of the gully, by the 5th, 6th and 7th-last depth intervals. Within half-traverses, the single gully footslope was represented by point measurements 5, 6 and 7.

Records of depth made in this section of the gully are summarised in Table 4.7. Overall, a small positive change in gully depth of, on average, less than 1 mm occurred at the footslope. In total, 187 individual footslopes exhibited an increase in depth of over 17 cm although, of the total number of observations, 52% experienced a decrease in mean gully depth. Both the mean and the total decreases in depth measured were, however, smaller than the mean increase in depth.

Table 4.7 Changes in gully depth recorded at gully footslopes.

Statistic	Changes in gully depth (cm)		
	<i>All</i>	<i>Positive</i>	<i>Negative</i>
Mean	0.09	6.01	-4.79
Standard Error	0.59	0.84	0.5
Median	-0.33	3.33	-2.5
Standard Deviation	8.04	7.52	4.9
Sum	17.5	487	-469
Count	187	81	98

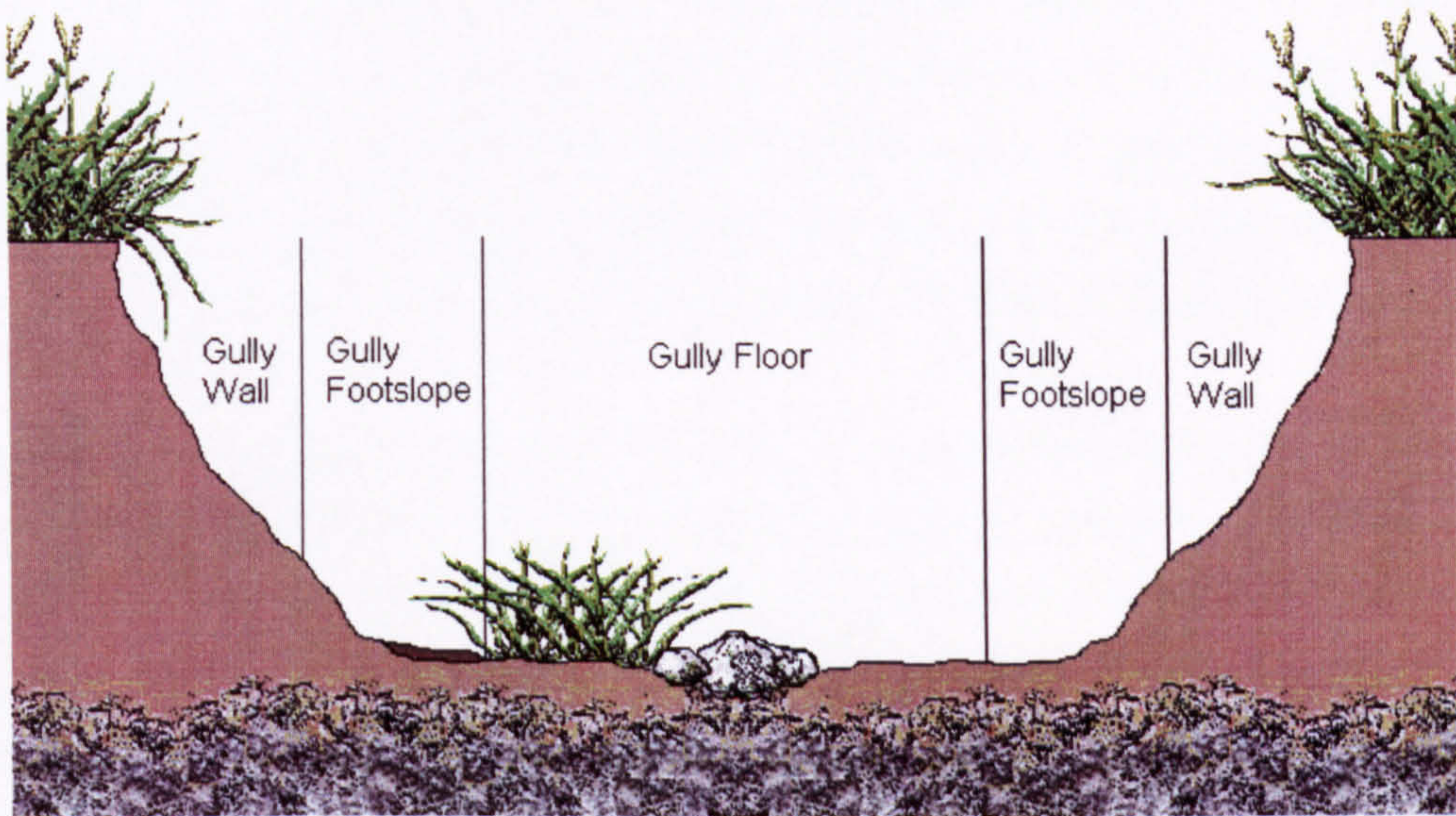


Figure 4.9 Gully subsections were defined to investigate changes in erosion and deposition rates at different points within traverses.



Plate 4.6 This half-traverse photograph displays the unsupported vegetation mat that forms the overhanging edge, a section of which has broken away.

4.6.4 Results: Gully floor

In this analysis, the gully floor was represented in two different ways, depending on the form of the field traverses. In half-traverses, measurements started at the surface of the gully wall on the original soil level and ended on the gully floor beyond the range of the gully footslope. Measurements on the gully floor were therefore represented by the last depth measurements made and in this analysis, the last four data points have been used as representative of changes in gully floor depth.

Within full traverses, the gully floor varied between several metres and less than half a metre in width. Of the entire set of depth measurements, it was first necessary to remove the data points that represented the gully wall i.e. the first and last four data points. As the next three depth measurements from both the traverse start and end represented the gully footslope, these too were omitted in consideration of the gully floor. Any remaining depth measurements were then used as indicators of the continued erosion or deposition on the gully floor. Traverses that were particularly short and which had insufficient data points to cover the gully floor were disregarded.

In Table 4.8, summary details are provided for the changes in depth recorded on the gully floor. Overall, the depth of the gully floor decreased by a mean of 1.3 cm, thus exceeding the mean positive change in depth by about half a centimetre. In the columns for separate positive and negative changes, it is clear that negative changes in depth occurred more frequently than positive changes and no overall change in gully floor depth occurred in a single traverse.

Table 4.8 Summary statistics for gully floor of both full and half-traverses.

Statistic	Changes In gully depth (cm)		
	All	Positive	Negative
Mean	-1.32	4.61	-5.06
Standard Error	0.75	1.23	0.61
Median	-1.00	2.00	-3.86
Standard Deviation	7.83	7.96	5.03
Sum	-145	194	-339
Count	110	42	67

4.7 DISCUSSION and CONCLUSIONS

4.7.1 Gully erosion and the environment

Patterns of gully erosion were not linked to many of the environmental or management factors recorded on field sites. Overall, gully depth increased with both increasing altitude and with increasing field site slope. There was also a marked difference between the changes in gully depth recorded on sites of different morphologies, with gullies located on convex sites clearly more prone to continued erosion. In terms of soil class gully erosion on wet mineral and peat soils was clearly greater than that on either dry or wet peaty mineral soils. Erosion was also greater in gullies located on the hydrologically more saturated heath/bog and bog vegetation communities. However, linear erosion gullies on grassland also experienced increased depth over the survey period.

Finally, a complex relationship was identified between field site grazing pressure and erosion within gullies. With altitude, decreased gully depths were measured under heavy grazing pressure. This apparent anomaly may be explained by the dominance of large-scale peat erosion at high altitudes. In such areas, the amount of grazing ground has usually been effectively diminished by the extent of the soil loss as, in some areas, only residual hags remain. Consequently, grazing pressure on residual vegetation may be severe, while, at the same time, recovery of eroded peat gullies or deposition of eroded material within gullies will continue.

The significant regression of low grazing pressure combined with increasing field site slope with decreases in gully depth may be similarly explained as field sites on steep slopes will automatically receive diminished levels of grazing.

The relationship between grazing and gully erosion analysed here used grazing pressure assessed from the vegetation within the field site boundaries. A more useful assessment of the influence of grazing animals on gully erosion could perhaps be based on direct evidence of animal interference, using signs of tracks and slip marks on the gully slope, dunging within gullies and topiary of within-gully vegetation. There may not, however, be any relationship between erosion and grazing animals: Harvey (1974) reported that sheep rarely strayed onto gullied slopes in the Howgill Fells and had very little direct effect on sediment yield there.

4.7.2 Gully erosion on different gully substrata

In terms of the changes in gully depth recorded on different soil and vegetation types, the greatest erosion recorded between 1997 and 1999 was measured on overhanging gully edges. These are particularly prone to soil loss because of their position, and their lack of solid ground support underneath (Plate 4.6). Erosion was also high on lichen-covered surfaces, which was most frequently recorded on the original soil surfaces at the gully edge, and therefore occurred predominantly in the same position as gully overhangs.

Overall negative changes in gully depth occurred on surfaces that were prone to deposition, such as on fine earth and redeposited peat and under water. Overall, decreased gully depth was also measured on bare fresh eroding peat surfaces. This substrate is more usually expected on the gully wall and to be prone to increased, rather than decreased, gully depth. Its designation here as an accumulating substrate suggests the misidentification, at least some of the time, of redeposited peat for bare uneroded peat.

4.7.3 Overall change

Overall, there was little or no difference between 1997 and 1999 point measurements. The mean change recorded from over two thousand pairs of measurements was less than 1 mm: this highlights the need for a greater time period between traverse remeasurements. Alternatively, it may indicate that, between 1997 and 1999, weather conditions were not ideal for the promotion of either erosion or deposition with upland gullies. In either case, additional measurements in the future are needed to aid the calculation of rates of erosion from linear gullies.

4.7.4 Sectional changes

It was possible to distinguish between erosion processes in different parts of the gully cross section using gully depth changes (Section 4.6). From that, it was seen that the greatest changes in gully depth occurred on the gully floor. On average, the depth of the gully in this section declined by 1.3 cm over the period between 1997 and 1999. This value is not, however, outside the range of experimental error for

gully traverses. It is most likely that the decreases in depth in this gully part are due to revegetation of bare soil and to redeposition of eroded material.

Overall, gully walls experienced continued erosion between 1997 and 1999, although the difference in numbers between positive and negative depth changes was very low. The mean change measured on gully walls was an increase in depth of less than half a centimetre, which was obviously within the range of experimental error.

Analysis of erosion within the gully section has also highlighted a drawback of the traverse procedure. As the gully wall is frequently vertical, or near vertical, continued soil loss may be more apparent as wall retreat, rather than surface lowering. Consequently, measurements of gully depth made at 25 cm intervals perpendicular to the traverse tape will not be sufficiently sensitive to these changes. It is therefore recommended that the traverse procedure be adapted to allow measurements on gully walls steeper than, for example, 45°. The procedure could determine lateral width between a rigid post embedded in the footslope and the gully wall. Measurements made at 1 or 5 cm intervals and repeated over time, using nails as markers of post position, would allow the rate of wall retreat to be determined. Using such permanently-positioned erosion pegs, Harvey (1974) measured gully headwall retreat and Evans (1974, 1977 and 1990) assessed erosional retreat of scar edges

In the gully footslope section, the overall increase in depth recorded between 1997 and 1999 was less than 1 mm. Although there were more instances of negative depth change, the mean positive change was greater and it may be assumed that there was no overall change in this gully section over the two-year period.

4.7.5 The overall success of the traverse procedure

There were no statistically significant differences between the depth measurements made on any traverse completed in 1997 or in 1998 and its corresponding traverse measured in 1999. Similarly, the experimental error calculated for depth measurements exceeded all changes in gully depth measured between 1997 and 1999. It is therefore important to acknowledge that the results presented above are not based upon statistical significance but rather are discussion of trends apparent in the data.

The traverse procedure was nonetheless successful in many respects. It proved to be a reliable means of making detailed assessments of erosion within a limited area. The successful recovery of traverse nails highlighted the advantages of this simple and economical way to mark gullies and traverses for future relocation.

No attempt was made to quantify the volumes of soil lost from erosion gullies using data from the traverse procedure for a number of reasons. The first of these was the lack of statistical significance of the data. Secondly, gullies, and hence traverses, were located in a wide range of environmental situations, as depicted in Figure 4.8. Because of the variable conditions affecting gully erosion, it was not possible to determine a standard rate of soil loss for upland gullies. Finally, traverses were completed objectively within gullies and were positioned, therefore, at all stages between the gully head and its end. As erosion rates vary considerably between different gully sections (Bridges and Harding, 1971), it was not possible to derive a satisfactory rate of gully erosion from the available data. There is evidence, nonetheless, that gully erosion accounts for a substantial annual loss of soil (Tallis, 1972) and it is recommended that future work concentrate on the determination of erosion rates within linear gullies.

Although changes in gully depth were generally within the experimental error of the method, the fact that any changes were measured at all is evidence of the potential of the traverse procedure. A longer interval between visits would require careful note-taking and positioning of nails to ensure return to the same traverse, but would also provide detailed information on the longer-term rates of soil loss and accumulation within erosion gullies. In the interests of promoting return to and remeasurement of erosion gullies in the future, all traverse marker nails were replaced in their original positions, paving the way for exciting and beneficial future research.

Chapter 5

Morphological features of field site sub-catchments

5.1 INTRODUCTION

In this chapter, the relationship between the field site sub-catchment and erosion extent is examined. The sub-catchment was defined as the area of land from which water flows across the field site. Sub-catchment size determines the amount of water yield and sub-catchment length, shape and relief all affect the rate of water and sediment yield (Gregory and Walling, 1973). This study therefore involved recording indicators of sub-catchment morphology from OS maps and relating those indicators to the extent and form of field site erosion.

Morphological mapping is defined as the representation of terrain as cartographical units and, in the mapping devised for morphological survey by the ITC (International Institute for Aerial Survey and Earth Sciences), erosional features were included in the maps produced (Verstappen, 1970). In this work, however, the technique was reversed. OS maps were used to describe important morphological features of the sub-catchment, such as slope and relief, and these features were then used to explain the presence of field site erosion.

5.1.1 Hypothesis

The extent and form of degraded soil has already been related to various environmental and management descriptors of the 0.7854 ha field site (Chapter 3). In this chapter, the hypothesis is that morphological and hydrological attributes of the field site subcatchment are responsible for the degree and form of field site erosion. That the degree of erosion depends on slope, landscape position and physiographic convergence or divergence has already been shown (Evans, 1990a; Hussain *et al.*, 1998; Moore *et al.*, 1986; Morgan, 1995) but much previous work has concentrated on erosion within plot or field-scale studies.

5.2 EXPERIMENTAL METHOD

The morphological features of the field site sub-catchment were determined using 1:25 000 Ordnance Survey maps, which Gregory and Walling (1973) had suggested were adequate for mapping drainage basin characteristics because of their contour interval and reliability. These maps also had the advantage of being readily available and, having been used in the field survey, were already annotated with the positions of field sites. The field sites used in this study are the same NSI and CS2000 field sites on which the 1997 and 1999 field surveys were based and are described in Section 3.3. Appendix 1 (Tables I and II) also lists field site grid references.

The traditional definition of a catchment was redefined here from the area of land drained by a watercourse (Whitten and Brooks, 1972) to the area of land that contributes water to the field site. As the field site effectively represented a point within the sub-catchment, the watershed limits were correspondingly difficult to define. In particular, it was impossible to define the area, one of the most important sub-catchment characters, for a number of reasons. In the calculation of area, a precisely delineated basin perimeter is essential (Gregory and Walling, 1973). In small sub-catchments, whose perimeter was difficult to define, miscalculation of the perimeter by as little as 1 mm lead to differences in area of an order of magnitude. A second factor that confused the calculation of area was the presence of streams within larger sub-catchments. As these naturally out-compete the field site in the drainage of water, it was impossible in some cases to define the sub-catchment perimeter, thus eliminating the possibility of defining area. It was judged safer, therefore, to confine the measurements made to the following.

The greatest distance between the field site and the sub-catchment perimeter was measured. Water is an important cause and maintainer of soil erosion, and this measurement represents the longest route over which sub-catchment water flows. It determines how quickly runoff is delivered to a site and may provide, therefore, an indicator of the potential for erosion within the field site.

Slope angle and morphology also influence the flow of water through the sub-catchment. Both characteristics were measured along the same hydrological path as the distance to watershed. The average slopes of the sub-catchment were grouped as in Table 5.1, after Hodgson (1997). Where sub-catchments had abrupt or severe

changes in slope, average slope was calculated across the slope break. Slope may also be assessed through field mapping (Savigear, 1965) but the method is time-consuming and does not provide quantitative indices of slope.

The morphology of the sub-catchment was described as concave, linear or convex, depending on the direction of water flow. Concave slopes, where water flow is directed or focussed inwards towards the field site, correspond to the receiving sites of the Soil Survey Staff (1960). On convex slopes, meanwhile, water flow is diverted outwards and shed in different directions. On these shedding sites (Soil Survey Staff, 1960), the water that encounters the field site is effectively reduced. Finally, on straight, or normal slopes (Soil Survey Staff, 1960), runoff flows vertically downslope and crosses the field site without deflection. Figure 5.1 illustrates the different forms of sub-catchment morphology. The shapes may also be defined using the proportion of a circle centred on a point on a hillside that lies at a higher altitude than the centre. Values of <0.5 occur on convex slopes, 0.5 indicates straight slopes, and values of >0.5 indicate converging slopes (Morgan, 1995).

In addition to the above descriptions of sub-catchment, the general aspect of the sub-catchment was recorded to investigate its influence on erosion extent.

Table 5.1 Slope groups and the contour intervals represented by them (Hodgson, 1997).

Slope group	Degrees	Description	Distance between contours (1:25 000 OS map)
1	≤ 3	Level / gently sloping	≥ 85 mm
2	4 - 7	Moderately sloping	36 - 84 mm
3	8 - 11	Strongly sloping	23 - 35 mm
4	12 - 15	Moderately steeply sloping	17 - 22 mm
5	16 - 24	Steeply sloping	1 - 16 mm
6	≥ 25	Very steeply sloping	< 1 mm

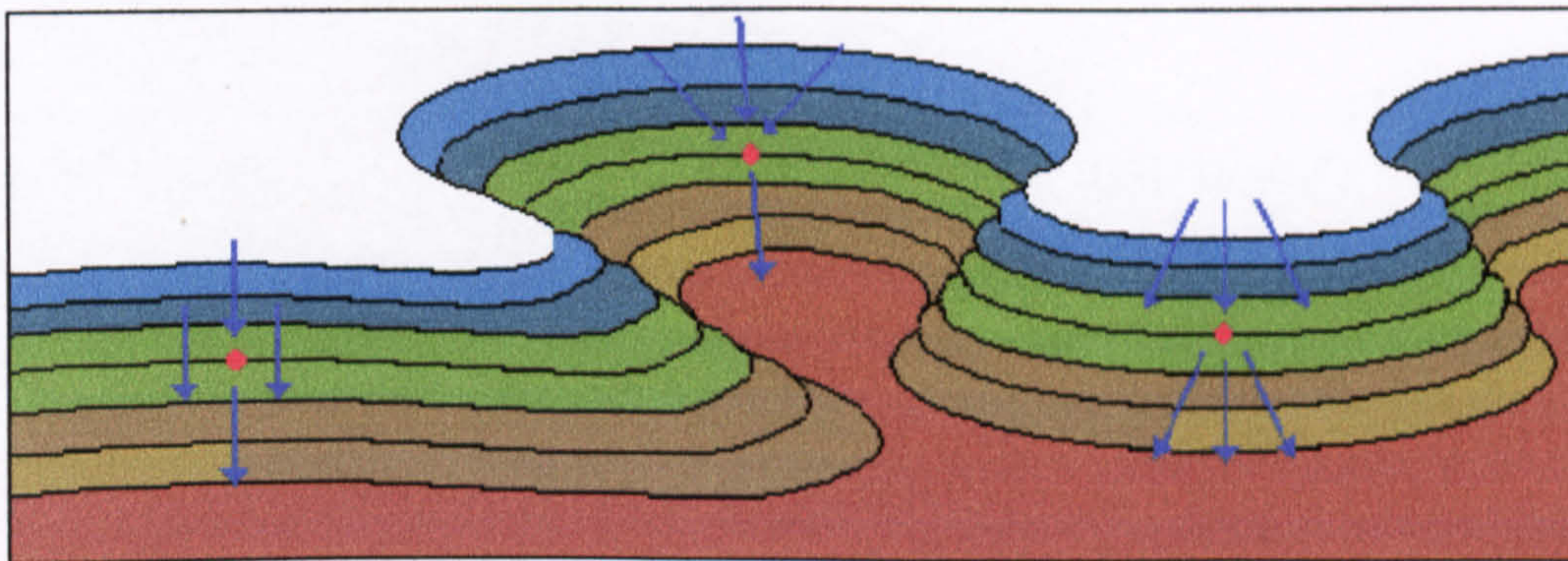


Figure 5.1 Basic landscape morphologies as defined by Soil Survey Staff (1960) and Morgan (1995). From left, the field sites (red points) are located on straight, focussing and shedding sub-catchments. Arrows indicate the general direction of water flow across field sites.

5.3 FIELD SITES ERODED WITHIN 10 M AND 50 M OF THE NODE

In the field survey described in Chapter 3, erosion extent was assessed within two circles, each centred on the NSI or CS2000 grid reference, or node. While the smaller field site extended to 10 m radius from the node, the boundary of the larger field site was 50 m from the node. Eroded area was calculated using the length and width of individual erosion features, and was expressed as a percentage of the field site area, i.e. 0.0314 ha and 0.7854 ha for 10 m and 50 m field sites respectively. The volume of eroded soil, meanwhile, was determined from the length, width and depth dimensions of individual erosion features. Eroded volumes measured in m³ on 10 m and 50 m field sites were multiplied by 31.8 and 1.27 respectively to achieve volume per unit area (m³ ha⁻¹).

Of the total number of field sites, catchment details were secured for 46 field sites eroded within 10 m and for 133 eroded 50m field sites. The relationships between sub-catchment features and field site erosion are presented here for both 10 m and 50 m field sites. The statistical analysis carried out to assess the significance, if any, of these relationships is described in Section 5.3.5.

By creating groups within the environmental variates, and examining the average erosion that occurred in different groups, the presence of potential links between the environment and erosion were revealed. Because of the number of field sites and the high variability of eroded area and volume records, this approach was preferable to the use of all raw data. The distribution of the data was, however, preserved in the values of standard error. The use of data averages also minimised the effects of outliers, and of disparities arising from groups with large numbers of sites.

In all of the following, values of 50 m eroded volume have been divided by 10 to allow direct comparison between its trends and those of 10 m eroded volume when linked to sub-catchment characteristics.

5.3.1 Soil erosion and sub-catchment distance to watershed

A primary aim of this section was to determine if the presence of erosion was influenced by the perpendicular distance between the field site and the watershed. This relationship is illustrated in Figure 5.2 for erosion recorded on both 10 m and 50 m field sites. For eroded area, there is clear evidence of an increase in the mean

erosion extent up to a threshold distance of 1.5 km from watershed. Above this distance, the average eroded area declined before increasing again at distances of over 2.5 km from the watershed.

The relationship between watershed distance and eroded volume is not so clear. The average eroded volume measured within 10 m field sites declined steadily after an initial peak on 1 km-long sub-catchments. Eroded volume measured on 50 m field sites shows more variability with distance to watershed. After a peak on short sub-catchments of up to 0.5 km long, mean eroded volume decreased apart from a peak on sub-catchments between 1 km and 1.5 km in length. This peak is at least partly attributable to NSI field site NY41/1010, on which a single eroded and revegetated gully contributed to 18% of the eroded area and a loss of over 10 000 m³ of eroded soil. Excluding this peak, there is a general decline in mean eroded volume with increasing distance to watershed.

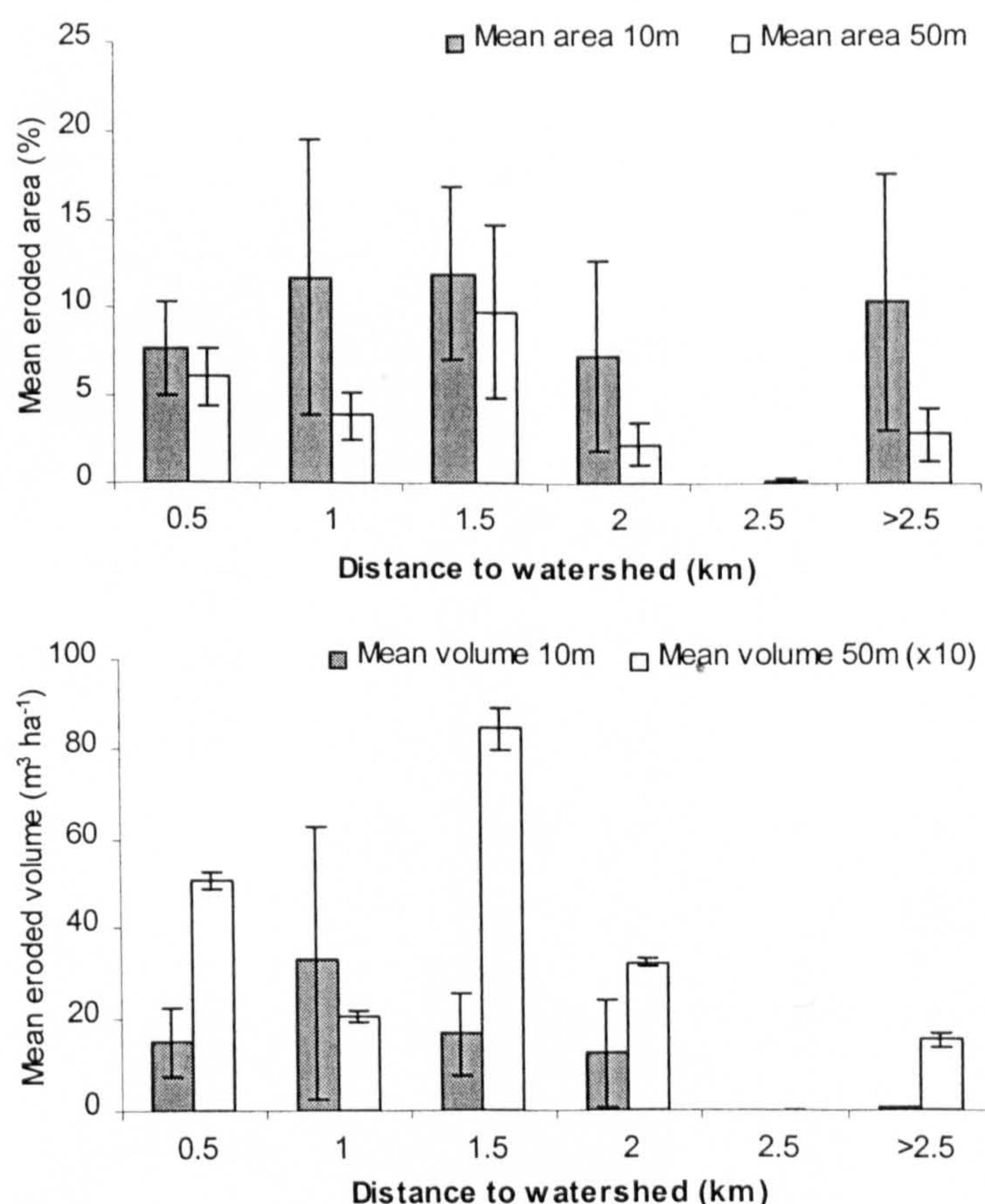


Figure 5.2 Average eroded area and volume, recorded on 10 m and 50 m field sites and plotted against distance to the sub-catchment watershed. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

5.3.2 Field site erosion and sub-catchment slope

The relationship between eroded area and the slope measured on field site sub-catchments is recorded in Figure 5.3. A clear threshold effect is exhibited by slope on both area and volume records of erosion. Within 10 m field sites, average eroded area and volume both increased on slopes up to 7°: following this, there was a steady decline in erosion extent until slopes greater than or equal to 25° are reached. There, mean 10 m field site erosion is at its greatest.

A similar relationship exists between 50 m erosion extent and sub-catchment slope. There, eroded area and volume were highest on slopes of less than 3°, and fell steadily on successively steeper slopes. Mean erosion was markedly low on sub-catchments with intermediate slopes of between 12° and 24°: on steeper slopes however, the extent of erosion, particularly of eroded volume, increased sharply.

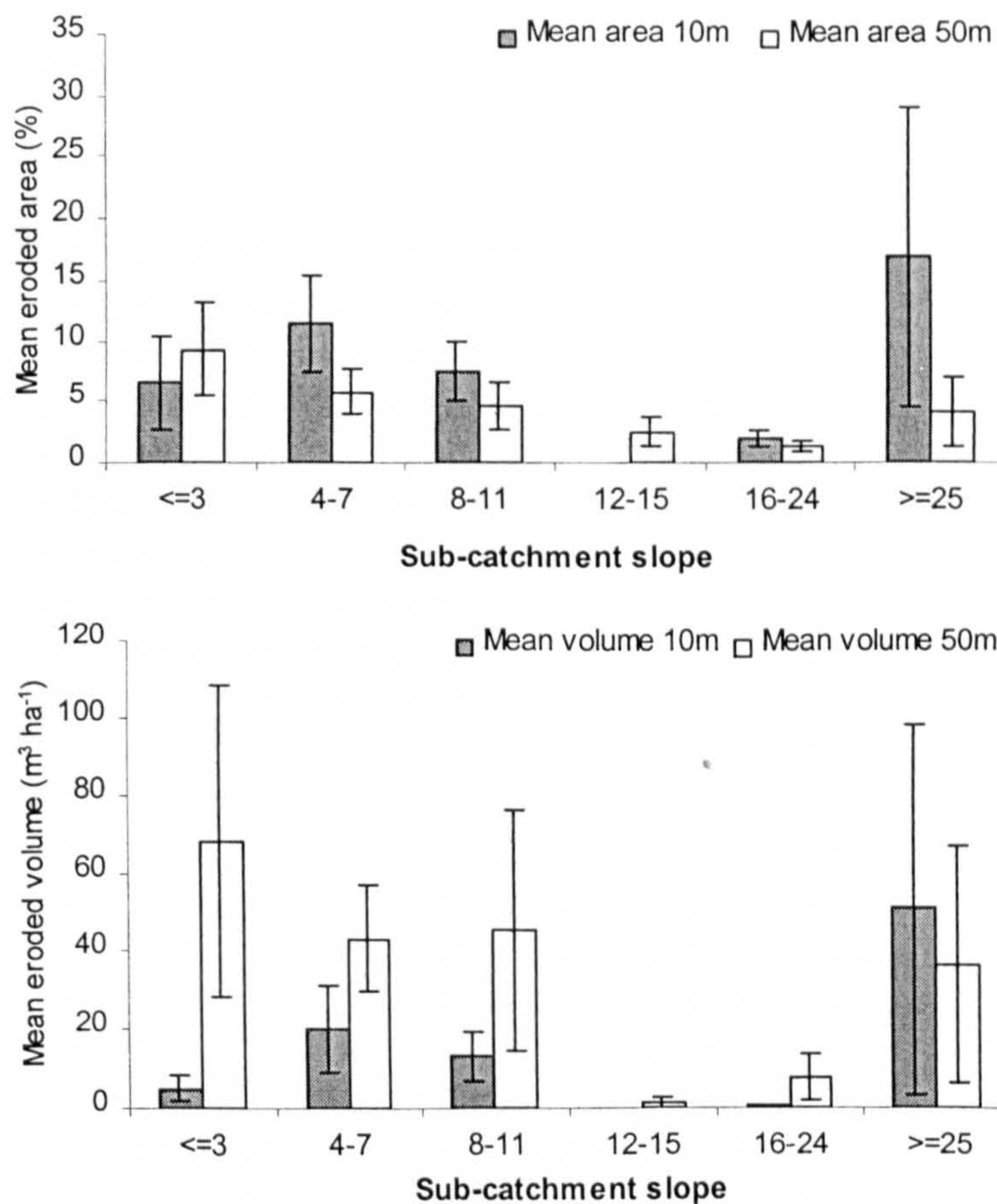


Figure 5.3 Mean eroded area and volume, recorded on 10 m and 50 m field sites located within sub-catchments of different slopes. Error bars represent standard error of the data (SE = SD / √n).

5.3.3 Sub-catchment morphology and field erosion

Figure 5.4 illustrates the relationship between the general morphology of the field site sub-catchment, and field site erosion. The three basic landforms described in Section 5.2 vary widely in the extent of erosion: both eroded area and volume were recorded at their greatest on field sites located on linear sub-catchments. Eroded area on concave and convex sub-catchments were equally low at approximately 5%. The eroded volume recorded on field sites was also greatest on linear slopes, although that on 50 m field sites within convex sub-catchments was also high, at $40 \text{ m}^3 \text{ ha}^{-1}$. Although this mean value is based on 46 field sites, its high standard error indicates the variability of the dataset. Again, the high erosion on field site NY41/1010 accounts for much of this peak.

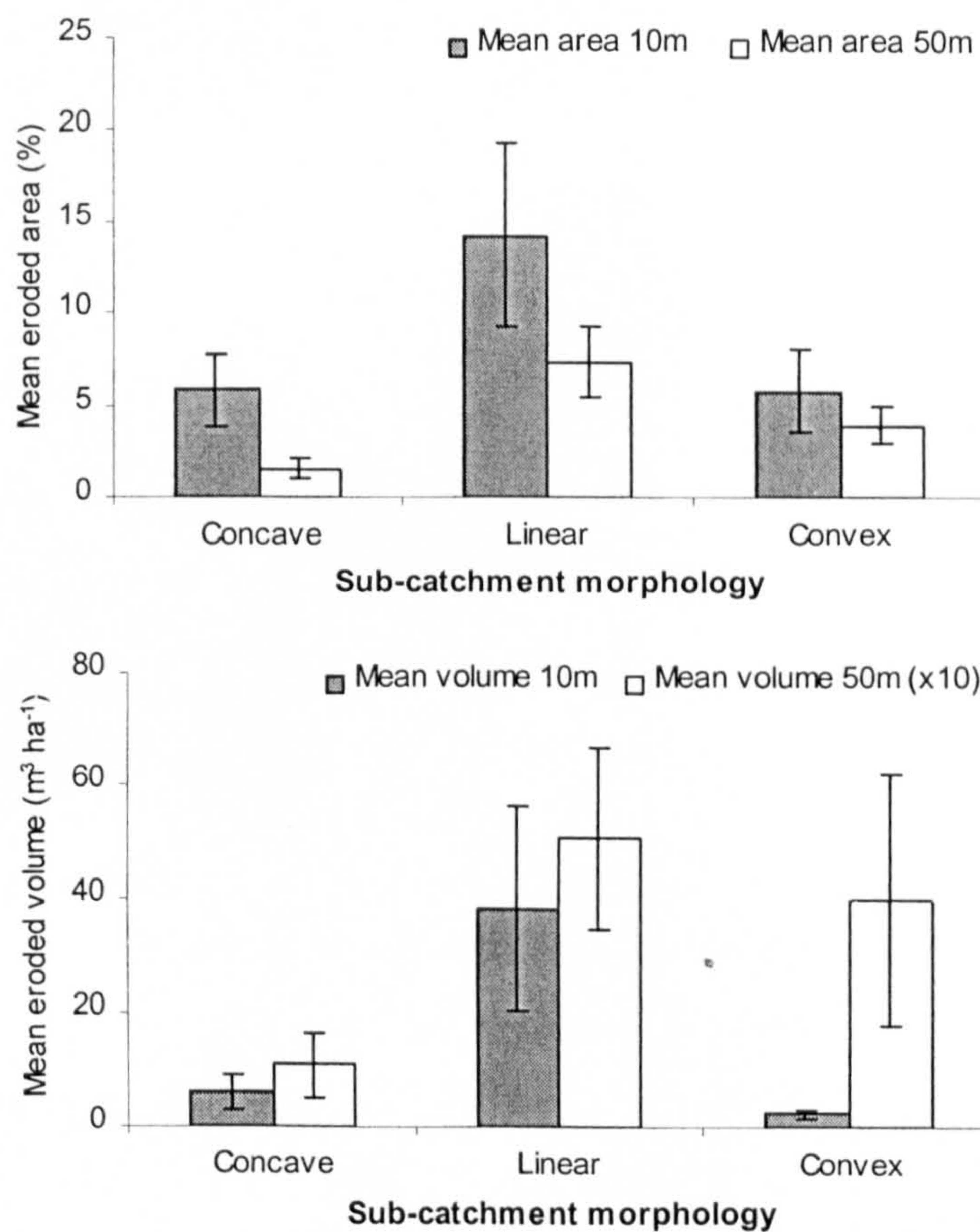


Figure 5.4 Mean eroded area and volume recorded on 10 m and 50 m field sites and linked sub-catchment shape. Error bars represent standard error of the data ($\text{SE} = \text{SD} / \sqrt{n}$).

5.3.4 Sub-catchment aspect and field site erosion

The relationship between aspect and erosion is illustrated in Figure 5.5 where mean eroded area and volume are clearly higher on S and SW-facing sub-catchments. The high mean eroded volume recorded on NW sub-catchments is due again to field site

NY41/1010. There is little other variation in mean eroded area or volume recorded on other aspects.

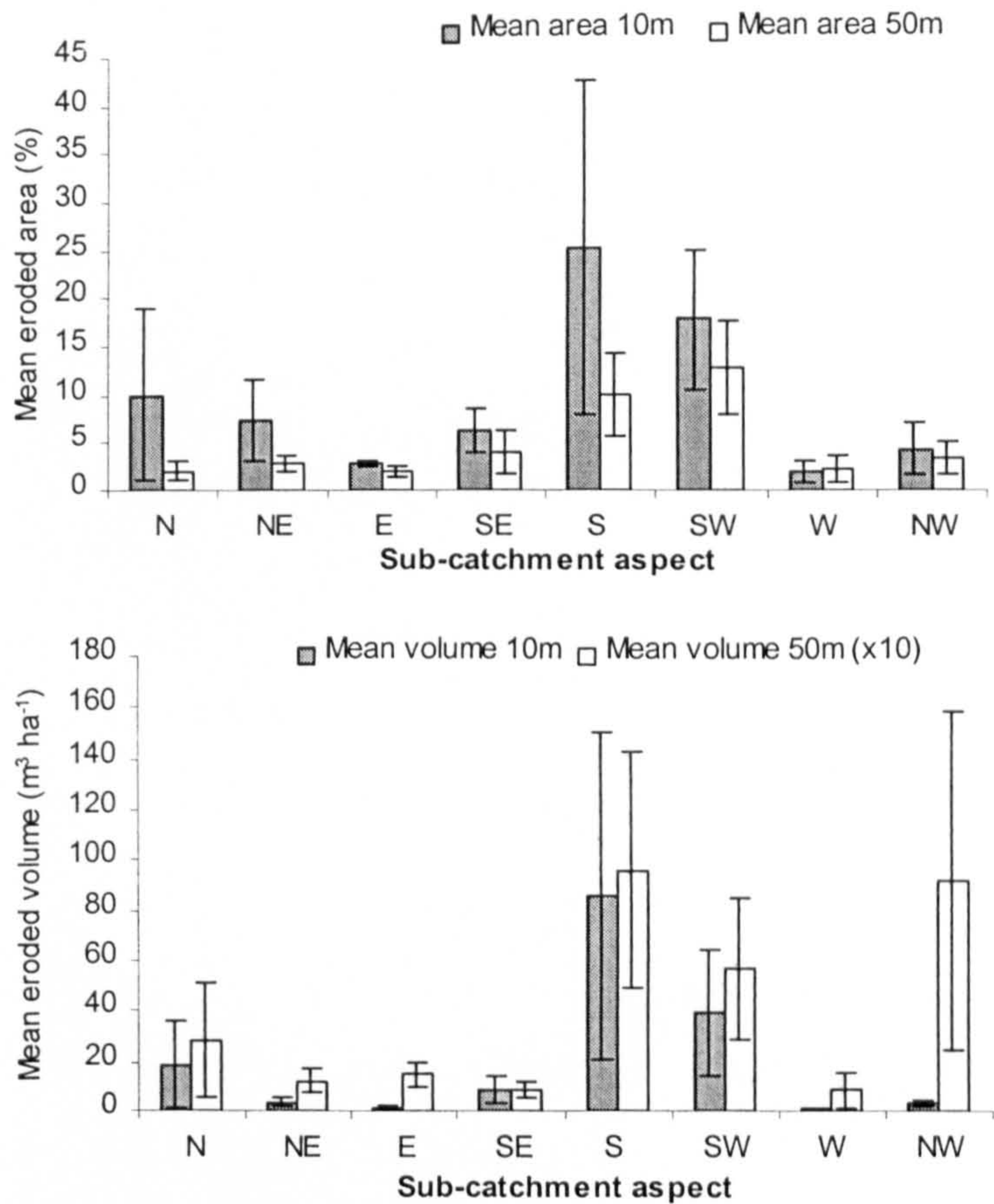


Figure 5.5 Mean erosion, recorded on 10 m and 50 m field sites located within sub-catchments of different aspects. Error bars represent standard error of the data ($SE = SD / \sqrt{n}$).

5.3.5 Statistics on field erosion and sub-catchment morphology

The datasets of eroded area and volume recorded within both 10 m and 50 m field sites were not normally distributed. In Table 5.2, for example, the lack of agreement between mean and median values indicates the skew of the data. After log-transformation of the data, mean and median values corresponded. As parametric statistical tests, such as those used here, require normally-distributed data, all statistical analyses were completed on transformed data.

Genstat (Release 4; Version 5.1) was used to investigate the statistical significance of the relationships between sub-catchment characteristics and erosion within both 10 m and 50 m field sites. The statistical tests used were based on regression analysis and ANOVA and are fully described in Appendix 4 (Sokal and Rohlf, 1995).

Table 5.2 Summary details for eroded area and volume recorded on 50 m field sites. Both raw and log-transformed data are presented.

Statistic	Total eroded area (%)	Total eroded volume (m ³)	Log (area)	Log (volume)
Mean	5.32	416	-0.05	1.29
Standard Error	1.05	114	0.08	0.11
Median	1.06	17.07	0.03	1.23
Standard Deviation	12.07	1312	0.95	1.25
Sum	708	55326	-6.23	171
Count	133	133	133	133

Within the 10 m dataset, there were no statistically significant relationships between erosion extent and the distance between field site and watershed. The individual relationships between erosion and sub-catchment slope, aspect or morphology were also statistically insignificant (ANOVA). Combinations of factors and variables, i.e. slope, aspect and morphology with distance to watershed, also failed to affect significantly erosion extent.

Within 50 m, there was a single significant parallel regression between sub-catchment slope in combination with distance to watershed and eroded volume (F pr 0.021): the variance accounted for by the relationship was low, at 7.3%. In that analysis, the greatest mean erosion was recorded on sub-catchments with slopes <3°.

In ANOVA, slope was also significantly linked with 50 m eroded volume (F pr 0.016). The mean erosion recorded on slopes between 12° and 15° was significantly lower than that recorded on all slopes less than 7°.

None of the other environmental factors measured were found to be statistically significant in the incidence of erosion within either 10 m or 50 m of the node.

5.3.6 Are the causes of erosion influenced by sub-catchment morphology?

In Figure 5.6, the percentage of 50 m field sites on which erosion was caused by the actions of humans, animals and water were divided into sub-catchment characteristic groups. As it was recorded on only two field sites, and as water erosion was also present on both of those field sites, wind erosion has been combined with water erosion in this section. Only 50 m data are presented, as these trends closely resembled those from the 10 m dataset.

From Figure 5.6, it is clear that the proportions of both biotic and water erosion recorded on 50 m field sites decreased with increasing distance between the field site and the watershed. In terms of the sub-catchment slope, the proportions of both biotic and water erosion increased up to slopes of 7°. Erosion extent was smaller on intermediate slopes, but showed signs of increase on slopes greater than 12° for biotic erosion and 16° for water erosion.

The proportions of both forms of erosion were greatest within linear sub-catchments and were at their smallest on field sites located within concave catchments. Finally, there was no clear trend of either biotic or water erosion associated with sub-catchments of different aspects.

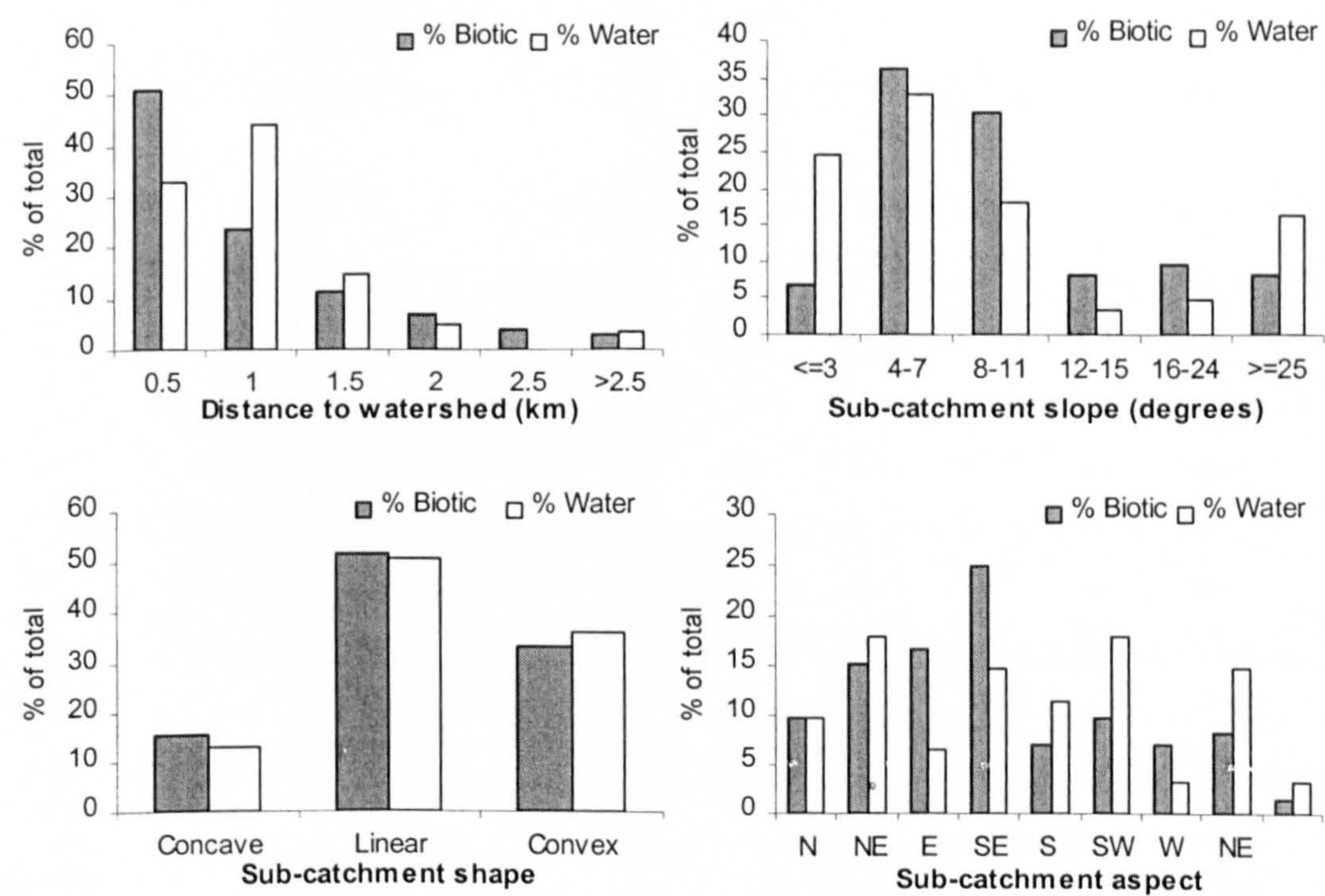


Figure 5.6 Eroded 50 m field sites subdivided into biotic and water causes, and expressed as percentages of the total numbers of eroded field sites.

5.4 DISCUSSION

The principal conclusions from morphological mapping of field site sub-catchments are presented here, along with recommendations for further research.

5.4.1 Sub-catchment distance to watershed and soil erosion

Overall, the extent of erosion within both 10 m and 50 m field sites declined with increasing distance to watershed although, initially, erosion extent increased up to distances to watershed of between 1 km and 1.5 km. This result may indicate a threshold watershed distance, below which the erosive power of water within the sub-catchment is sufficient to initiate erosion or to maintain erosion where it is otherwise activated. Where field sites were located at distances from the watershed greater than the threshold of 1.5 km, the loss of energy experienced by overland water flow may cause an attendant reduction or elimination of the incidence of erosion.

It is also likely that, with increasing distance between the field site and the watershed, water flow is more likely to become channelled into rivers or streams, effectively reducing overland flow, and consequently minimising the risk of erosion. Alternatively, the decrease in erosion within long catchments may reflect the different landscape zones that exist within catchments (Collard, 1988). Near the watershed, soil creep is common and high energy is available to remove soil and transport eroded material away. Further away from the watershed, beyond the point of inflexion on linear slopes where energy requirements and yield are balanced, there are gentler concave slopes. Here, the increased momentum and power of eroded material reduce the need for a steep slope. Field sites located at a considerable distance from the watershed are, therefore, more likely to be within this depositional, low-slope concavity of reduced erosion incidence (Collard, 1988).

Plot studies have also shown that erosion varies according to the position of the site on the hillside because different types of erosion predominate at different hillslope points (Morgan, 1995). Soil creep close to the summit gives way to overland flow and then to rill or gully erosion. If rills do not occur, however, the effect of slope length on erosion may be negative.

Gilley *et al.* (1985) proved that the rate of detachment of soil particles decreased with slope length in spite of the increase in transporting capacity of overland flow. As

slope length increases, the variability of soil loss increases, depending on whether rills form (Abrahams *et al.*, 1991; Morgan, 1995).

This research has not considered sub-catchment soils when describing the incidence of erosion. In work on sandy loam and loamy sand soils, Gabriels (1999) reported that soil loss per unit area on increasing slope lengths varied between soils. In order to understand completely the interactions between sub-catchment and erosion, it is therefore necessary to include information on the soil subgroup of the area of interest.

5.4.2 Sub-catchment slope and soil erosion

Field site erosion was greatest within sub-catchments with slopes of between 7-11°. On steeper slopes, the extent of both eroded area and volume were diminished, until on slopes $\geq 25^\circ$ where the extent of erosion increased again. These results indicate a threshold effect of slope on soil erosion, with erosion encouraged on very low and very steep slopes. In spite of fewer very steep slopes, the area and volume of erosion produced on these is equivalent to that produced on the many sites on low and intermediate sloping sub-catchments.

The relationship between slope and erosion has been defined by the equation

$$E \propto \tan^m \theta L^n$$

where E is soil loss, θ is the slope angle and L is the slope length (Morgan, 1995). A combination of results from studies that concentrated on the slope exponent m suggested a curvilinear relationship between soil loss and slope steepness. Erosion increased rapidly with increases in slope steepness from gentle to moderate and reached a maximum on slopes on about 8 - 10°, before decreasing with further increases in slope (Morgan, 1995).

The influence of slope gradient on erosion rates varies, however, according to the erosion type: where there are rills or gullies, erosion rates increase substantially more with increasing slope (Fox and Bryan, 2000). Within this research, it was shown that both biotic and water erosion decreased in extent on intermediate slopes. From Figure 5.6, however, it is clear that, while biotic erosion showed no change above 12° slopes, water erosion increased steadily. This may suggest that gully erosion is the

predominant erosive form on very steep slopes while non-gully-forming biotic erosion is concentrated on low slopes.

5.4.3 The influence of sub-catchment morphology on soil erosion

In spite of research that has identified differences between the three main slope morphologies (D'Souza and Morgan, 1976), no statistical relationships were identified between erosion and slope morphology in this research, although there was significantly more soil erosion on linear slopes. The absence of statistical significance may be a reflection of the scale over which morphology was recorded. From the records on distance to watershed, over half of all sites are situated on basins of greater than 0.5 km length. The categorising of this area into one of three groups, and the use of maps at 1: 25 000 scale to accomplish this, has generalised a considerable amount of inherent landscape variability.

To account comprehensively for this variability may only be possible from fieldwork or from aerial photographic interpretation with ground verification: both approaches have the added advantage of allowing assessment of sub-catchment vegetation. As different vegetation types increase or decrease rainfall infiltration rates, they are an important influence on the erosive power of runoff and their consideration could help to elucidate the link between basin shape and erosion.

5.4.4 The effect of sub-catchment aspect on soil erosion

S and SW-facing slopes were the predominate aspects of sub-catchment with eroded field sites: there was little variation in the extent of erosion recorded on other sub-catchment aspects. The susceptibility of these aspects to erosion may be due to the greater radiation received by S-facing slopes in the Northern Hemisphere. Greater radiation means enhanced vegetation growth and consequently, higher grazing pressures on southerly aspects.

In Figure 5.6, however, there was no evidence of pronounced biotic erosion on S-facing slopes, although biotic erosion was greatest on SE-facing slopes. This aspect also experienced some of the lowest mean eroded area and volumes (Figure 5.5). Freeze-thaw cycles may also be more frequent on south-facing slopes, because their daily temperature fluctuations are greater. There is, however, some doubt that the diurnal difference, if any, is sufficient to influence erosional processes (Harrod *et al.*, 2000). Finally, as rainfall is an important contributor to soil erosion process, there

may be a connection between aspect and rainfall intensity or volume, although there is no literature to substantiate this.

5.4.5 Causes of erosion within the sub-catchment

Field sites eroded by both water and the actions of humans and animals were predominant on sub-catchments of short length, low slope and linear morphology. Clearly, therefore, the scale at which sub-catchment characteristics were made and, perhaps, the available information on causes of erosion were not specific enough to enable causes of erosion to be linked to specific sub-catchments.

5.4.6 Relationships between variables

The issue of inter-relativity between subcatchment characteristics and erosion should not be overlooked, in spite of the absence of statistically significant relationships. Of the potential combinations, statistical analysis identified only the interaction between slope, distance to watershed and 50 m eroded volume. Further relationships between the variates measured and erosion may not be apparent within 10 m because of the limited dataset. It is also likely that the characteristics measured were too generalised to reflect sub-catchment variability and therefore could not be satisfactorily linked to erosion.

Further problems may be associated with the use of and comparison of the effects of the environment on eroded area and volume. While eroded area was calculated as a percentage of the field site area, values of eroded volume are converted to volume per unit area of one hectare. In many erosion forms, however, the area and volume of soil lost are not related. Examples include deep erosion features of limited area, such as eroding gullies or grips, and extensive areas of limited-depth erosion, such as poaching. In addition, erosion measured on 10 m field sites requires a different scaling-up factor to that required for 50 m erosion (31.8 compared with 1.27). Some distortion of the eroded volume data is therefore unavoidable.

5.5 CONCLUSIONS

In this study, the extent of erosion decreased with increasing distance to watershed. Nonetheless, the range of environmental conditions that vary within sub-catchments mean it is impossible to explain this relationship using the limited information collected. Subsequent research could further this work, however, by concentrating on greater information from a smaller number of sub-catchments. The numbers and positions of gullies within sub-catchments, as well as details of other erosion forms, could help to account for the increased variability that results from increasing sub-catchment length.

Future detailed fieldwork or remote sensing research could also help to record the extensive morphological variability inherent within all catchments that was necessarily omitted in this study. In this way, information on the effect of different slope length and shapes on erosion could be furthered.

The high incidence of erosion on subdued slopes reflects the need to direct erosion prevention and rehabilitation plans towards these areas, rather than to the eroding but more infrequently occurring steeper slopes. They also warrant further investigation into the factors that cause and maintain erosion on these low slopes. From the broad classification of erosion used in 5.3.6, both human and animal factors and water erosion cause erosion on low slopes, although the proportion of water eroded sites exceeds that of biotically eroded sites. Further research could clarify any dominance by measuring the individual contributions of different erosion forms, such as footpaths, gullies, sheep scars and poaching, to overall erosion extent. Such information on the principal causes of degradation within catchments would allow erosion remediation, and the prevention of further soil loss, to be effectively carried out.

Chapter 6

Aerial photographs and changes in erosion extent

6.1 INTRODUCTION

Remote sensing plays a vital role in our understanding of process and pattern in the landscape and tools such as aerial photographs can be used to interpret and describe changes in the environment (Carroll *et al.* 1977). Aerial photographs have been used to monitor patterns of soil redistribution and gully development (Burkard and Kostaschuk, 1997; Vandaele *et al.*, 1996), to classify and measure the extent of upland erosion (Grieve *et al.*, 1995; Keech, 1968) and to identify areas of pronounced erosion (Jones and Keech, 1966). They have also been used to assess the effects of landuse and climate change on erosion (Gobin *et al.*, 1999; Jakeman *et al.*, 1999; Morgan, 1995) and to determine the factors that control ephemeral gully erosion (Vandaele *et al.*, 1997).

Aerial photographs are frequently used either as a supplement to field studies (Johnson, 1957) or as a principal investigative technique requiring subsequent ground verification (Evans, 1988, 1992b). Because of the objective information provided on changes in land management (Hester and Sydes, 1992) and as changes in vegetation cover and density may be easily assessed (Eckhardt *et al.*, 2000; Tekle and Hedlund, 2000), aerial photographs have also been used to map ground features or vegetation (Keech, 1968; Morgan, 1995; Nature Conservancy Council, 1987).

The advantages of aerial photographic surveys listed by Keech (1968) were that

- Small-scale erosion features of as little as 0.2 m² were readily identifiable
- Direct identification of features resulted in objective studies
- With training, staff worked objectively and could cover extensive areas quickly.

Here, archived aerial photographs were used to assess changes in erosion over 45 years. This chapter describes the history of vertical air photography in the UK, the experimental method used and results from the data gathered.

6.2 VERTICAL AERIAL PHOTOGRAPHY

Upland erosion clearly occurs over long periods and any field survey, such as that described in Chapter 3, is limited to an examination of the contemporary extent of erosion. Longer-term information on erosion is available from other sources, such as books, letters, postcards and pictures. While these sources may provide clear evidence of erosion they are rarely available either systematically or over sufficiently long periods to reveal changes over time. Vertical aerial photographs, however, provide detailed evidence of landscape changes in erosion and vegetation.

Vertical aerial photographs provide a three-dimensional image of the ground surface when viewed in overlapping stereoscopic pairs. They are taken at a variety of scales from 1:5 000 where each photo covers an approximately 1 km², to 1:25 000 where the area covered is nearer to 30 km² (Carroll *et al.*, 1977).

Panchromatic film, which records using black and white tones, is most frequently used in aerial photography. Photographs in infra-red film are particularly good, however, for assessment of vegetation changes because that wavelength is strongly reflected by green plant cell walls. True colour films are sensitive to the range of colours visible to the human eye but were little used until the 1990s because of critical flying and exposure times, expensive prints and difficult processing (Carroll *et al.*, 1977). Colour infra-red combines the advantages of infra-red with colour and is particularly good for mapping semi-natural vegetation such as grassland (Barth and Kubiniok, 1998).

An inherent problem of vertical aerial photographs is the feature distortion that occurs towards the periphery of the photo. This is caused by the camera lens and requires a correction factor. Other distortions result from crabbing, as the aeroplane corrects for crosswinds without reorientation of the camera with respect to its ground track, or tilting, where the aircraft and camera are not horizontal at the time of exposure. In addition, variations in plane height, or flight across relief changes, mean photos may not have a standard scale. Early photos were also frequently taken through cloud or fog, which restricted the discernible information.

The information gained from the comparison of aerial photographs taken on assorted dates is compromised also if the photos were taken at different scales. Unless there is confidence that the scales are similar or unless scale correction factors are used, direct comparison of the sizes of ground features does not yield reliable information.

In spite of these drawbacks, many of which are corrected by contemporary imaging techniques such as orthophotography (Duhaime *et al.*, 1997), vertical aerial photographs represent a valuable archive of information on both past and present landscapes.

6.3 EXPERIMENTAL METHOD

For this work, the collections of aerial photographs held by the Royal Commission on the Historical Monuments of England (RCHME¹) in Swindon and the Air Photo Unit of the Welsh Assembly² were viewed. These official collections hold archival photos from 1946 to 1989 in the case of the Welsh Assembly and to 1979 in RCHME.

6.3.1 Site selection

A small number of field sites were selected for aerial photographic interpretation to maximise the information gathered on changes in erosion extent. The selection process was designed to ensure that a representative number of field sites were selected for interpretation. Only field sites on which erosion was recorded in the 1997 field survey were considered, using the following procedure.

- The extent of erosion was assessed in both 1997 and in 1999 on 399 NSI and CS2000 field sites. In total, erosion was measured on 206 field sites.
- These sites were split into groups, according to field site slope (Table 6.1).
- Each set group of sites was then subdivided into one of four hydrologically distinct soil classes using the soil subgroups defined by Avery (1980).

¹ National Monuments Records Office, Great Western Village, Kemble Drive, Swindon SN2 2GZ

² Central Registry of Air Photography for Wales, The National Assembly for Wales, Room G-003, Crown Offices, Cathays Park, Cardiff CF10 3NQ

- Where there were less than ten sites per slope/soil category, the field site with the greatest area of erosion was selected for assessment.
- Where there were more than ten sites per category, the number of sites per group was further reduced by subdividing each slope/soil group into altitude divisions (Table 6.1). The field site of greatest erosion was then selected from each slope/soil/altitude class.

Grid references, altitudes, slopes and soil classes for the 26 field sites selected are provided in Table 6.2. Photos were obtained for a range of dates between 1946 and 1989, at scales that varied between 1: 7500 and 1: 26600.

Table 6.1 Slope, altitude and soil were used to select field sites for aerial photographic study: soil class constituents are soil subgroups as described in (Avery, 1980).

Altitude (O.D.)	Slope	Soil classes			
		<i>Dry mineral</i>	<i>Wet mineral</i>	<i>Wet peaty mineral</i>	<i>Peat</i>
<200 m	≤3°	3.13	6.41	7.21	3.11
201-300 m	4-7°	3.14	6.42	8.71	10.11
301-400 m	8-11°	5.42	6.43		10.13
401-500 m	12-15°	5.47	6.51		10.23
501-600 m	16-24°	6.11	6.52		
601-700 m	≥25°	6.12	6.54		
>700 m		6.21	7.13		
		6.31	7.15		
		6.32			
		9.2			

Table 6.2 Grid references, slope, altitude and soil classes of NSI and CS2000 field sites used in aerial photographic study.

Grid reference	Altitude	Slope group	Soil Class	Photograph sortie dates
NT91/1060	438	5	Wet mineral	1946, 1960, 1980
NU12/1060	173	2	Wet peaty mineral	1946, 1951, 1972, 1980
NY67/6060	286	1	Peat	1946, 1961
NY73/1010	665	2	Peat	1953, 1956, 1965, 1969
NY73/6010	636	1	Peat	1953, 1969, 1971
NY73/6060	557	2	Peat	1951, 1953, 1960, 1976
NY79/6060	330	3	Wet peaty mineral	1951, 1960
NY83/1110	510	2	Wet peaty mineral	1953, 1965, 1969, 1972
NY88/1060	206	4	Wet peaty mineral	1948, 1960, 1974
NY94/1060	467	2	Peat	1951, 1975
NZ01/1010	337	1	Wet peaty mineral	1948, 1965, 1972
SE00/6060	509	1	Peat	1948, 1968
SE01/1010	443	1	Peat	1948, 1954
SE01/6010	370	2	Wet mineral	1957, 1964, 1972
SE07/6010	501	2	Peat	1952, 1955, 1968, 1972
SE16/1060	303	3	Wet mineral	1955, 1968, 1972
SH70/1060	588	3	Wet mineral	1946, 1971, 1976, 1989
SH71/6061	255	2	Dry mineral	1946, 1971, 1976, 1985, 1989
SH82/600125	638	2	Wet mineral	1946, 1973, 1989
SK19/6060	377	2	Peat	1953, 1968
SN75/1060	417	1	Peat	1946, 1976
SN81/2575	470	1	Peat	1975, 1985
SN82/6010	518	2	Wet peaty mineral	1947, 1977, 1985
SN87/1010	522	1	Peat	1946, 1976, 1985
SN88/1010	533	2	Peat	1948, 1975, 1985
SN89/1010	461	2	Peat	1946, 1975, 1985

6.3.2 Aerial photographic interpretation

Observations of the changes in erosion extent and form were ideally made within a 1 km² area around each field site node. Where the aerial photographs did not cover the node and surrounding site clearly or entirely, an additional adjacent area, as near to the node as possible, was used for interpretation.

Photographs for different years were compared directly. Within the 1 km² site, detailed examination was made of individual erosion features using a

stereoscope to 10 x magnification and a hand-held magnifying glass. In some cases, tracings of photos were made onto acetate or transparent paper, but generally, suitably clear photos of equivalent scale were compared directly.

In this research, the aerial photographs were taken at a variety of scales between 1:50 000 and 1:5 000. Because of the difficulties of comparing the sizes of erosion features recorded on photographs of various scales, it was impossible to assess changes in the areal extent of erosion over time. Instead, individual erosion features were examined for changes in their appearance, numbers, shape and degree of vegetation. Within small-scale features, continued erosion was evident as the numbers of scars or the extent of mineral exposure increased.

Change in larger erosion features was determined at specific points within the feature. Within eroded peat, for example, individual hags, distinctive sections of the gully floor and other obvious locations were inspected individually for indications of continued erosion. The outline of eroded peat areas was also examined in detail: the loss of vegetated overhangs or retreat of the vegetated margin indicated further degradation while revegetation of gully floors or sides was interpreted as erosion stabilisation. In many cases, further loss of soil was noticeable only as a change in soil colour from the darker soil surface layers to the lighter subsoils or the mineral layer. In the area of peat erosion shown in Plate 6.1, facets of the retreating peat margin are clearly visible, as are the regions of mineral exposure. The annotations also highlight other erosion features, including the footpaths along the fence and the bare soil around the trigonometric point.

These interpretations were applied also to areas of mineral soil erosion on gentle slopes. Although they may have been of sufficient extent to allow changes in shape to be ascertained, mineral soil erosion on steep slopes was assessed by counting individual scars. In this way, the photographic distortions of light and shape that occur on steep slopes were avoided.

Each observation of a change in scar or hagg numbers, of newly exposed soil or mineral material, or of the revegetation of a specific area was counted. The

number of observations was then used to assess changes in the form and extent of erosion over time.

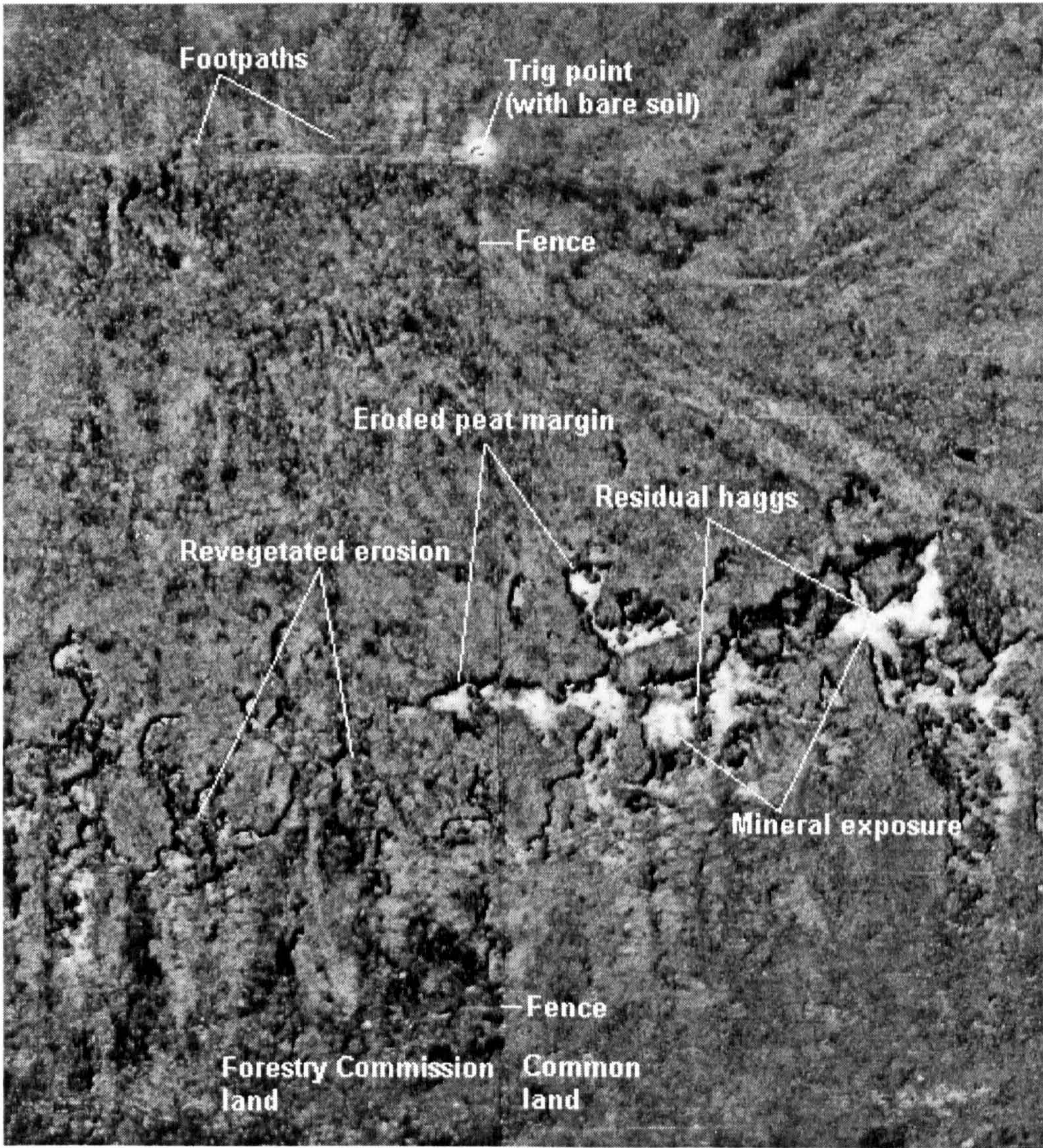


Plate 6.1 Aerial photograph of peat erosion, showing some of the features examined for change between 1946 and 1989.

6.4 RESULTS

The results from aerial photograph interpretation are presented here as the overall changes in erosion (Section 6.4.2), causes of erosion (6.4.3) the changes in specific erosion forms (6.4.4) and the variation in erosion forms associated with time (6.4.5). First, data presentation is discussed (6.4.1).

6.4.1 Data classification

Observations of erosion were categorised as ***Recovered***, ***Unchanged*** or ***Deteriorated***. These categories refer to erosion features that indicated erosion stabilisation or revegetation, no change in bare soil extent, or further soil and vegetation loss respectively. New erosion features were classified as ***Deteriorated*** as they indicated continued erosion.

Individual erosion features were defined by cause into one of four groups:

- Erosion caused directly by humans included moorland grips, tracks and machinery poaching (defined in Section 1.3.3) and rutting.
- Scars caused directly by grazing animals, such as sheep scars, paths and poached areas.
- Large-scale peat degradation of both Type I and Type II erosion (Section 1.3.1).
- Large-scale erosion of mineral soils on steep slopes.

Although features classified as peat and mineral soil erosion may have been initiated by the actions of humans, or may be maintained by grazing pressures, it is impossible to be certain of their origins. To avoid their misclassification or their omission and because of their areal and erosional significance, peat and mineral erosion are grouped separately.

The principal aim of accessing aerial photographs was to interpret changes in erosion between 1946 and the present. Photos taken since the early 1990s, however, were not available from either archives (Section 6.3) and all assessments are based therefore on information up to the late 1980s.

The large number and irregular dates of flight sorties (Table 6.2) were grouped into half-decades or decades. As the interval between photographs was frequently as great as 30 years, however, changes in erosion could not always be assigned to a specific short period. The observational date was taken, therefore, as the year half way between the two sortie dates.

Table 6.3 Numbers of individual erosion features examined in aerial photographs. *Grid references are of NSI and CS2000 field site nodes, at the centre of the 1 km² area examined.

Grid reference*	Individual observations of erosion change			Overall change
	<i>Recovered</i>	<i>Unchanged</i>	<i>Deteriorated</i>	
NT91/1060	14	58	19	Recovered / Unchanged
NU12/1060	9	6	71	Deteriorated
NY67/6060	5	20	0	Recovered / Unchanged
NY73/1010	2	21	7	Recovered / Unchanged
NY73/6010	19	59	17	Recovered / Unchanged
NY73/6060	17	49	44	Recovered / Unchanged
NY79/6060	0	2	3	Deteriorated
NY83/1110	8	75	19	Recovered / Unchanged
NY88/1060	5	13	52	Deteriorated
NY94/1060	3	13	15	Recovered / Unchanged
NZ01/1010	20	40	43	Recovered / Unchanged
SE00/6060	7	0	30	Deteriorated
SE01/1010	1	16	12	Recovered / Unchanged
SE01/6010	0	23	2	Deteriorated
SE07/6010	25	19	10	Recovered / Unchanged
SE16/1060	9	53	16	Recovered / Unchanged
SH70/1060	2	2	8	Recovered / Unchanged
SH71/6060	0	12	4	Recovered / Unchanged
SH82/600125	25	86	9	Recovered / Unchanged
SK19/1060	4	17	36	Deteriorated
SN75/1060	1	2	14	Deteriorated
SN81/2575	12	21	23	Recovered / Unchanged
SN82/6010	3	0	0	Recovered / Unchanged
SN87/1010	7	39	17	Recovered / Unchanged
SN88/1010	5	7	13	Deteriorated
SN89/1010	9	10	50	Deteriorated
<i>Total observations</i>	<i>212</i>	<i>663</i>	<i>534</i>	<i>Recovered / Unchanged</i>
<i>Mean observations</i>	<i>8.2</i>	<i>25.5</i>	<i>20.5</i>	<i>Recovered / Unchanged</i>

6.4.2 Overall changes in erosion

In Table 6.3, individual observations of erosion changes are summarised for the entire period over which photos were examined. Between 1946 and 1988 on field site NY67/6060, for example, five scars in total showed signs of revegetation while twenty scars remained unchanged in form and exposure.

Generally, erosion on all field sites showed a high degree of stabilisation and recovery. Of the total number of 26, overall erosion continued on 12 field sites. A low number of sites showed overall recovery of degraded soil (2 sites or 8% of the total) while the individual erosion features that exhibited recovery was 15% of the total. On average, each of the 26 field sites contained 54 erosion features, each of which was examined for changes in erosion between 1946 and 1989. In total, over 1 400 features were examined: unchanged scars and areas of continued erosion accounted for 47% and 38% of this total respectively.

6.4.3 Causes of erosion

Information on the causes of upland erosion, interpreted from aerial photographs, was used to determine several characteristics of upland soil degradation. Initially, the information was used to establish the contribution of erosion determinants such as humans and animals to the overall extent of erosion. The extent of recovery or deterioration of erosion of different origins highlights the effects of landuse on upland habitats and identifies both historical and contemporary threats to the upland environment.

As stated in Section 6.4.1, erosion features were subdivided into human, animal, peat and mineral soil erosion groups. The total and percentage changes in erosion recorded within these groups are shown in Figure 6.1. The greatest numbers of observations, as well as the greatest number of unchanged erosion features were recorded on peat erosion.

On both peat and mineral soil degradation, the greatest proportion of erosion features did not degrade further. Erosion caused by both humans and animals experienced high proportions of further eroded scars. Less than 15% of all erosion features, including peat and mineral soil erosion, showed recovery. The total numbers of observations made, and the groups into which they were placed, is shown in Table 6.4.

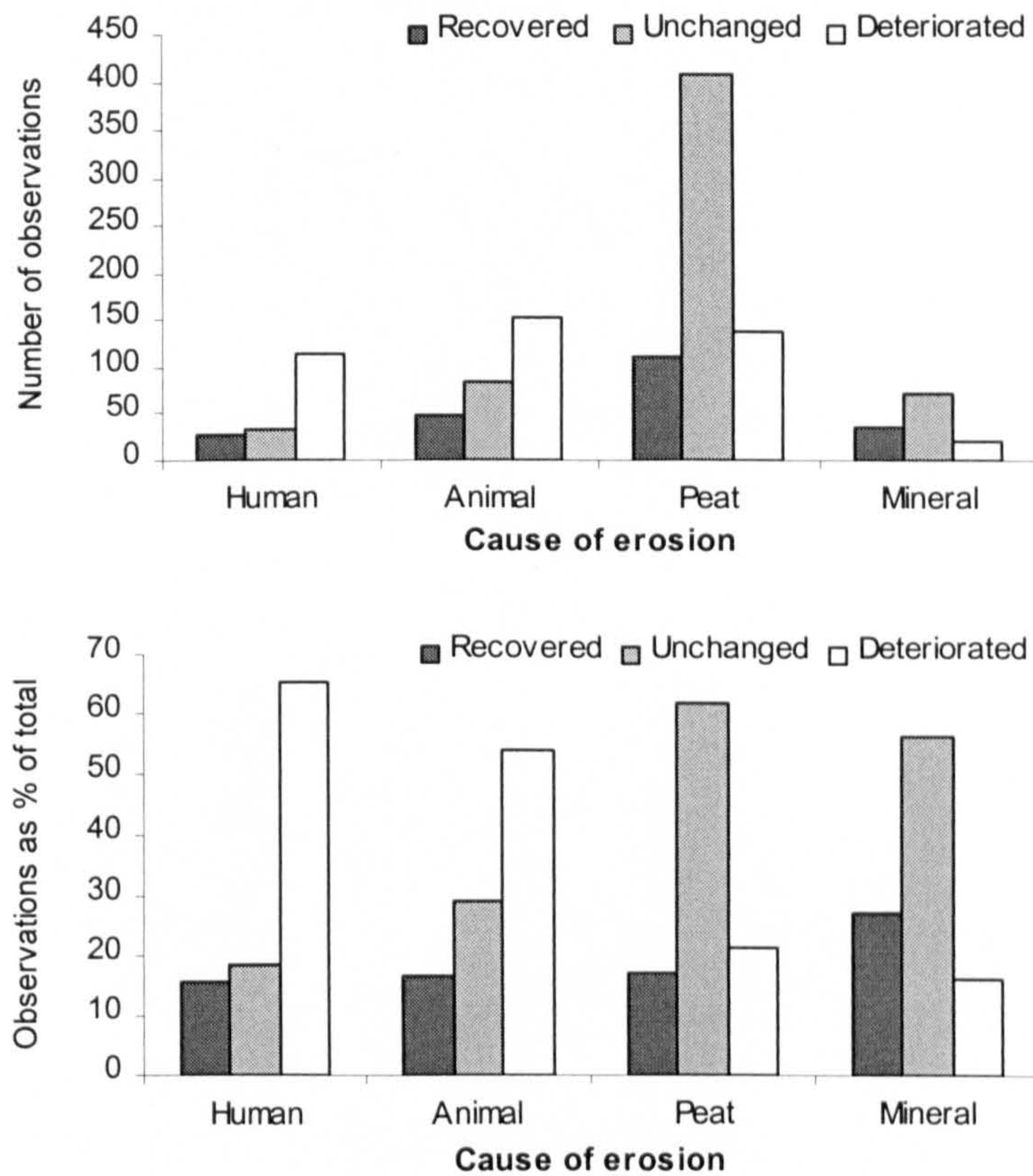


Figure 6.1 Actual and percentage counts of improved, unchanged and deteriorated observations of erosion obtained from aerial photographs.

Table 6.4 Number of observations and groupings of erosion scars accessed through aerial photographs and caused by water, humans (m) and animals (a).

Erosion	Number of Observations	Group (total observations)
Drain	127	
Poaching (m)	21	Human (190)
Track	42	
Mineral	185	Mineral (185)
Peat	710	Peat (710)
Poaching (a)	72	Animal (316)
Scars (a)	244	

6.4.4 Erosion change between 1946 and 1989

Figure 6.2 shows the changes in erosion over time for all erosion features examined in aerial photographs. Individual observations refer to the changes in erosion features such as sheep scars, or in part of larger eroded areas such as

peat hags. As described in Section 6.4.1, the range of sortie dates was subdivided into half-decades to allow trends in erosion over time to be described. However, as only nine observations were made on aerial photographs taken between 1946 and 1950, this total was summed with that of the subsequent five years; hence the first category refers to years 1946-54.

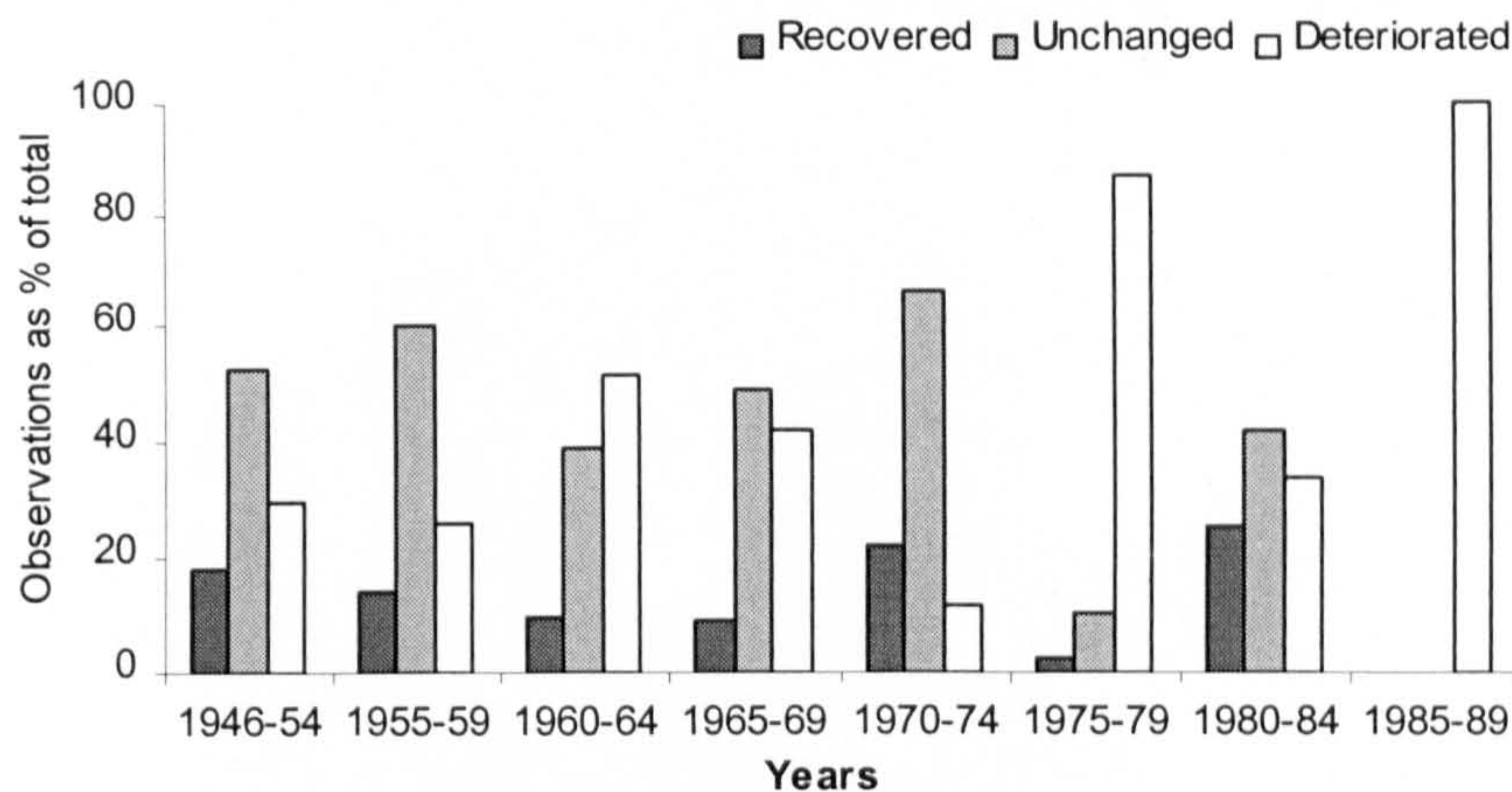


Figure 6.2 Observations of changes in erosion features assessed over a forty-year period from aerial photographs.

Overall, there was little variation in the proportion of recovered erosion features. In half-decades 1975–79 and 1985-89, however, few recovered observations were made of erosion recovery. While the total number of observations was also low between 1985 and 1989, a total of 40 observations were made between 1975 and 1979, almost 90% of which reflected deterioration in the erosion features examined.

With the exception of a similarly small proportion between 1975 and 1979, observations on unchanged erosion varied little throughout the photographic period.

Between 1946 and 1989, meanwhile, the proportion of deteriorated observations consistently increased. A single significant decrease in the proportion of deteriorated sites occurred between 1970 and 1974. As this decline is based upon over 150 observations in total, it reflects an adequate sample population (Table 6.5). The reason for the decline is uncertain but may become clear when changes in erosion caused by different factors are considered within half-

decades (Section 6.4.5). In contrast, the single observation obtained between 1986 and 1989 reduces the viability of that information and highlights a need for access to aerial photographs for all years after 1985 (Table 6.5).

Table 6.5 Observations of recovered, unchanged and deteriorated erosion features from aerial photographs between 1946 and 1989.

Years	Recovered	Unchanged	Deteriorated	Total
1946-59	9	1	2	12
1950-54	10	55	29	94
1955-69	14	61	26	101
1960-64	30	117	156	303
1965-79	14	75	64	153
1970-74	33	102	18	153
1975-89	1	4	35	40
1980-84	58	96	77	231
1985-89	0	0	1	1

6.4.5 Changes in different forms of erosion with time

In Figure 6.3, observations of erosion made within different decades are divided into human and animals causes (Section 6.4.1), allowing the changing focus of upland erosion to be seen. Between 1960 and the end of the 1980s, for example, the graph of changes in human erosion is dominated by the further deterioration of erosion, which far exceeds both recovered and stabilised erosion. A similar situation is obvious in the graph of animal-induced erosion, where deteriorated observations exceed those of recovering features between 1950 and 1979. Following this, insufficient observations limit the information gained.

In contrast, Figure 6.4 illustrates the changes observed on water-eroded peat and mineral degradation in the same period. Unchanged and recovered observations are the dominant features of these graphs. On eroded peat, unchanged features dominated observations made within each decade. There was also, however, a steady increase in the observations of recovered erosion between 1946 and 1989. With its smaller number of observations (Table 6.4) it is more difficult to establish a trend in the development of mineral erosion. It is clear however that at all points between 1946 and 1989, mineral erosion that indicated continued degradation was exceeded by either unchanged erosion (1960s-70s) or by recovered erosion (1980s).

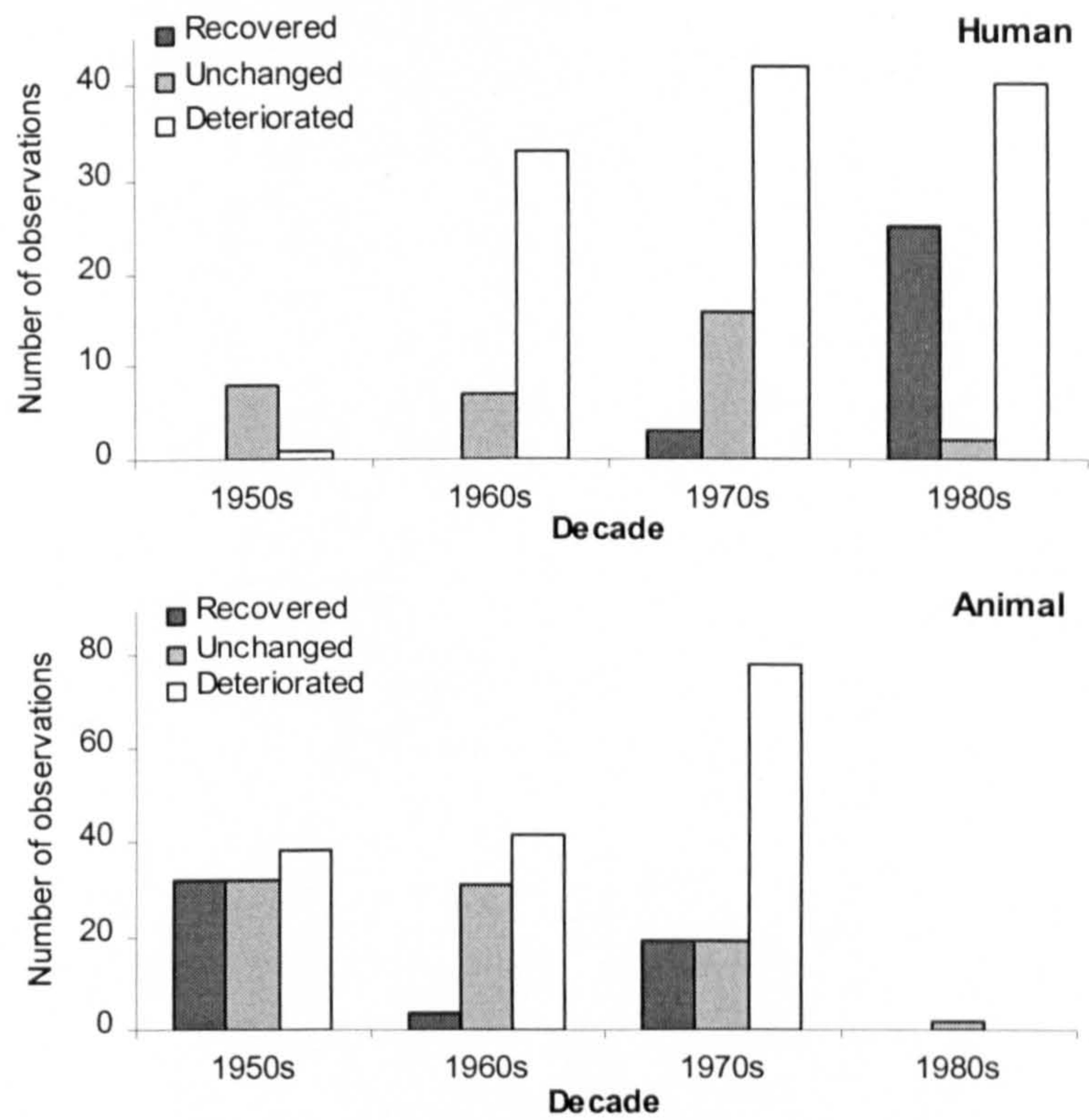


Figure 6.3 Observations on human and animal erosion made from aerial photographs taken in different decades.

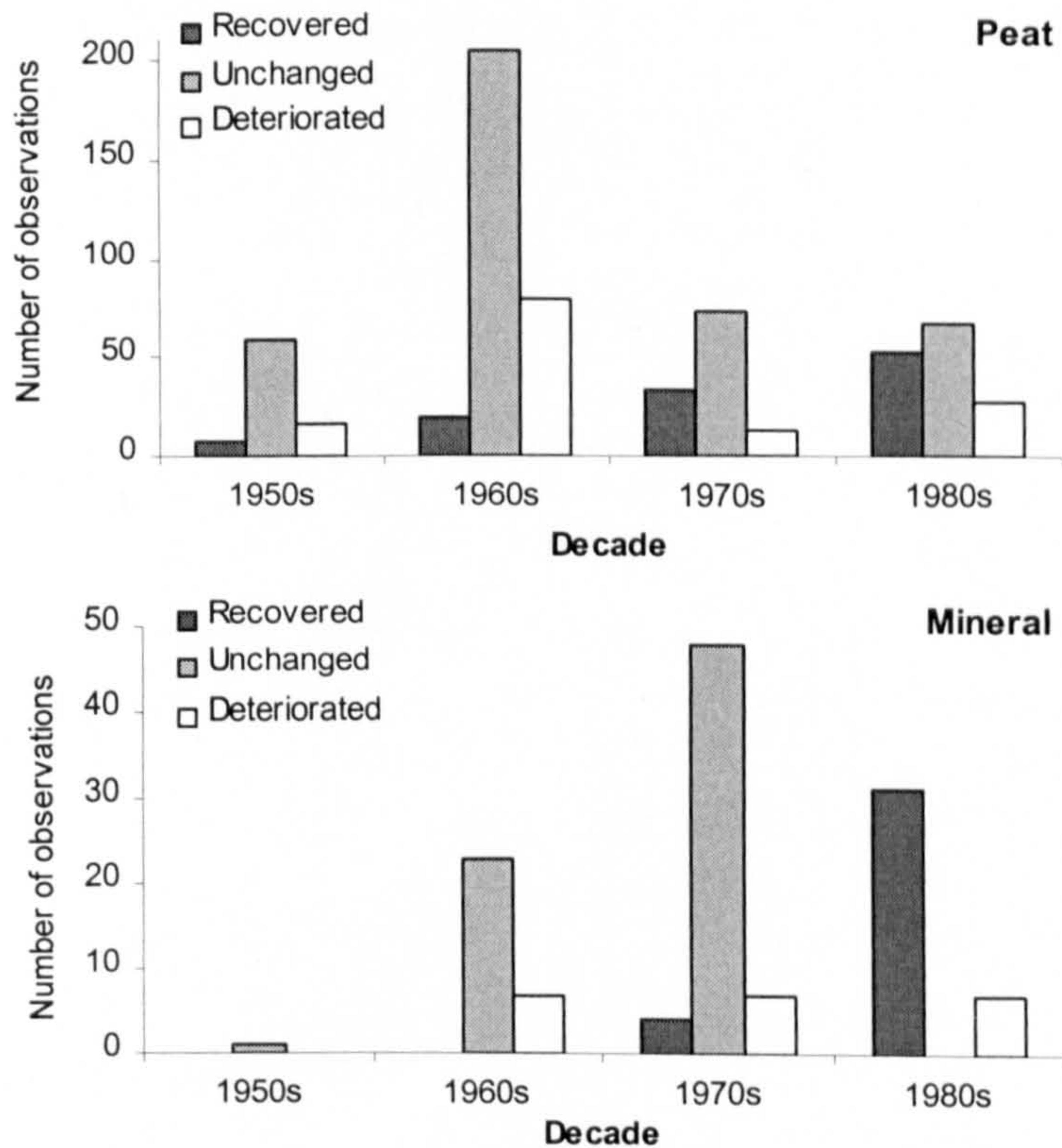


Figure 6.4 Changes in mineral and peat erosion between 1946 and 1989.

6.5 DISCUSSION

The following interprets the results from this small study on aerial photographs and discusses their significance.

6.5.1 Changes in human and animal-induced erosion

There are marked differences between the proportions of recovered, unchanged and deteriorated observations recorded on peat and mineral erosion and those recorded on human and animal-induced erosion (Figure 6.1). Both peat and mineral erosion appear relatively stable, with approximately 60% of the erosion features in both categories showing no change in erosion over the observation period.

Conversely, between 55% and 65% of erosion caused by landusers and by grazing animals deteriorated further in the same period. These results do not indicate, however, that the extent of peat or mineral erosion was at its greatest when aerial photographs were first taken in England and Wales. Instead, the majority of observations indicated no change in erosion over the period between 1946 and 1989, and therefore that the extent of peat and mineral erosion had not changed over that period. Over the same time-frame, instances of both human and grazing animal erosion had increased both in numbers and in extent.

Biotic erosion contrasts with both mineral and peat erosion because it is directly caused and maintained by the actions of humans or grazing animals, particularly sheep. Examples include footpaths, sheep scars, poached areas and erosion associated with new tracks. In contrast, while peat and mineral erosion may have been initiated by excessive burning, grazing or draining (Evans, 1993; Ratcliffe and Oswald, 1988; Tallis, 1994), soil loss is principally perpetuated by the actions of water and wind.

Another important distinction between biotic and peat or mineral erosion is the scale of the individual features. Generally, biotic erosion consists of small-scale, localised areas of erosion while peat erosion, in particular, is capable of developing uniformly over several hectares. While this study indicates that biotic erosion should be of more concern than peat or mineral erosion, perception of

the problem of erosion, based only on the areal significance of different erosion forms, would encourage emphasis on peat erosion only. It is important, therefore, to consider the effects on the upland landscape of accelerated erosion that is insignificant in terms of area but is controlled in its incidence and spread by a population of almost 60 million people and 44 million sheep (NSA, 1995).

Similar work with aerial photographs has been completed by Evans (Harrod *et al.*, 2000). In comparing evidence of erosion over several decades, he found stabilisation in peat erosion in areas such the Peak District, with obvious increases in footpath erosion and in sheep scars in the Lake District. Carr (1990) also examined aerial photographs between 1970 and 1983. She reported increases in the numbers and severity of sheep scars and path erosion in Coledale Valley (Lake District), while stabilisation and some recolonisation were noted on other erosion, particularly screes.

The value of aerial photographs as records of changing landscapes is reflected also in the use of ordinary oblique photographs. In his re-examination of eroded peat photographed by Bower (1960), Warburton (1998b) found either little or no change in the extent of bare peat or that the peat had revegetated.

6.5.2 Peat and mineral soil loss

The absence of an observable degree of continued soil loss from peat erosion features may be true in terms of its areal extent. However, there is evidence from the field survey (Chapters 3 and 4) that, while the overall extent of erosion may not be expanding, there is continued soil loss from areas of bare peat. Within hagged and gullied peat, there is a large surface area of bare peat upon which water and wind can continue to act. Unless the soil loss resulted in a change between soil horizons or in an obvious modification of the erosion feature outline, however, it would not be obvious in aerial photographs.

This study also suggests that the dynamics of mineral soil erosion are limited. This result must be considered in light of the conditions imposed on aerial photographic interpretation of erosion on steep mineral slopes. These slopes make it difficult to judge changes in feature colour and size accurately and also result in distortion of the photographic image. Assessment of change on mineral

erosion is limited therefore to the initiation of new scars or to obvious feature stabilisation through revegetation: continued erosion and removal of soil from these features may have been overlooked. Mineral erosion on steep slopes may not be an important feature of upland soil erosion, but this should be determined through more research.

9.5.3 Erosion and time

In half-decades where sufficient records of erosion change were made, observations of recovered erosion consistently equalled or exceeded those of deteriorated erosion. However, when broken down into different erosion forms, the overall trends varied considerably. Both human and animal-induced erosion deteriorated steadily between 1945 and 1989 while, in the same period, eroded peat and mineral soil recovered or stabilised.

The finding that continued erosion is primarily attributed to biotic factors, raises questions about attitudes towards erosion prevention and rehabilitation. Although they were available only to the late 1980s, the aerial photographs imply that management of upland ecosystems was not aimed then at protection of the upland environment. This important result will be combined with those from the field study, as described in Chapters 3, 4 and 7, and used to define current threats to the upland environment and to propose erosion remediation and prevention measures (Chapter 8).

6.5 CONCLUSIONS

Land managers and users and grazing animals are important contributors to the initiation of new erosion and the continued development of existing erosion. This influence is important, as uplands cover 30% of the UK (Orr, 2000). As grazing animal numbers are controlled by farmers, their combined effects add further to the sum of human influence on erosion.

The aerial photographs also indicate that peat and mineral erosion were not important sources of continued erosion or of newly initiated degradation between 1946 and 1989. The difficulties of assessing soil loss from within these areas may

mean that an important aspect of erosion, the continued removal of soil by water or wind from large-scale eroded areas without an associated increase in the areal extent of the feature, is neglected.

The need for detailed and repeat surveys of eroded areas has been emphasised by Evans and Felton (1987) and Grieve *et al.* (1994). This study suggests that, in spite of the small number of sites used, valuable information may be gained from the interpretation of aerial photographs. Future work could usefully concentrate on fully using archives of vertical aerial photographs on a greater area of the uplands.

Chapter 7

Extent, causes and rates of upland soil erosion in England and Wales

7.1 INTRODUCTION

In this chapter, the extent of degraded ground is calculated at field-site level and for upland England and Wales using data on erosion quantified through the 1997 and 1999 field surveys. The causes of upland erosion are discussed and the degree and locations of changes in eroded soil extent recorded between 1997 and 1999 are detailed.

The field surveys consisted of repeat visits to 399 locations at 5 km intervals around upland England and Wales. All observations were made within two concentric circles of 10 m and 50 m radii centred on the field site node. Where degradation was located within a field site boundary, the dimensions of individual erosion features were recorded and the extents of vegetated and unvegetated erosion feature sections were assessed. Full details of the field survey methodology, and the interpretation of its results, are contained in Chapter 3.

7.2 THE EXTENT OF UPLAND SOIL EROSION

The extents of total, bare and vegetated eroded ground calculated directly from the field survey are presented here. These values of erosion are then scaled up to account for the degree of erosion in the entire upland area of England and Wales (Section 7.2.3). In Table 7.1 and in subsequent tables, summary information on erosion is provided as an overview of the data.

7.2.1 Field extent of erosion

Table 7.1 summarises information on the total area and volume of erosion recorded within both 10 m and 50 m field sites in 1999. In total, seventy-four 10 m field sites and two hundred and six 50 m sites were eroded: these represented 18.5% and 52% of the total number of field sites respectively. Values of eroded area are presented as the percentage of the field site eroded, while those for erosion volume are in cubic metres.

Table 7.1 Summary statistics for total erosion recorded within both 10 m and 50 m of the field site node.

Statistic	10 m field sites		50 m field sites	
	Area (%)	Volume (m ³)	Area (%)	Volume (m ³)
Mean	9.03	18.26	4.77	433
Standard Error	1.74	5.56	0.81	98.37
Median	2.85	1.4	1	16.62
Standard Deviation	14.94	47.80	11.6	1412
Sum	668	1351	983	89189
Number of sites	74	74	206	206

The 10 m and 50 m field sites covered 0.0314 ha and 0.7854 ha respectively. In total, erosion measured on 10 m field sites covered 0.2 ha (668% of 0.0314 ha), while that recorded on 50 m field sites was 7.72 ha or 983% of 0.7854.

The mean erosion on each field site varied widely: on 10 m field sites the mean area of erosion of 9.03% represented a degraded soil surface of 28.35 m². The mean area of erosion recorded within 50 m field sites, meanwhile, was 4.77% or 374.6 m². Differences of this magnitude are a frequent problem when comparing erosion values recorded within 10 m with those recorded on 50 m sites and are discussed later.

The total volume of erosion recorded within 10 m field sites was 1 351 m³. As this erosion was recorded within 74 field sites at 0.0314 ha each, the rate of soil loss per unit area was 581.43 m³ ha⁻¹.

Within 50 m, meanwhile, erosion recorded on 206 field sites amounted to a total volume of 89 189 m³. In total, 206 eroded 50 m field sites covered an area of 162 ha. The rate of soil loss per hectare was therefore 551.26 m³ ha⁻¹.

The differences between mean and median values presented in Table 7.1 reflect the non-normal distribution of the data while the variation in the data is indicated by the values of standard deviation. The two order-of-magnitude differences between standard deviations of 10 m and 50 m volume data also reflect the high variability of 50 m data when compared with 10 m data.

7.2.2 Bare and vegetated eroded ground

As well as the total extent of erosion that was assessed during the 1999 survey, the area of bare and vegetated eroded ground on each field site was measured to indicate the degree of erosion recovery. Fully vegetated features were taken to indicate stabilised erosion, while erosion features that did not show signs of

vegetation encroachment were classified as bare and considered to be subject to continued active erosion. This distinction between eroded states enhanced the information on the total extent of erosion, which otherwise would not give any impression of the activity of erosion within the uplands.

Bare area was quantified from the length and width measurements of the non-vegetated portion of the erosion feature. Vegetated area was represented by the extent of vegetation encroachment onto the original feature, the extent of which was usually obvious from the surrounding landscape. The vegetation itself frequently helped to identify the original perimeter of the erosion feature, as revegetated areas often comprise plants of different species, age, and density to those of the surrounding area.

Table 7.2 details the area of bare and vegetated eroded ground measured within 10 m and 50 m field sites. Almost 65% of the total eroded area measured within 10 m was not vegetated, while 51% of the entire area of erosion measured on 50 m field sites was bare (Table 7.1). Mean areas of bare erosion exceeded those of vegetated eroded ground on both 10 m and 50 m field sites. On 10 m field sites, the total area of eroded and vegetated soil was 0.07 ha, approximately 54% of that of bare soil. On 50 m field sites, meanwhile, areas of bare and vegetated soil were almost equal, at 3.92 ha and 3.80 ha respectively.

Table 7.2 Summary statistics for bare and vegetated eroded ground, recorded as a percentage of 10 m and 50 m field sites.

	10 m area (%)		50 m area (%)	
	<i>Bare</i>	<i>Vegetated</i>	<i>Bare</i>	<i>Vegetated</i>
Mean	5.85	3.18	2.42	2.35
Standard Error	1.3	1.3	0.48	0.61
Median	1.8	0	0.60	0
Standard Deviation	10.8	11.5	6.95	8.73
Sum	433	235	499	484
Number of sites	74	74	206	206

7.2.3 Erosion extent within upland England and Wales

The values for area and volume of erosion measured within both 10 m and 50 m field sites were scaled up to determine the approximate area and volume of eroded soil in the entire upland region of England and Wales. In completing this, assumptions were made regarding how representative the field survey data are of the uplands as a whole. However, even with these possible errors, some indication of upland erosion

extent in England and Wales was necessary and useful information that may be used to identify the scale of the problem and direct further, more comprehensive research.

Within this field survey, field sites were located at 5 km intervals: each field site therefore represented 25 km² of uplands. As 399 field sites were used, the total area of ground sampled by this research was 9 975 km² (25 x 399). While the entire field survey was fully representative of upland England and Wales, the reduced datasets of eroded 10 m and 50 m field sites represent more limited upland regions. Consequently, in the following, the upland area represented by individual 10 m and 50 m datasets was calculated and used to determine erosion extent.

The mean erosion recorded at each of the seventy-four 10 m field sites on which erosion was recorded was 9.03%, which equalled a mean soil loss of 903 m² ha⁻¹. Seventy-four field sites correspond to a total surveyed area of 1850 km² of upland England and Wales (74 x 25 km²). The eroded area of upland England and Wales estimated from the 10 m field survey was therefore 16 705.5 ha or 1.67% of the total.

In the same way, the mean volume of 18.26 m³ of soil recorded within seventy-four 10 m field sites equalled 581.5 m³ ha⁻¹. The volumetric extent of soil loss within England and Wales was therefore 107 577 500 m³ or 0.108 km³.

Similarly, the 50 m eroded field site data may be scaled up to represent erosion within England and Wales. Two hundred and six eroded 50 m field sites represent 5150 km² of upland England and Wales. The mean eroded area on all eroded 50 m field sites was 4.77%, which is equivalent to 477 m² ha⁻¹. From eroded 50 m field sites, therefore, the eroded area of England and Wales was estimated as 24 565.5 ha. This is equal to 2.46% of the surveyed uplands of England and Wales.

The volume of eroded soil in England and Wales in 1999 was similarly calculated as 0.284 km³ from a mean erosion of 551 m³ ha⁻¹.

Bare and vegetated eroded ground measured on 10 m field sites had mean areas of 585 m² ha⁻¹ and 318 m² ha⁻¹ respectively. These were equal to 10 822.5 ha and 5 883 ha respectively of the total eroded area in England and Wales. Within 50 m field sites, meanwhile, bare and vegetated eroded areas were 12 463 ha and 12 102.5 ha respectively.

7.2.4 Distribution of eroded field sites

The distribution of field site erosion is presented graphically in Plates 7.1 and 7.2. Each point represents a field site, colour-coded according to the area or volume of erosion recorded there: the legends assign a range of eroded area or volume to each colour. Within 10 m field sites, 100% erosion was not recorded and hence the maximum eroded area portrayed is 89%.

Plate 7.1 shows the distribution of the 74 eroded 10 m field sites. The lowest categories of both eroded area and volume, recorded on the greatest numbers of field sites, were evenly distributed across the uplands. The mean area of erosion on 78% of 10 m field sites was less than 3% of the 0.0314 ha site, or 9.4 m². Almost 90% of 10 m field sites had lost less than 56 m³ of eroded soil: on average, therefore, these sites had lost little over 5 m³ (Table 7.3).

Overall, concentrations of eroded 10 m field sites were greatest in the Brecon Beacons and along the Pennines, with few eroded 10 m field sites in the Southwest, the Lake District, North York Moors, Cheviots or in Mid or North Wales. Within the Pennines, a break in the distribution of eroded sites occurs south of the Yorkshire Dales and north of the Peak District, either side of which there were more degraded field sites. Eroded 10 m field sites were most common, therefore, in areas dominated by peat (Pennines and Brecon Beacons) and were limited elsewhere. The greatest extents of erosion were measured in Mid- and South-Wales, and in the North Pennines, in the region of Teesdale and Weardale.

Also classified in terms of their areal and volumetric erosion extent, 50 m eroded field sites are presented in Plate 7.2. Their much greater distribution gives the impression of pervasive and almost entire erosion of the uplands. In reality, the majority of 191 sites was eroded to no more than 16% and their mean eroded area was 2.1% or 165 m² (Table 7.4).

Table 7.3 The ranges of eroded area and volume, measured on 10 m field sites and shown in Plate 7.1.

Value	Range	Number of sites	Mean
10 m eroded area	0-14%	58	2.96%
	15-29%	10	19%
	30-44%	3	38.8%
	45-59%	2	50.5%
	60-74%	0	0%
	75-89%	1	89%
10 m eroded volume	0-1779 m ³	66	5.18 m ³
	1780-3557 m ³	6	85.92 m ³
	3558-5335 m ³	1	157 m ³
	5336-7113 m ³	0	0 m ³
	7114-8891 m ³	0	0 m ³
	8892-10669 m ³	1	335 m ³

Eroded 50 m field sites were evenly distributed across the country. In both the Cheviots and the Lake District, few sites were eroded and on those that were, total degraded area was less than 16%. Eroded sites also occurred within Wales and in Devon, but again, these were limited to the lowest ranges of eroded area and volume. Field sites eroded to 16% were located in North and South Wales but were concentrated in the Peak District, Yorkshire Dales, Howgill Fells, Bowland Forest and in Durham and South Northumberland. The field site with 100% erosion occurred in the NW Pennines. These were areas dominated by deep blanket peat on gently sloping hillsides and on flat mountain plateaux. This apparent relationship between peat and erosion will be examined again in Section 7.4.

Table 7.4 Classes of eroded area and volume measured within 50 m field sites and used in Plate 7.2.

Value	Range	Number of sites	Mean
50 m eroded area	1-16%	191	2.1%
	17-33%	9	24.6%
	34-50%	3	49%
	51-66%	2	59.4%
	67-83%	0	0%
	84-100%	1	100%
50 m eroded volume	0-1958 m ³	193	122 m ³
	1958-3917 m ³	7	3254 m ³
	3917-5875 m ³	3	4458 m ³
	5875-7833 m ³	1	7721 m ³
	7833-9792 m ³	0	0 m ³
	9792-11750 m ³	1	9880 m ³

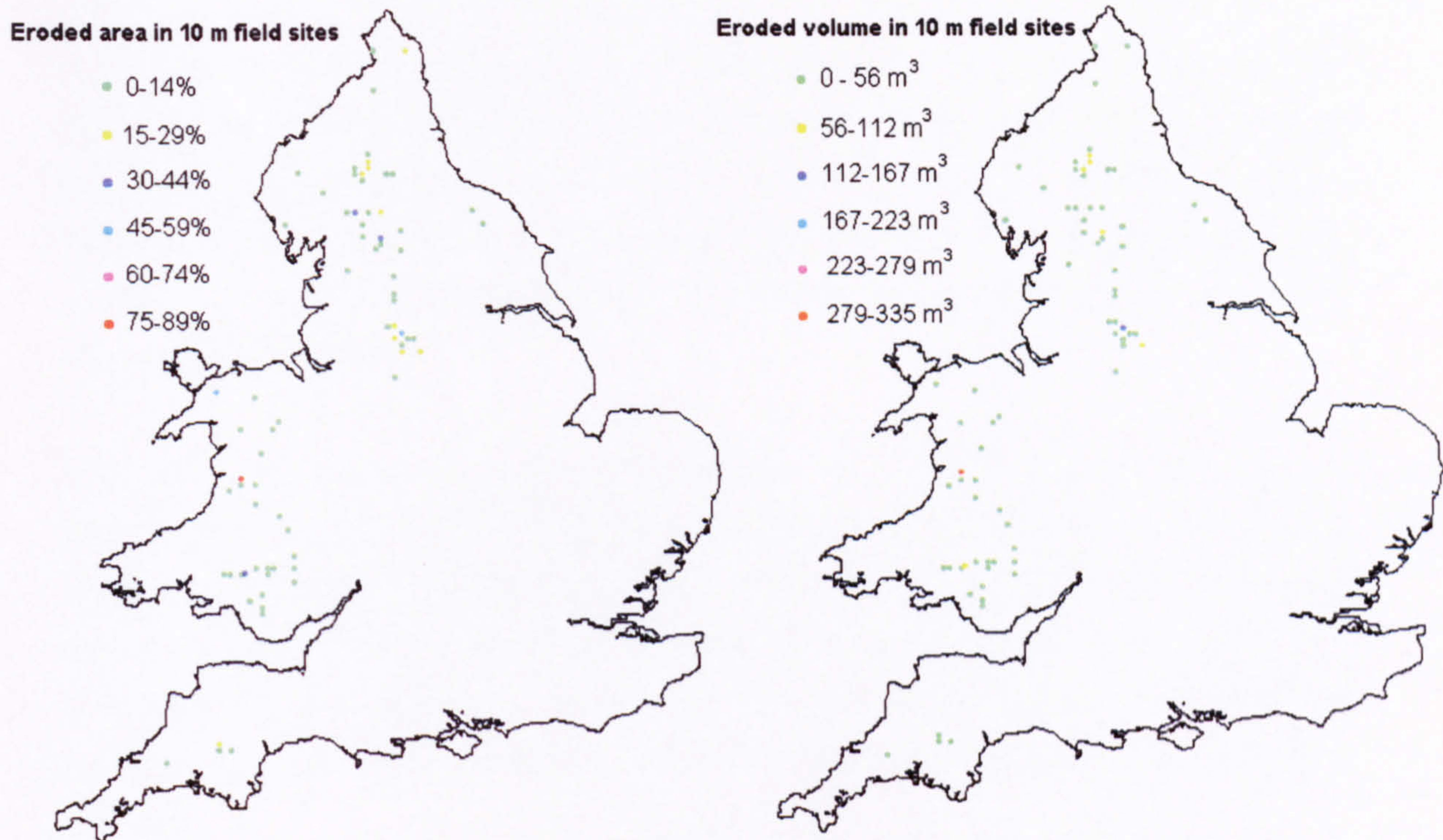


Plate 7.1 All field survey sites in upland England and Wales: coloured points represent the areas and volumes of erosion recorded within 10 m field sites.

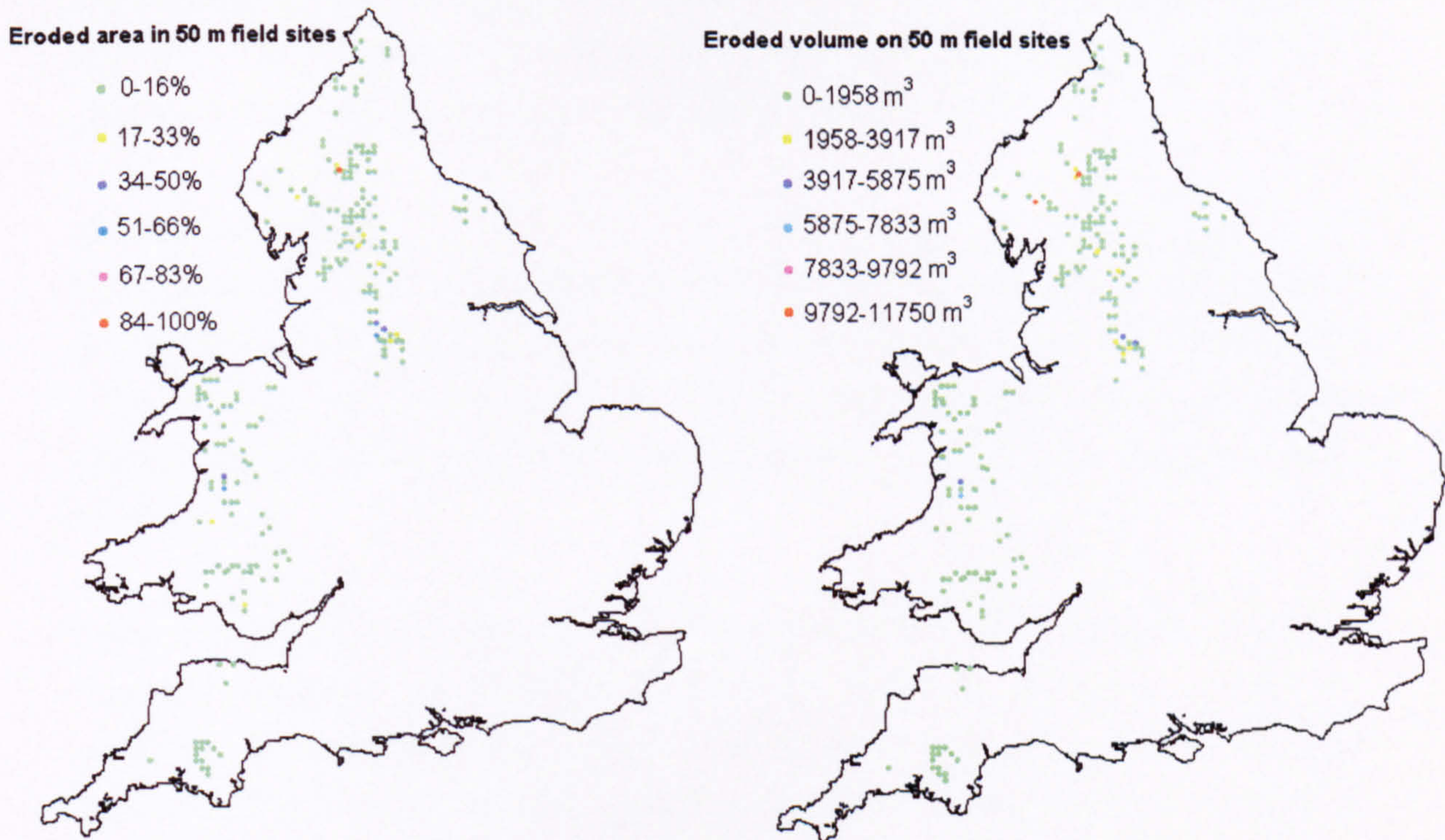


Plate 7.2 Distribution of eroded 50 m field sites, presented in ranges of eroded area and volume.

7.3 CAUSES OF EROSION IN UPLAND ENGLAND AND WALES

In addition to the measurements of erosion extent made in the 1999 field survey, the apparent causes of soil degradation were determined from the position, form, activity and overall appearance of individual erosion features. In this way, field site erosion was attributed to a single cause or to a number of different causes. As all areas of exposed soil were included, this section of the study was a useful assessment of the causes of soil erosion.

In general, the appearance of erosion features immediately allowed their principal determinants to be readily identified: scars caused by humans, for example, were easily distinguishable from those caused by water flow (Plate 7.3). Field site erosion was assigned to one of three broad causal groups, the principal features of which are discussed in the following. It is important to remember, however, that while the causes of erosion may be separated, they all frequently act together to exacerbate soil loss.

Causes of erosion were then linked to the area and volume of soil loss to allow the most frequent causes of degradation and their contribution to the area and volume of soil loss to be identified. This information, in turn, was used to suggest methods for upland habitat protection and erosion rehabilitation (Chapter 8).

7.3.1 Biotic erosion

Biotic erosion refers to soil degradation caused directly by the actions of humans or grazing animals. Features caused by grazing animals include scars, tracks and areas of poaching. As all of the erosion measured in the field survey and attributed to grazing animals was due to sheep, grazing animals and sheep are synonymous in the following.

Human erosion, due to either amenity or agricultural use of the uplands, was most frequently apparent as footpaths, official and unofficial car parks, rutting and poaching by machinery, and drainage, particularly moorland gripping. Although tracks are frequently constructed to enable easier access through difficult terrain or to remote areas, newly created tracks represent a potent source of suspended material and increased runoff (Elliot *et al.*, 1999; Theurer *et al.*, 1998).

Although erosion features are classified as biotic, wind and water are important erosive agents once soil is exposed. Grip erosion is a particular example of erosion initiated by humans that is perpetuated by the flow of water. Because of position, proximity to other drains and their standard width, however, grips are easily distinguished from linear erosion gullies. In this and other cases, as far as the original erosion features remained discernible, soil loss that occurred after the original degradation was disregarded in favour of the earliest initiators of erosion.

7.3.2 Water erosion

This group encompassed all erosion features caused by the channelled or unchannelled flow of water. Linear erosion gullies, which act as conduits for the rapid runoff of water and suspended material, were included here, as was large scale peat deterioration. This latter frequently results in complete removal of a deep layer of blanket peat, and can extend over very wide areas. Peat erosion is, consequently, an important constituent of upland soil erosion.

In spite of previous research, it remains difficult to ascribe a single cause to peat erosion, as described in Section 1.3. While the initial causes of peat erosion are uncertain, however, contemporary peat erosion is almost entirely promoted through water flow (Plate 7.3) and it was therefore included in this group.

7.3.3 Wind erosion

Wind erosion occurs on dry, exposed peat surfaces. The need for surface drying of the peat meant wind erosion was difficult to observe in the field. It also occurs when the surface skin of unvegetated saturated peat is blown as a slurry (Plate 7.4). Research has shown that wind erosion may account for the removal of significant volumes of peat (Curtis, 1965; Maltby, 1980).



Plate 7.3 (Left, from top) Erosion caused by humans, water flow and wind and sheep. (Right) linear erosion gully on mineral soil.



Plate 7.4 Wave patterns on exposed peat surface, caused by wind under saturated peat conditions.

7.3.4 Extent of erosion caused by biotic, water and wind factors

In Table 7.5, data are presented on erosion measured within 50 m field sites and attributed to different causes. Water accounted for a greater total and mean area and volume of erosion than either wind or biotic causes, although, at 141, the greatest numbers of field sites were eroded by biotic factors.

The maximum areas of erosion caused by each factor also vary widely: the largest area of biotic erosion was 33% of a 50 m field site. A single water-eroded field site, meanwhile, was 100% degraded. The extent of wind erosion did not exceed a maximum of 1.3%. The high variability of the water, wind and biotic erosion datasets are indicated by the standard deviations of the data and by the differences between mean and median erosion.

Table 7.5 Summary details for water, wind and biotic erosion measured within 50 m field sites in 1999.

Statistic	Biotic		Water		Wind	
	Area(%)	Volume (m ³)	Area(%)	Volume (m ³)	Area(%)	Volume (m ³)
Mean	1.27	63.16	3.50	369	0.007864	0.062462
Standard Error	0.22	15.78	0.81	98.01	0.006492	0.050021
Median	0.15	1.82	0	0	0	0
Standard Deviation	3.17	226	11.56	1407	0.093173	0.72
Sum	261	13010	720	75939	1.62	12.87
Count	206	206	206	206	206	206

The values in Table 7.5 can be scaled up to estimate the area and volume of erosion attributed to water, wind and biotic factors within upland England and Wales. Using the same procedure as in Section 7.2.3, water erosion was calculated to account for a total area of 18 025 ha and a volume of 241 959 511 m³ (0.242 km³). Wind erosion, meanwhile, was responsible for a total area of 40 685 m² (4.1 ha) and a volume of 40 982 m³ in upland England and Wales. Finally, the extent of biotic erosion within upland England and Wales was estimated as 6 540.5 ha (65.4 km²) and 41 415 075 m³ (0.04 km³).

7.3.5 Distribution of erosion causes

Plate 7.5 (page 196) illustrates the distributions of 10 m and 50 m field sites, colour coded to reflect the causes of erosion. Within 10 m, biotic and water erosion were evenly distributed, and occurred in similar numbers in all upland regions. The same distribution pattern was obvious in 50 m eroded sites (Plate 7.6), although there were

twice as many biotically-eroded sites as there were water-eroded sites. Both wind eroded sites occurred within the North York Moors.

7.3.6 Causes of erosion linked to the environment

In the following, the altitudes, slopes and soils over which biotic, water and wind erosion developed are assessed. In Figure 7.1, the volumes of erosion recorded within field sites are distributed along an altitude gradient. Values were transformed to correct the non-normal distribution of the data because, as small volumes of eroded soil were measured on a large number of field sites, raw data was grouped at the lower end of the erosion scale. Transformation spread the data more clearly.

Within both 10 m and 50 m field sites, more soil was eroded at altitudes greater than 250 m (50 m dataset) and 300 m (10 m dataset): this erosion was caused by water. In contrast, humans and animals were responsible for smaller volumes of erosion on both 10 m and 50 m sites, and their influence was concentrated at lower altitudes.

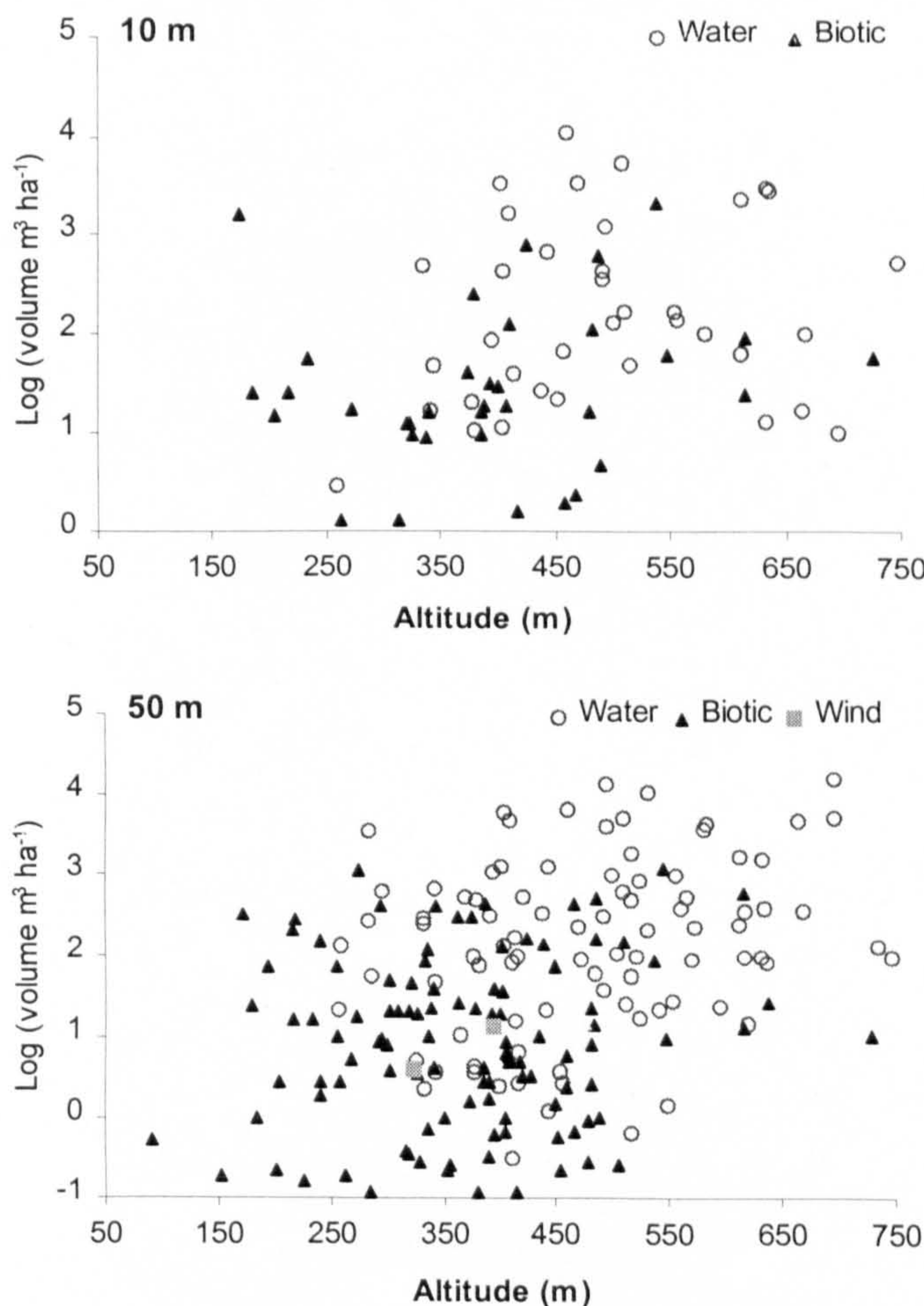


Figure 7.1 Distribution of water, biotic and wind-eroded field sites with altitude.

The distribution of eroded volumes and causes was also related to slope (Figure 7.2). Within 10 m, there was a regular distribution of biotic and water-induced erosion across all slopes to a maximum of approximately 27°, after which only biotic erosion occurred. As seen previously, the volumes of erosion were consistently greater on water-eroded sites than on sites where humans or animals were responsible for erosion.

Within 50 m, the same general trend was visible, although the presence of many more eroded field sites blurs the distinction between causes. Again, human induced erosion was responsible for erosion on the steepest slopes. Although water erosion was found on slopes up to 29°, its incidence declined sharply above 10°.

As wind erosion was measured on only two field sites, it was impossible to draw conclusions about its relationship with slope.

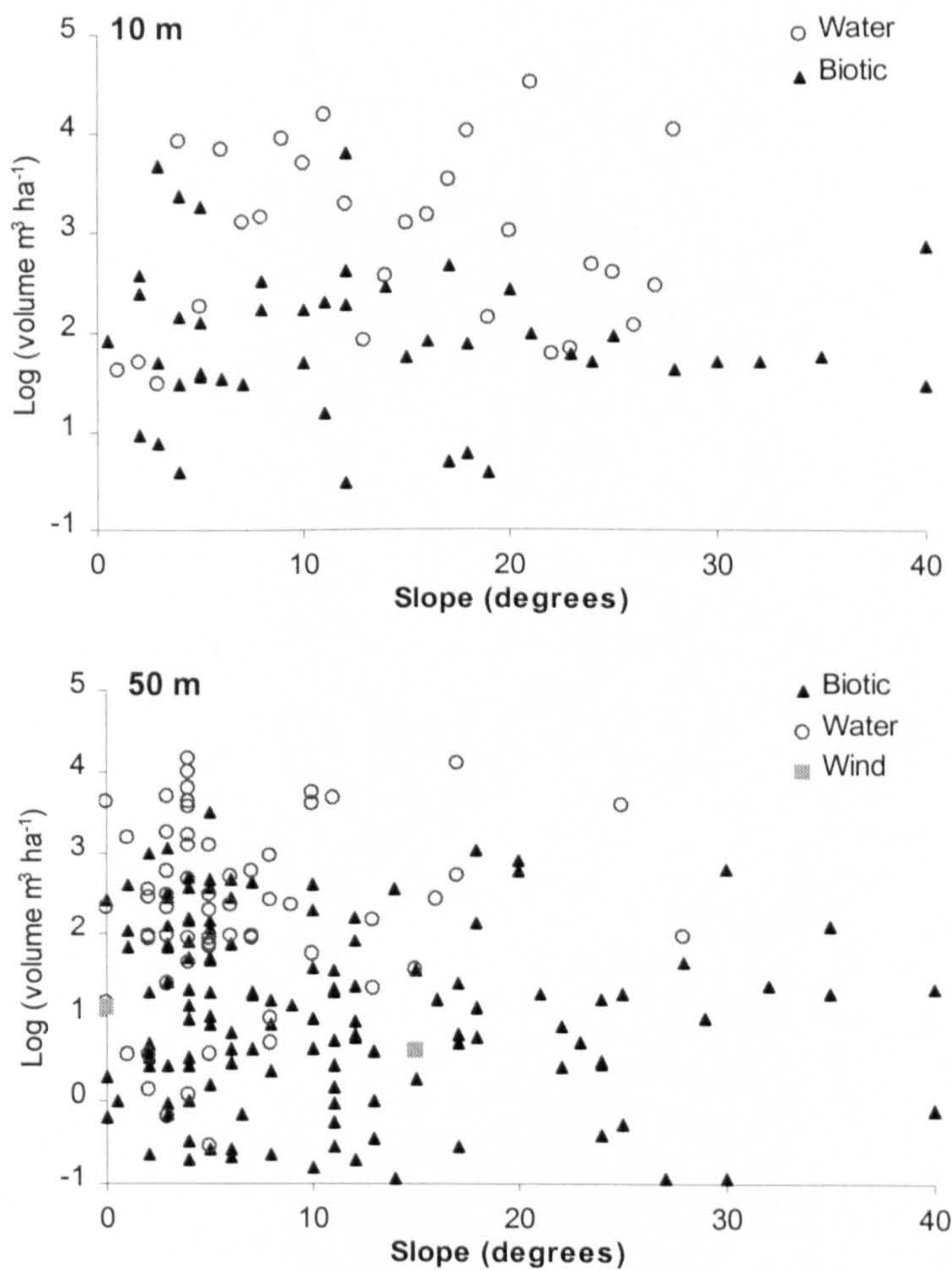


Figure 7.2 Erosion within 10 m and 50 m field sites, classified by cause and field site slope.

The relationship between field site eroded volume and causes of erosion was also assessed on different soil groups (Figure 7.3). Although the measured eroded volume varied considerably in different soil classes, both minimum and maximum volumes were greatest on wet mineral and peat soils (Classes 2 and 4 respectively).

Within both 10 m and 50 m, water erosion dominated wet mineral soil and peat soils while biotic erosion was evenly distributed among the soil classes. Water erosion did not occur on dry mineral soils within 10 m, and there was only one incidence on 50 m field sites. Both occurrences of wind erosion were on peat.

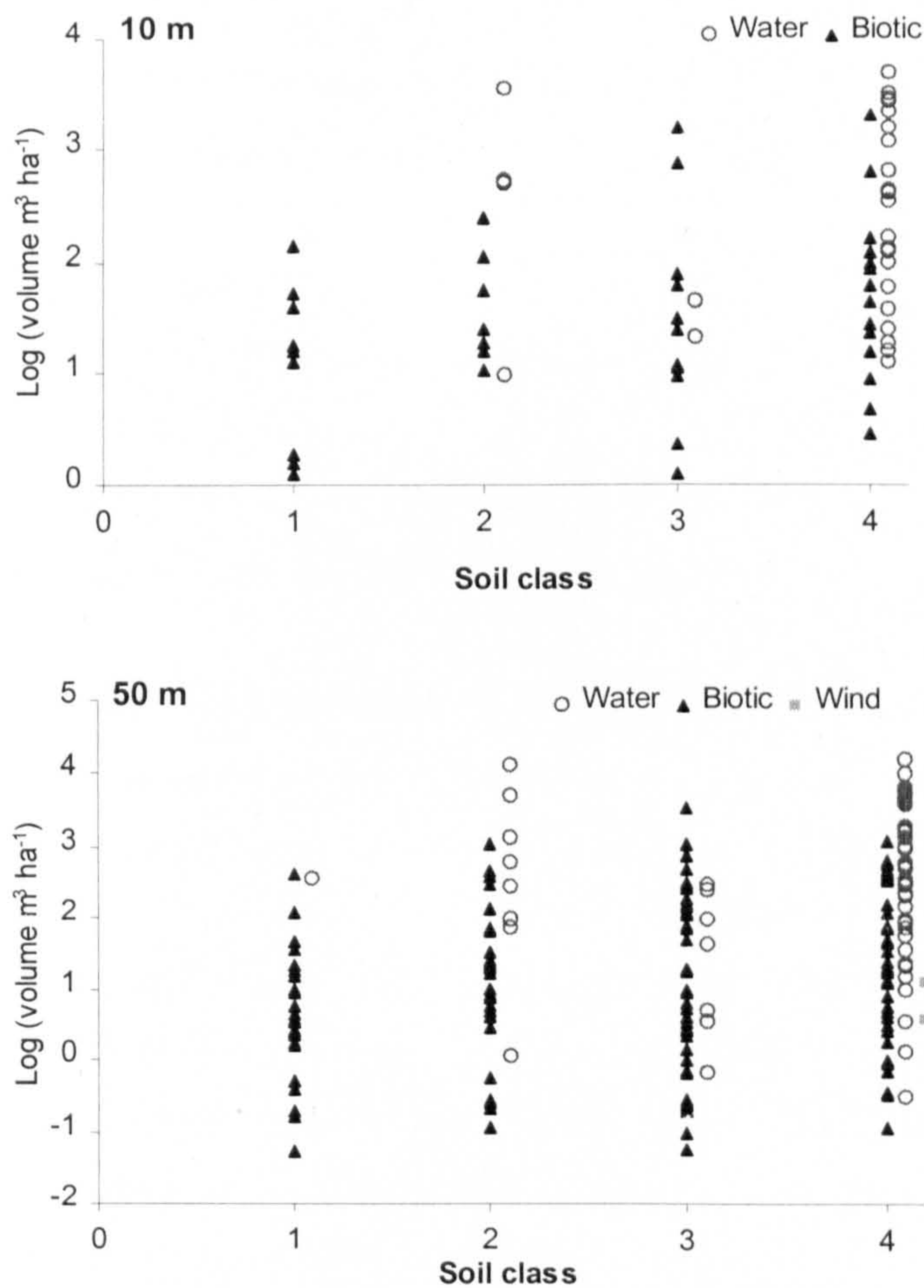


Figure 7.3 Eroded volume on 10 m and 50 m field sites, defined by causes and classified within dry mineral (1), wet mineral (2), wet peaty mineral (3) and peat (4) soil classes.

7.4 RATES OF EROSION

Previous research has quantified rates of soil loss through erosion in a number of different ways. In the short term, sediment traps in gullies or streams provide evidence of sediment load in runoff (Crisp and Robson, 1979; Tallis, 1972). In the longer term, palaeostratigraphic analysis of the build-up of eroded materials in lakes

and reservoirs allows the erosional history of a catchment to be reconstructed (Battarbee *et al.*, 1985; van der Post *et al.*, 1997).

In this study, rates of erosion were determined from the differences between erosion recorded in the 1997 and 1999 field surveys. As described in Chapter 3, changes were made to the field survey protocol during the 1997 field season. These were applied to enhance the capabilities of the research and to account more comprehensively for erosion in the upland environment (Appendices 2 and 3). A consequence of these changes, however, was that directly comparable 1997 and 1999 field results exist for only about one third of all field sites. Here, changes in erosion extent quantified on these field sites were examined in relation to the environmental and management variates recorded and to the causes of erosion.

7.4.1 Presentation of results

Results were presented for total erosion change measured within 50 m field sites only. Changes in erosion occurred on twelve 10 m field sites, which therefore provided an insufficient database for interpretation. Full descriptions of the field sites and the field methodology were provided in Chapter 3.

Analysis of the statistical significance of relationships between the environment and field site change in erosion was carried out using Genstat (Version 5; Release 4.1). Prior to analysis, however, frequency histograms revealed the non-normal distribution of the data (Figure 7.4). As parametric statistical tests require normally distributed data, log transformation was required. In Table 7.6, agreement between the median and mean values of transformed data reflects the near-normal distribution of the logged data. While data transformation was necessary to conduct the statistical analyses, however, raw data on changes in erosion over time were related to different levels of environmental variables and factors.

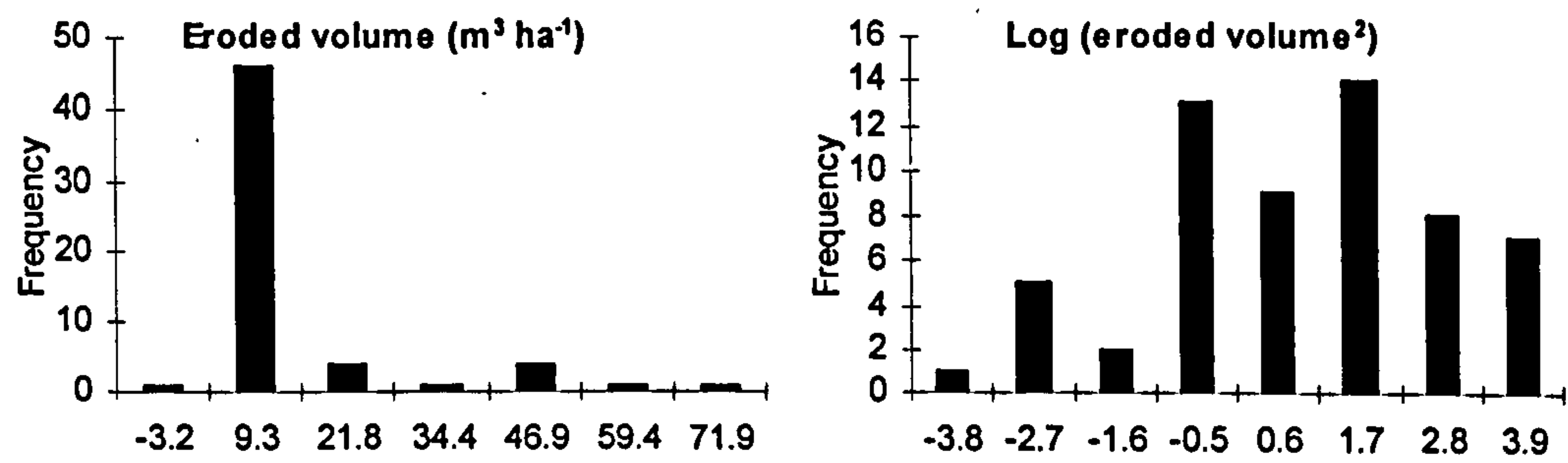


Figure 7.4 Frequency distributions for raw and transformed records of the change in eroded volume recorded on 50 m field sites between 1997 and 1999.

Table 7.6 Summary statistics of the total change in erosion extent and volume recorded between 1997 and 1999 within 50 m field sites. Data is presented for both raw and log-transformed data.

	Total area (%)	Total volume (m ³ ha ⁻¹)	Log (area ²)	Log (volume ²)
Mean	0.3514	7.10	-1.72	0.13
Standard Error	0.10	1.82	0.23	0.25
Median	0.10	0.93	-1.49	0.16
Standard Deviation	0.75	14.01	1.76	1.96
Sum	20.73	419	-102	7.50
Number of sites	59	59	59	59

7.4.2 Statistical summaries of the changes in erosion between 1997 and 1999

In total, 158 field sites were surveyed using identical and hence directly comparable field protocols.

Differences in erosion that occurred within both 10 m and 50 m of the node were included in this discussion. Summary statistics for the 12 sites on which change was recorded are provided in Table 7.7, where positive and negative changes in erosion have been separated. Positive changes refer to sites where the extent of erosion increased between 1997 and 1999. Conversely, on negative sites, erosion extent declined.

More field sites experienced increases than decreases in erosion. The increases in both mean area and volume were significantly greater than the mean decreases in erosion (P = 99.9% and 99% respectively).

Table 7.7 Summary details for the changes in erosion recorded within 10 m field sites. Data are subdivided into total, positive change only, and negative change only sites.

Statistic	Area %			Volume (m ³)		
	Total	Positive	Negative	Total	Positive	Negative
Mean	1.37	2.75	-0.56	3.36	14.63	-9.50
Standard Error	0.61	0.64	0.13	4.51	2.44	6.72
Median	0.73	2.50	-0.66	4.63	12.26	-2.75
Standard Deviation	2.13	1.71	0.30	15.62	5.98	15.03
Sum	16.44	19.25	-2.81	40.27	87.79	-47.52
Number of sites	12	7	5	12	6	5

Summary statistics were also calculated for the change in erosion recorded within 50 m field sites (Table 7.8). On sites where change was recorded, the extent of both

eroded area and volume increased between 1997 and 1999 with mean increases of 0.35% (27.5 m²) and 7.10 m³ ha⁻¹ respectively. The total increase in eroded area was 1649 m² (21%) while the total increase in volume was 419 m³. Both datasets are skewed, as represented by the differences between mean and median values.

The positive and negative changes in area and volume of erosion are also presented in Table 7.8. In eroded area, the mean increase in erosion was almost equalled by the mean decrease, although the total positive change far exceeds the total negative change. In terms of eroded volume, the positive change in erosion was significantly greater than the negative change, indicating a general trend towards further soil loss between 1997 and 1999. As with the dataset for eroded area, a large majority of sites experienced a positive change in erosion.

Table 7.8 Changes in eroded area and volume measured within 50 m of the field site nodes between 1997 and 1999.

Statistic	Area %			Volume (m ³)		
	Total	Positive	Negative	Total	Positive	Negative
Mean	0.35	0.47	-0.45	7.10	8.00	-0.86
Standard Error	0.10	0.10	0.24	1.82	1.99	0.36
Median	0.10	0.15	-0.18	0.93	2.00	-0.59
Standard Deviation	0.75	0.73	0.59	14.01	14.51	0.88
Sum	20.73	23.42	-2.69	419	424	-5.18
Number of sites	59	50	6	59	53	6

7.4.3 Rates of erosion increase

Where erosion extent changed with time, the mean increase in eroded area measured on 50 m field sites between 1997 and 1999 was 0.35% (Table 7.8). This change was recorded on 59 field sites, which represents 1475 km² of the uplands of England and Wales. The extent of erosion in upland England and Wales was estimated, therefore, to have increased by 5 162 500 m², or 516.25 ha between 1997 and 1999.

A similar assessment of the increase in eroded volume over the same period estimated a positive change of 1 333 397 m³ (0.001 km³) in erosion volume.

These figures correspond to an annual increase in bare soil extent of 258 ha and to an annual loss of 666 696 m³ of soil from the English and Welsh uplands.

7.4.4 Influences of environment and land management on changes in erosion

The principal environmental and management features of each field site were recorded in both 1997 and 1999 surveys. Here, the relationships between these variates and the change in erosion measured over time were identified.

While both 10 m and 50 m datasets were examined in the statistical analyses, only the 50 m information is presented graphically (Figures 7.5-7.10). The erosion change measured on only twelve 10 m field sites was insufficient information on which to base conclusions.

7.4.4.1 Altitude

Figure 7.5 and Table 7.9 represent the relationship between 50 m erosion change and altitude. Altitude has been split into seven groups because, when presented as a continuous variable, the high data variance reduced the clarity of the altitude-erosion relationship. For the same reason, the other environmental and management variates were also subdivided into groups. Because of the difference in magnitude between mean eroded area and volume values, volume data were reduced by 10 to allow their direct comparison with area data.

In Figure 7.5, the area of erosion change declined with altitude, while eroded volume changed little until it increased at and above 400 m. Above 600 m, the volume of soil loss declined again. The wide range of standard errors associated with the data at all altitudes reduces the reliability of the trends.

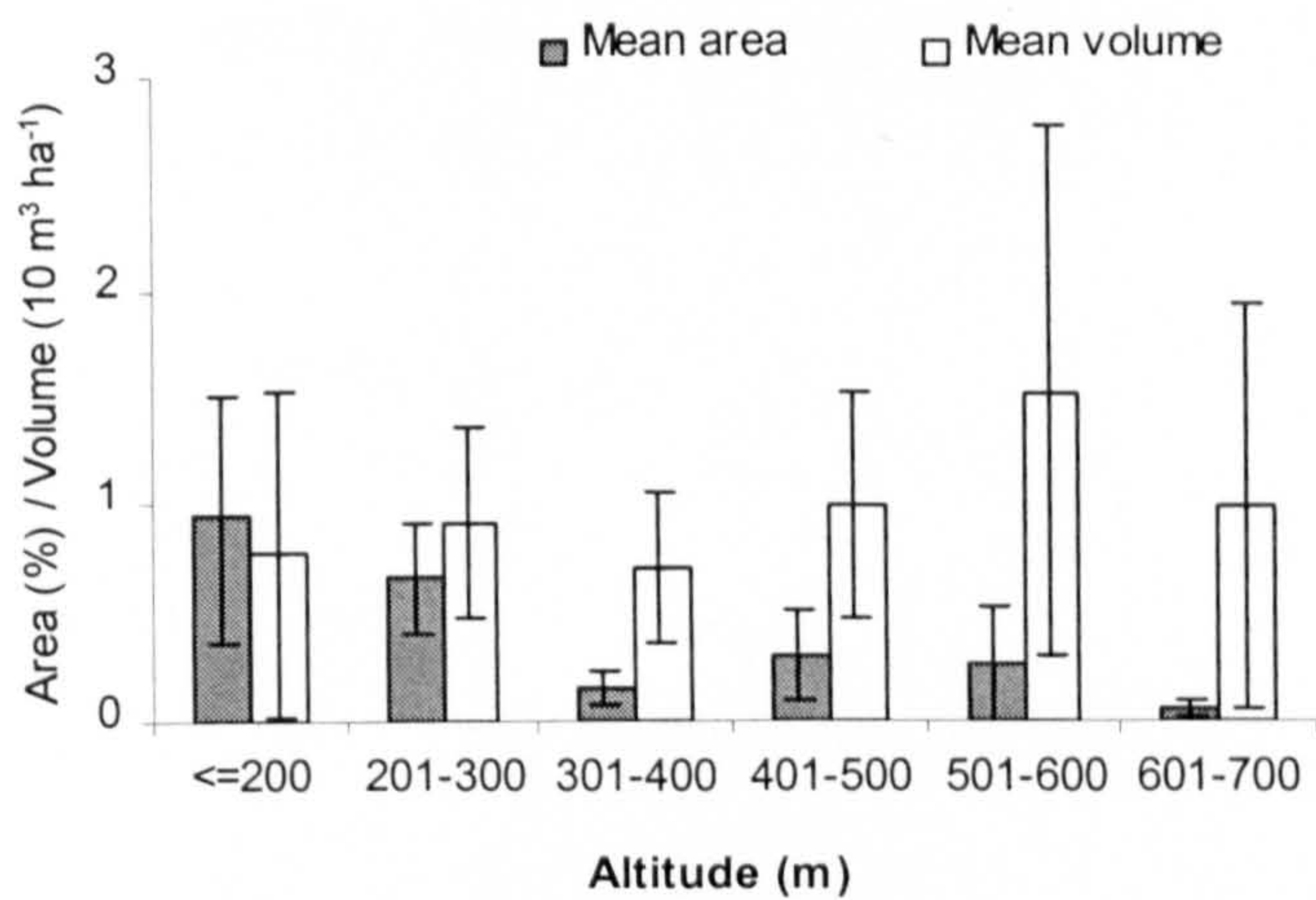


Figure 7.5 Changes in erosion area and volume with altitude. Data are shown for erosion recorded within 50 m field sites. Error bars reflect standard error of the data ($SE = SD/\sqrt{n}$).

Statistically, there was a positive relationship between altitude and the change in eroded area recorded within 50 m, although the variance accounted for by the relationship was very low (F pr 0.092; R^2 3.2). There were no significant relationships between altitude alone and erosion change within 10 m.

The interaction between altitude and erosion change may be affected by other environmental or management factors. Evidence of these influences are discussed in the following sections on changes in erosion related to aspect, soil, grazing pressure, vegetation and field site morphology.

Table 7.9 Eroded area and volume measured in 50 m field sites and classified into altitude groups.

Altitude	Area				Volume (10m ³ ha ⁻¹)		
	Number of sites	Total	Mean	SE	Total	Mean	SE
<=200	3	2.81	0.94	0.57	23.4	0.78	0.76
201-300	13	8.52	0.66	0.26	119	0.91	0.44
301-400	19	2.80	0.15	0.08	134	0.71	0.35
401-500	19	5.72	0.30	0.21	191	1.00	0.53
501-600	3	0.79	0.26	0.26	46.1	1.54	1.24
601-700	2	0.09	0.05	0.04	19.99	1.00	0.94

7.4.4.2 Slope

Changes in both eroded area and volume increased with slope at very low angles (up to 7° for volume and 11° for area), before decreasing (Figure 7.6 and Table 7.10). On slopes steeper than 15°, the mean increase in erosion extent rose sharply again. Statistically, there were no significant relationships between slope alone and either 10 m or 50 m erosion change. Interactions between slope and other environmental factors did result in significant relationships: these are discussed in the following relevant sections.

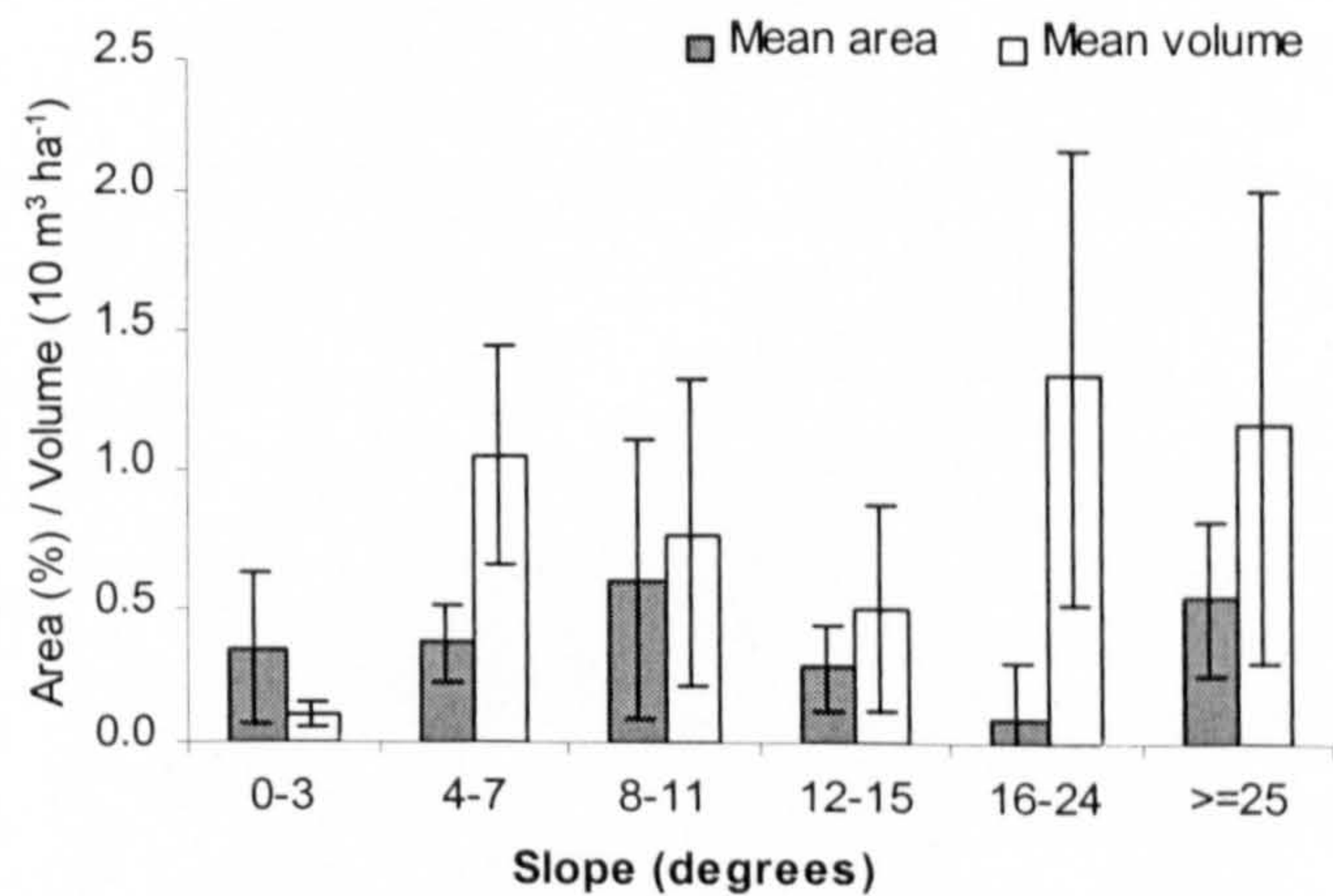


Figure 7.6 Changes in erosion measured on 50 m field sites and classified according to field site slope. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

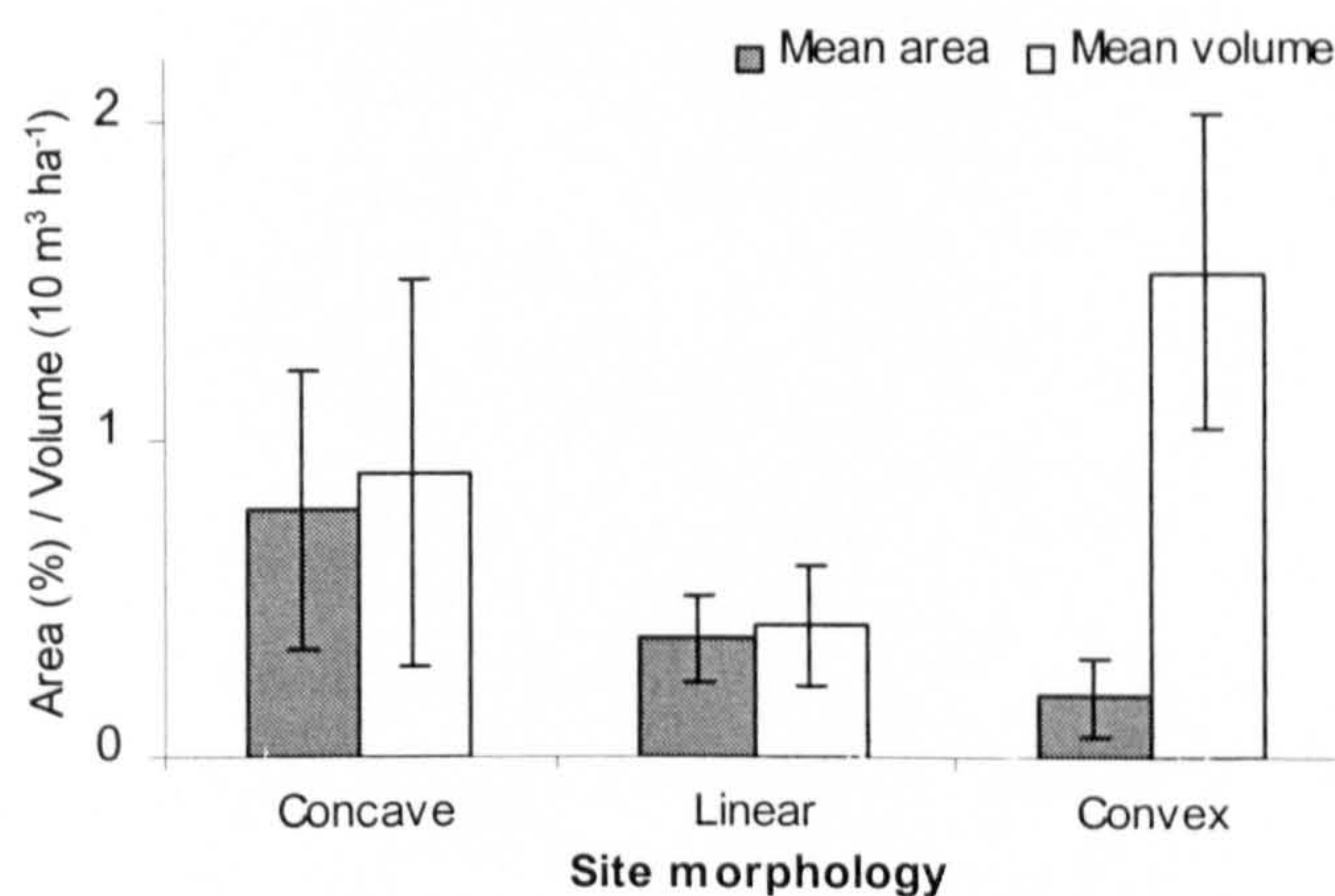
Table 7.10 Summary of the number of sites and extent of erosion change recorded within slope groups

Slope	Area %				Volume (10m ³ ha ⁻¹)		
	Number of sites	Total	Mean	SE	Total	Mean	SE
0-3°	7	2.43	0.35	0.28	7.26	0.10	0.04
3-7°	24	8.87	0.37	0.14	252	1.05	0.39
8-11°	7	4.15	0.59	0.51	53.41	0.76	0.55
12-15°	6	1.68	0.28	0.16	29.83	0.50	0.37
16-24°	10	0.93	0.09	0.21	133	1.33	0.82
>24°	5	2.67	0.53	0.28	57.38	1.15	0.86

7.4.4.3 Field site morphology

Figure 7.7 shows the relationship between field site morphology and the change in erosion recorded between survey years on 50 m sites. The greatest total change in erosion area occurred on linear field sites, although a larger mean increase in area was measured on concave sites.

The biggest increases in total and mean eroded volume occurred on convex sites where the total increase was more than double that recorded on linear sites. This was in spite of the greater number of linear sites with increased erosion (29 compared with 23; Table 7.11).

**Figure 7.7** Change in erosion within 50 m field sites, and site morphology. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).**Table 7.11** Increases in eroded area and volume, recorded on 50 m field sites of different morphology.

Morphology	Area %				Volume (10 m ³ ha ⁻¹)		
	Number of sites	Total	Mean	SE	Total	Mean	SE
Concave	7	5.45	0.78	0.44	62.82	0.90	0.61
Linear	29	10.91	0.37	0.14	119.12	0.41	0.19
Convex	23	4.37	0.19	0.12	351.45	1.53	0.50

In the statistical analyses the only significant relationship was in ANOVA between 50 m change in eroded volume and field site morphology (F pr 0.034). No significant differences were identified between erosion change on different site morphologies, however. Other statistical tests failed to identify relationships between site morphology in combination with other environmental variables and changes in soil erosion between 1997 and 1999. Appendix 4 (Tables VI and VII) summarises results from the range of statistical analyses completed.

7.4.4.4 Soil classes and changes in erosion extent

In Figure 7.8, the increases in erosion recorded within 50 m were related to the soil classes on which sites were located. The greatest increases in erosion area occurred on wet peaty mineral soils, while volume increases were highest on wet mineral soils. The smallest areal and volumetric changes in erosion were recorded on peat soils, even though this soil class had the second-largest number of sites on which erosion change was recorded, after wet peaty mineral soils (Table 7.12).

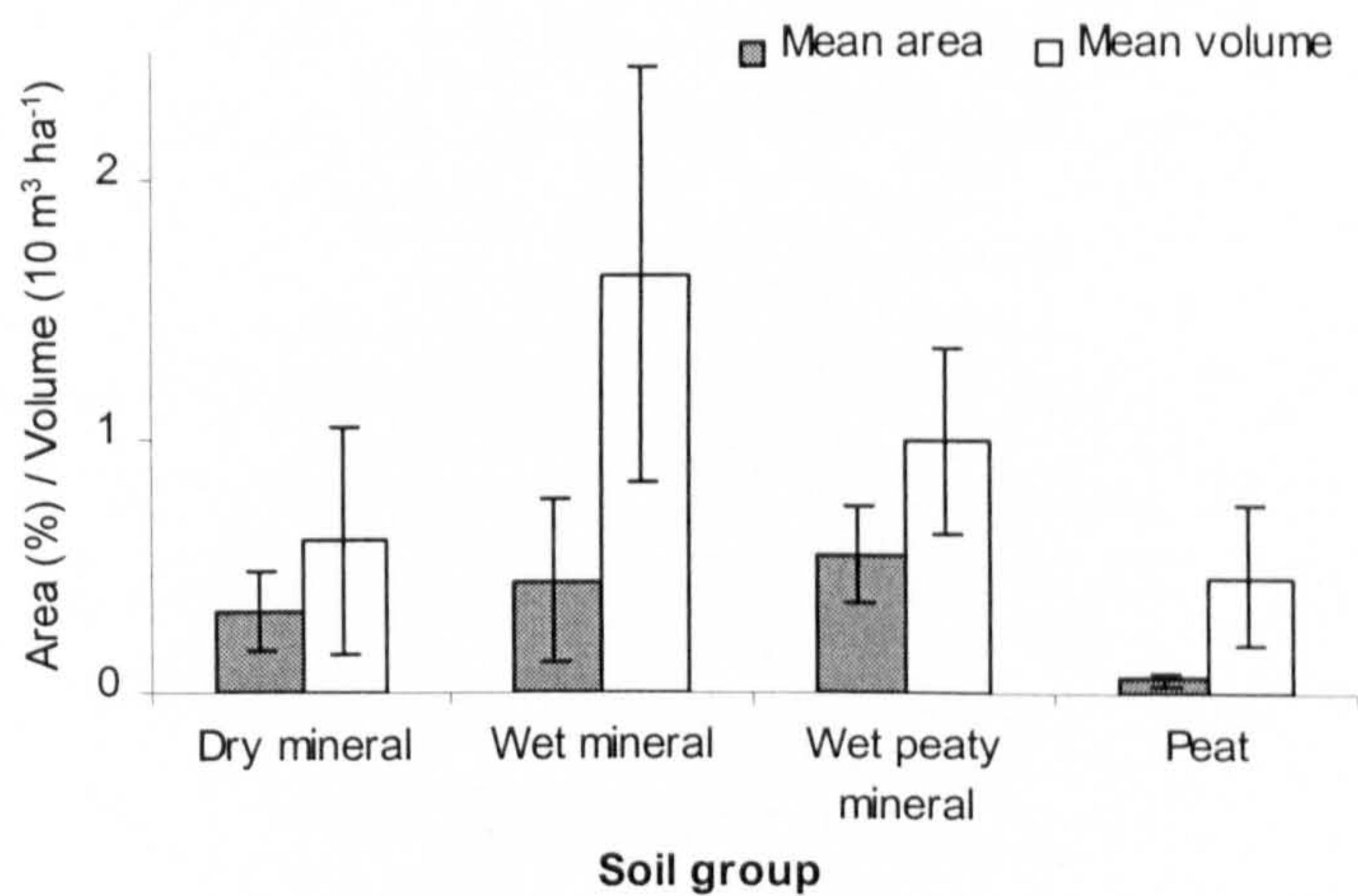


Figure 7.8 Mean increases in erosion area and volume, recorded on 50 m field sites between 1997 and 1999, and grouped into soil classes. Error bars represent standard error of the data (SE = SD/ \sqrt{n}).

Table 7.12 Changes in erosion recorded on 50 m field sites on different soil classes.

Soil	Area %				Volume (10 m³ ha⁻¹)		
	Number of sites	Sum	Mean	SE	Sum	Mean	SE
Dry mineral	10	3.3	0.33	0.16	60	0.60	0.44
Wet mineral	12	5.22	0.44	0.32	195	1.63	0.81
Wet peaty mineral	21	11.34	0.54	0.19	205	0.98	0.36
Peat	16	0.87	0.05	0.03	73.23	0.46	0.26

In the statistical analyses, ANOVA identified a significant relationship between soil and 50 m eroded area (F pr 0.058). Significant differences were identified between the mean erosion change on peat soils and the other three soils classes. Mean erosion was greatest on wet mineral soils and was progressively less in wet peaty mineral, dry mineral and peat soil classes.

Significant parallel regressions with erosion change were also identified when soil class was combined with slope. The greatest mean eroded area occurred on wet peaty mineral soils, while the largest mean eroded volume was measured on wet mineral soils. In addition, a multiple linear regression with groups (MLRG) identified a significant parallel relationship between change in eroded volume and soil class, with the greatest change in mean volume recorded on wet mineral soils. The results from all statistical analyses completed on 50 m data are presented in Table VII (Appendix 4).

Statistically, a single significant, nonparallel relationship existed between 10 m eroded volume and soil class combined with altitude (F pr 0.092; R^2 39.5). Wet mineral soils were established as the most prone to erosion change.

7.4.4.5 Vegetation

As described in Chapter 3, field sites were categorised, using the principal vegetation types found on the field site, into one of six classes. These ranged from scrub and bracken covered slopes to blanket bog, and encompassed the range of grassland and moorland communities.

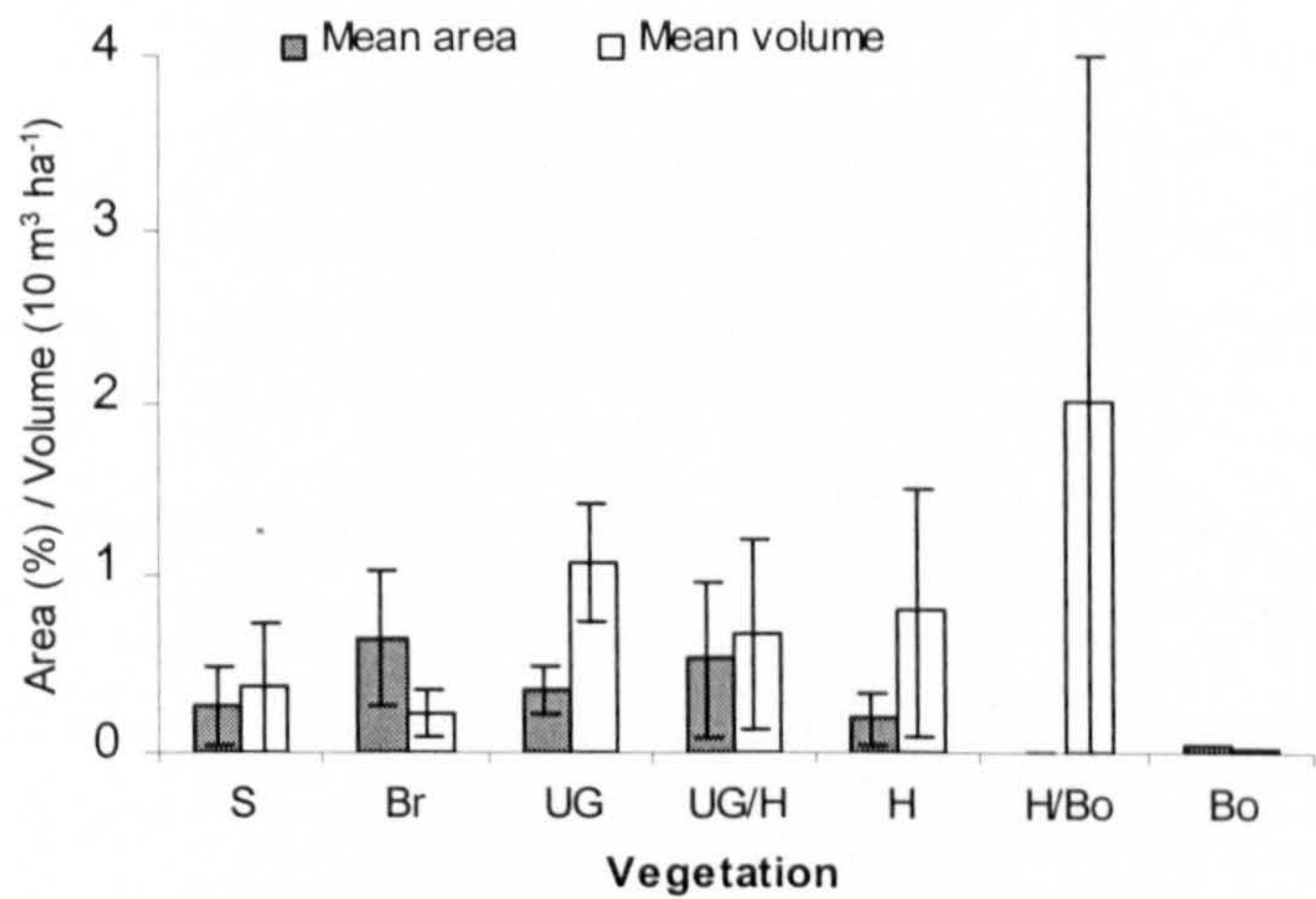


Figure 7.9 Changes in erosion recorded on 50 m field sites, and grouped according to vegetation. Descriptions of abbreviated vegetation communities are provided in Table 7.13. Error bars represent standard error of the data ($SE = SD / \sqrt{n}$).

In Figure 7.9, changes in erosion volume was obviously greatest on sites with a mixture of heath and bog vegetation, although the increase in eroded area on sites with this vegetation, at 0.01%, was too small to be clearly represented. The next largest mean increase in volume was measured on upland grassland sites. This vegetation group also experienced the greatest number of sites with changed erosion between 1997 and 1999 (Table 7.13).

Table 7.13 Site details for the increase in erosion recorded within 50 m between 1997 and 1999.

Vegetation			Area %			Volume (10 m ³ ha ⁻¹)		
Name	Abbrev.	Number of sites	Total	Mean	SE	Total	Mean	SE
Scrub	S	2	0.54	0.27	0.23	7.46	0.37	0.37
Bracken	Br	4	2.58	0.65	0.38	8.65	0.22	0.13
Grassland	UG	33	11.57	0.35	0.13	352	1.07	0.33
Grass / heath	UG/H	8	4.24	0.53	0.44	53.57	0.67	0.53
Heath	H	9	1.74	0.19	0.14	71.63	0.80	0.70
Heath / Bog	H/Bo	2	0.01	0.01	0.01	40.08	2.00	1.99
Bog	Bo	1	0.05	0.05	0.00	0.25	0.03	0.00

Statistically, the vegetation on each field site was repeatedly related to erosion changes recorded within both 50 m and 10 m field sites. In simple linear regression with groups, slope and vegetation were related to changes in both eroded area and volume. The non-parallel regression (F pr 0.021; R² 12.1) established that heath/bog mixed vegetation and bog vegetation alone were most prone to changes in erosion volume over the survey period. The same communities were also most susceptible to changes in eroded area over the survey period (F pr 0.073; R² 6.2).

Multiple linear regression within groups linked slope and altitude with vegetation in a significant, non-parallel relationship with change in 50 m eroded volume (F pr 0.097; R² 6.9). Heath/bog and bog vegetation were equally susceptible to continued erosion.

ANOVA also recognised a significant relationship between vegetation and change in 50 m erosion, but failed to identify significant differences between changes on different vegetation communities. A summary of these statistical results, as well as those for additional non-significant tests, is provided in Table VII (Appendix 4) .

The same statistical tests were carried out using the dataset for changes in erosion recorded on 10 m sites and site vegetation. While ANOVA did not identify a significant relationship between erosion change and vegetation alone, linear

regressions of vegetation in combination with slope illustrated significant links between vegetation and erosion change. With slope, vegetation was related to eroded area and volume at F pr of 0.038 and 0.002. The variances accounted for by both of these relationships were high, with R^2 values of 41.1 and 78.2 respectively. In both, mixed upland grass and heath vegetation was the most prone to erosion.

Regressions of vegetation, in combination with slope and altitude, and changes in erosion on 10 m sites were also significant (F pr 0.003 (area) and 0.004 (volume)). The associated R^2 values were also high at 83.2 and 77.1% respectively. In these analyses, upland grassland vegetation was established as the community most prone to increases in eroded area and volume, while heath was the community least likely to experience further erosion.

7.4.4.6 Aspect

The changes in erosion measured on 50 m field sites between 1997 and 1999 were also related to field site aspect (Figure 7.10). The greatest increases in eroded volume occurred on E and S-facing sites, while the greatest changes in eroded area were on W and NW-facing sites. There was little other variation in this figure, which suggests that site aspect did not influence increases in erosion extent. Similarly, in Table 7.14, it can be seen that the aspects on which most sites continued to erode were S-facing and N-facing. This makes the likelihood of an interaction between erosion and aspect further unlikely.

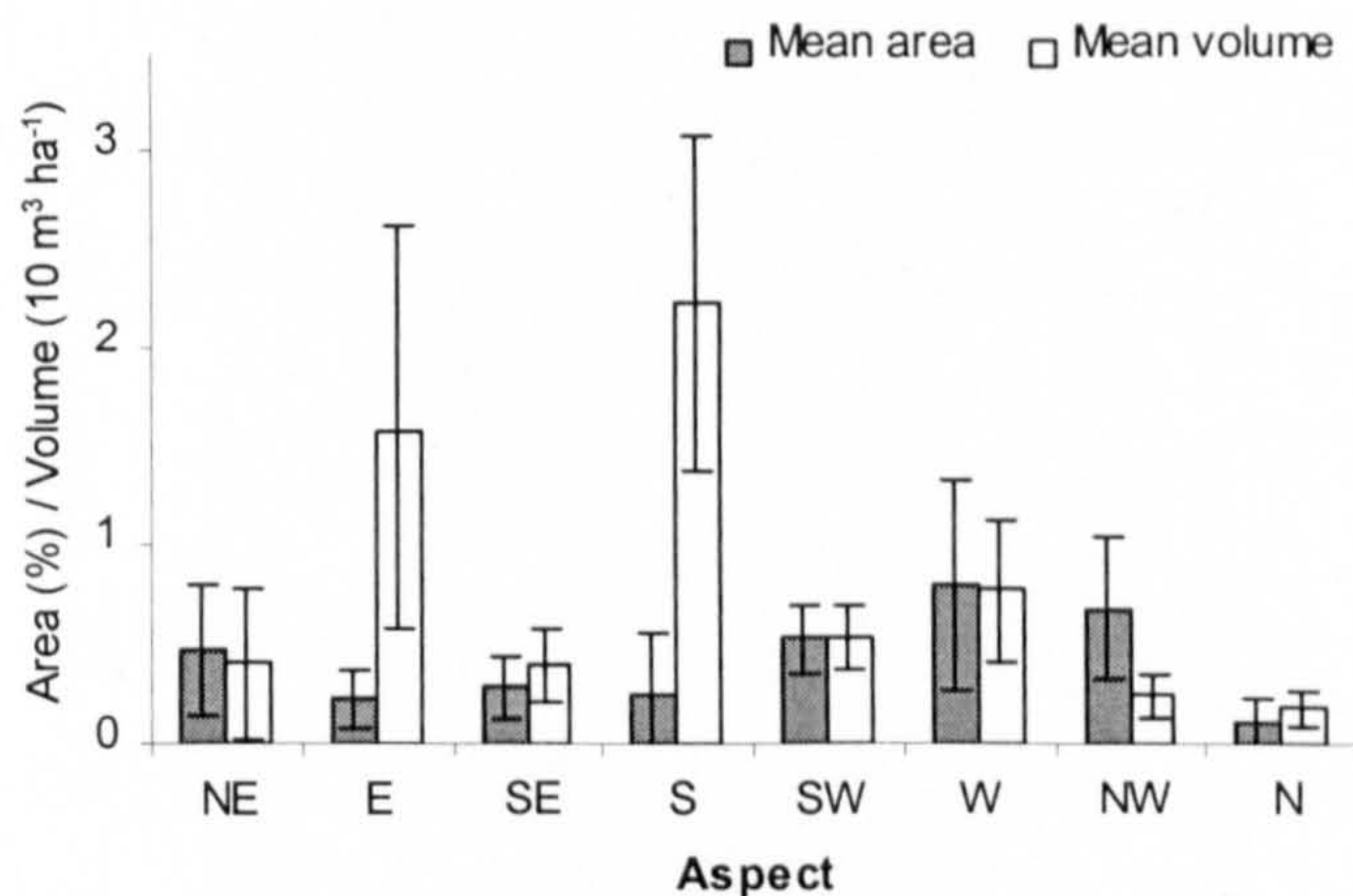


Figure 7.10 Changes in erosion area and extent on field sites of different aspect: all records were made between 1997 and 1999. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

Table 7.14 Field site aspect and change in eroded area and volume recorded within 50 m field sites between 1997 and 1999.

Aspect	Area %				Volume (10 m ³ ha ⁻¹)		
	Number of sites	Total	Mean	SE	Total	Mean	SE
NE	6	2.82	0.47	0.33	24.19	0.40	0.38
E	7	1.59	0.23	0.13	112	1.60	1.01
SE	5	1.38	0.28	0.16	19.55	0.39	0.20
S	12	2.85	0.24	0.31	267	2.23	0.84
SW	6	3.18	0.53	0.17	32.09	0.53	0.16
W	6	4.81	0.80	0.53	46.54	0.78	0.35
NW	4	2.75	0.69	0.36	9.50	0.24	0.12
N	12	1.34	0.11	0.11	21.92	0.18	0.09
Level	1	0.01	0.01	0.00	0.64	0.06	0.00

Within 10 m also (12 field sites only), there was no evidence of a distinct trend between erosion and aspect. The statistical analyses also failed to identify any significant relationships between 10 m or 50 m erosion change and aspect.

7.4.4.7 Grazing pressure

The changes in erosion that occurred under conditions of varying grazing intensity are illustrated in Figure 7.11 and summarised in Table 7.15. While the mean change in area increased slightly with grazing pressure, mean eroded volume behaved in the opposite way. There were greater numbers of eroded sites at the interim grazing intensities of 2 and 3 (described in Section 3.3.3). No field sites with grazing at level 5 showed signs of continued erosion between 1997 and 1999.

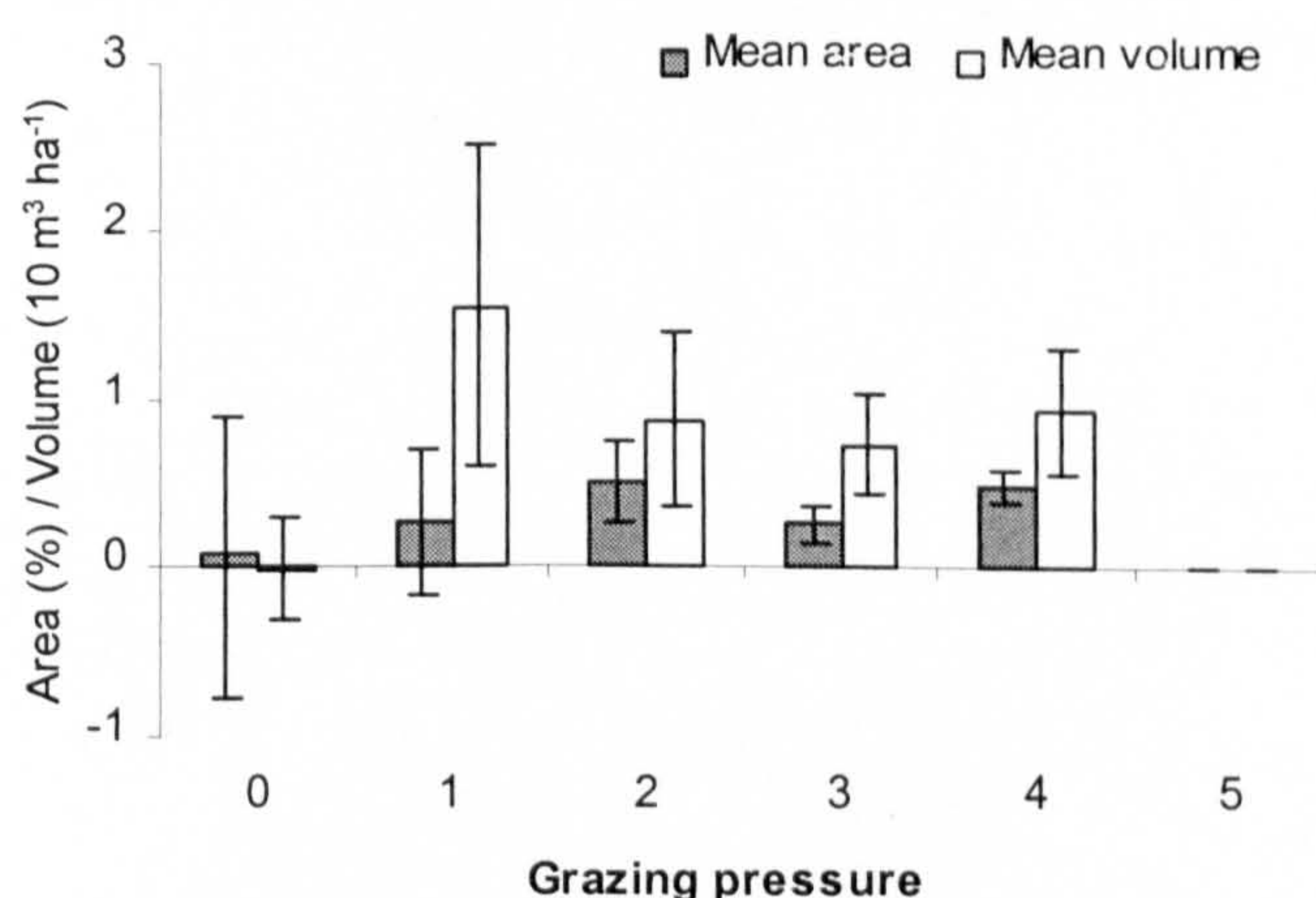
**Figure 7.11** Change in erosion area and volume recorded between 1997 and 1999 within 50 m sites and grouped using grazing pressure. Error bars represent standard error of the data ($SE = SD/\sqrt{n}$).

Table 7.15 Total and mean erosion change recorded within 50 m between 1997 and 1999

Grazing	Area %				Volume (10 m ³ ha ⁻¹)		
	Number of sites	Total	Mean	SE	Total	Mean	SE
0	2	0.12	0.06	0.83	-0.41	-0.02	0.30
1	9	2.36	0.26	0.43	140	1.56	0.96
2	14	6.96	0.50	0.25	123	0.88	0.53
3	22	5.54	0.25	0.10	159	0.72	0.30
4	12	5.75	0.48	0.11	112	0.93	0.37

Statistical analysis was completed here as with the other erosion change datasets. There were no individual significant relationships between change in erosion and grazing pressure within either 10 m or 50 m field sites. In addition, combinations of grazing pressure with altitude and slope also failed to significantly effect erosion. It was therefore reasonable to assume that, from this data, there was no obvious relationship between continued soil degradation and grazing pressure measured in the field. As grazing animals and humans were the principal causes of continued soil erosion (Section 7.3) this suggests an inadequacy in this dataset that may derive from the small number of field sites available for analysis. Alternatively, it may be a symptom of the method for evaluating grazing pressure: this is discussed further in Section 7.6. Finally, it is possible that grazing pressure influences on erosion prior to 1997 ceased between 1997 and 1999: this is disproved, however, in the next section.

7.4.5 Changes in erosion linked to cause

The causes of erosion identified at each field site, as described in Section 7.4, were linked to the changes in erosion extent over the survey period to allow the principal mechanisms of erosion change to be identified.

In total, erosion increased or decreased on 59 field sites (Table 7.8). The mean increase in erosion on each site was 0.35% and 9.04 m³ ha⁻¹: this mean change combined different causes of erosion. In Tables 7.16 and 7.17, field sites have been subdivided into two groups, depending on whether the change in erosion was caused by biotic factors or water. The contributions of the different causes to increased erosion over a two-year period can be clearly seen.

Most erosion that worsened or was newly created between 1997 and 1999 was caused by the actions of humans and animals. Of 59 field sites, increased erosion on 55 sites was classified as biotic. In Table 7.16, the mean area of erosion caused by

animals or humans on all field sites was 0.3511%, equivalent to an area of 27.58 m² on each field site.

In contrast, increased water erosion occurred on only 4 field sites out of 59 and the mean increase in area was correspondingly small at 0.02 m² (Table 7.17). The mean increase in eroded volume caused by water was 0.607 m³, which is equal to 0.77 m³ ha⁻¹. Again, this was far less than the mean increase in soil lost due to biotic activity, at 8.27 m³ ha⁻¹.

Table 7.16 Summary statistics for the change in eroded area and volume caused directly by the activities of humans and animals within 50 m field sites.

Biotic erosion only	Total eroded area (%)	Total eroded volume (m ³)
Mean	0.3511	6.493
Standard Error	0.098	1.782
Median	0.1	0.8
Standard Deviation	0.75	13.69
Sum	20.71	383
Number of sites	59	59

Table 7.17 Summary statistics for the change in eroded area and volume caused by water erosion and recorded within 50 m field sites.

Water erosion only	Total area %	Total volume (m ³)
Mean	0.00027	0.607
Standard Error	0.0002	0.535
Median	0	0
Standard Deviation	0.0015	4.107
Sum	0.016	35.84
Number of sites	59	59

Changes in erosion measured on 10 m field sites over the same period are summarised in Table 7.18. Change was measured on only 12 field sites, and was caused in all instances by human and animal activity. The total increase in erosion, of 16.44% represented a ground area of 51.62 m², while volumetrically, biotic-induced erosion recorded within 10 m removed 1.61 m³ of soil between 1997 and 1999. The low number of 10 m sites resulted in low means of erosion change. On average, each 10 m field site experienced an increase of 0.88 m² in eroded area and of 0.027 m³ in eroded volume.

Table 7.18 Summary details for erosion change measured on 10 m field sites between 1997 and 1999.

All erosion causes	Total area (%)	Total volume (m ³)
Mean	0.279	0.027
Standard Error	0.141	0.036
Median	0	0
Standard Deviation	1.081	0.277
Sum	16.44	1.61
Number of sites	59	59

The distribution of field sites on which biotic and water erosion occurred are shown in Plate 7.6. It was clear from both maps that continued and newly created erosion caused by humans and animals dominated the landscape. The widespread scatter of biotic erosion means that no significantly large area of the uplands avoided erosion of this form.

7.4.6 Rates of increase of biotic and water erosion

Continued erosion occurred on 59 field sites out of a total survey of 399 sites (Table 7.18). This proportion applied to the area of uplands in England and Wales covered by the field survey means 1 475 km² were susceptible to further erosion. On 50 m field sites, the mean increase in eroded area caused by biotic factors was 0.3511%. This is equivalent to 517.87 ha. Of the total increase in erosion recorded between 1997 and 1999 (Section 7.4.3), therefore, 99.9% was due to humans and animals.

Volumetrically, the mean increase in erosion on 50 m sites caused by biotic activity was 6.493 m³, which is equal to 8.267 m³ ha⁻¹. In upland England and Wales, this corresponds to 1 219 382.5 m³ of soil lost between 1997 and 1999.

The increase in eroded area and volume attributed to water causes was calculated similarly, using data from Table 7.17. As only four water-eroded field sites experienced increased erosion, however, the estimated increases in eroded area and volume in upland England and Wales were correspondingly small at 3982.5 m² and 113 996 m³.

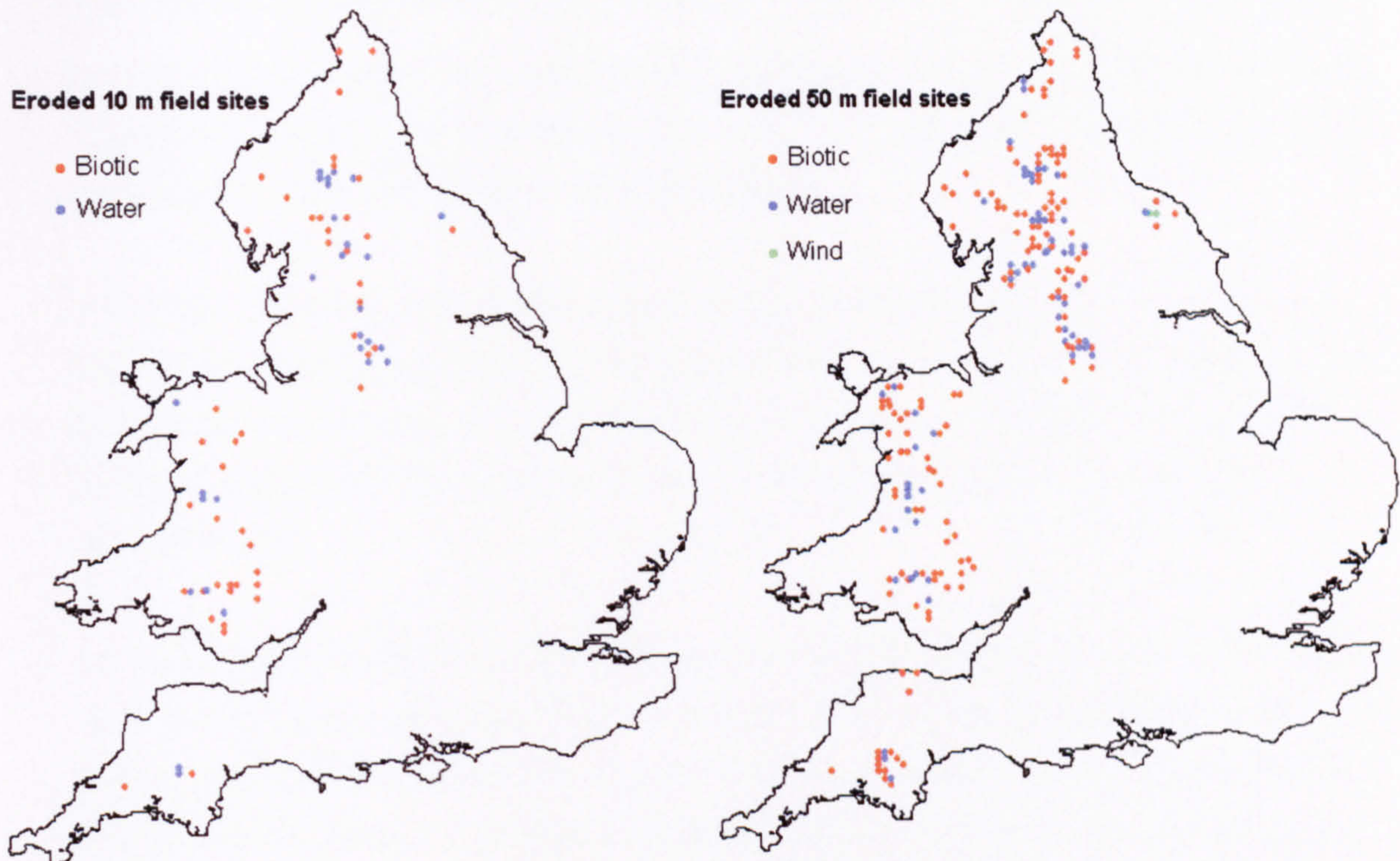


Plate 7.5 The distribution of 10 m and 50 m eroded sites, classified according to erosion cause.

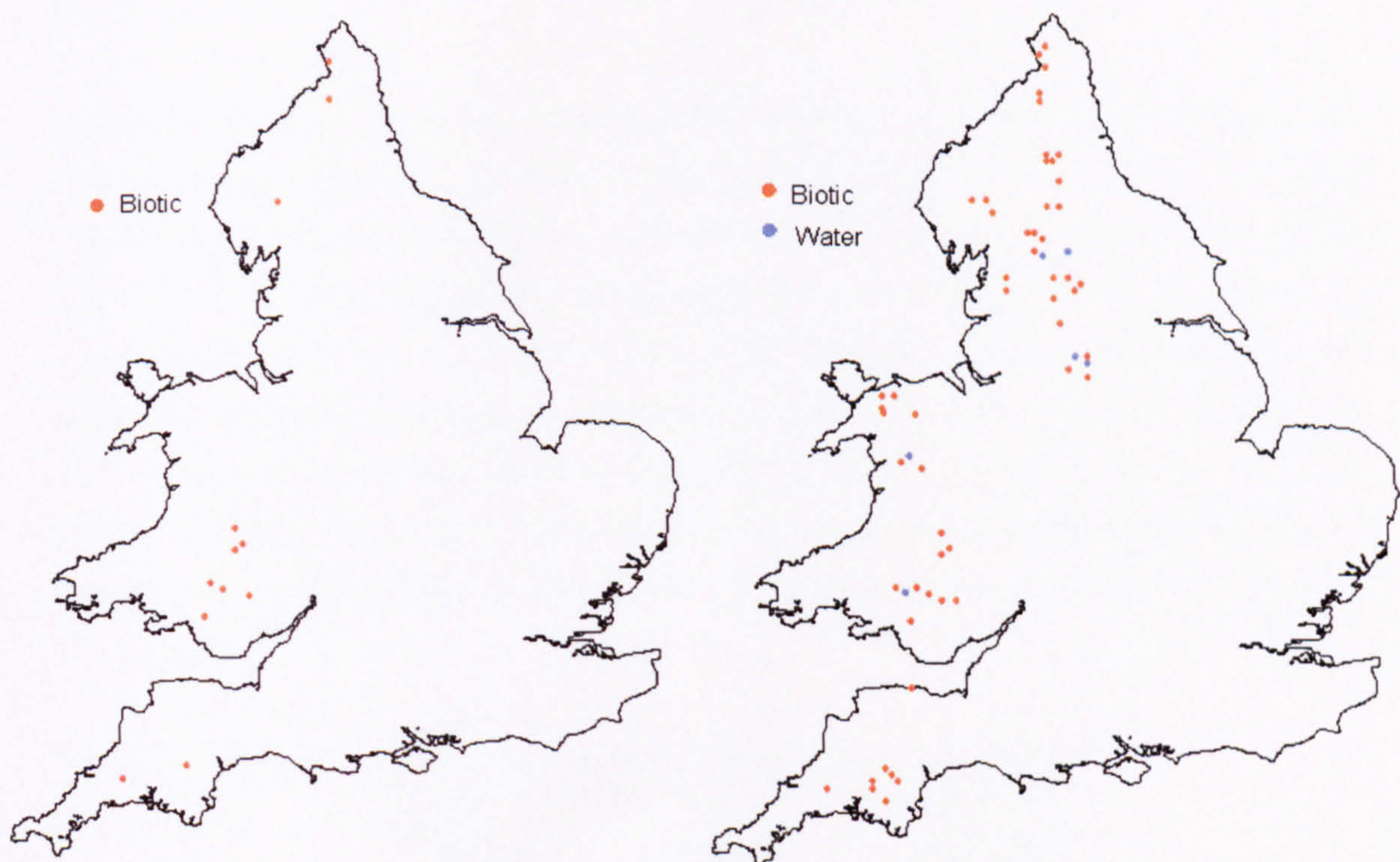


Plate 7.6 Distribution of field sites on which erosion extent changed between 1997 and 1999. Data are shown for biotic eroded 10 m sites (left) and both biotic and water erosion recorded within 50 m (right).

7.5 DISCUSSION

In this chapter, the three fundamental questions of this research have been addressed, based upon the information from the large-scale survey of field sites conducted in 1997 and again in 1999 (Chapter 3).

7.5.1 The influence of field site size on measurements of erosion

The issue of ideal site size, and the possibilities of specific erosion determination from different site sizes, has been addressed in Chapter 3. Here, the discrepancies between values of erosion measured on 10 m field sites and those on 50 m field sites are explained.

Conversions are required to translate eroded volume on both 10 m and 50 m field sites to volume per unit area. The conversion allows direct comparison between the data recorded on the two field sites and facilitates comparison with published data on soil erosion. However, 10 m data is expected to overestimate erosion extent because of the large correction factor required to scale from its small area (0.0314 ha) to a single hectare. The 50 m values also require up-scaling, but here, the correction factor is smaller, as a 50 m field site already represents almost one hectare (0.7854 ha).

Examples of the considerable discrepancies between 10 m and 50 m field site data are presented in Table 7.19. What is clear is that results from the 10 m data, rather than presenting an overestimation of erosion extent, are consistently smaller than those for 50 m data. The most likely explanation for the differences derives from the numbers of eroded 10 m and 50 m field sites. In total, 206 field sites were eroded within 50 m, while there were only 74 eroded 10 m field sites. The larger database is preferable because of its effect on reducing variation. As can be seen in several tables, including Table 7.2, the standard deviation of data is consistently less for 50 m data than for 10 m data. From this, it is more reasonable to adopt results from the 50 m dataset.

Table 7.19 Comparison of erosion extent measured on 10 m and 50 m field sites

	10 m	50 m
Total area	16 705.5 ha	24 565.5 ha
Total volume	0.108 km ³	0.284 km ³
Bare area	10 822 ha	12 463 ha
Vegetated area	5883 ha	12 102.5 ha

The discrepancies between records made on different site sizes also raises the issue of the ideal site size for erosion surveys. Obviously, a field survey that requires the least scaling-up to unit area is preferable, and it is suggested that future erosion work should concentrate on field sites of at least one hectare. Field sites greater than this may have the added advantage of allowing data to be scaled down and would also include regions of soil deposition as well as of erosion, thus helping sediment delivery to streams to be determined.

7.5.2 Extent of erosion

Overall, the extent of erosion, quantified within upland England and Wales using 50 m field data, was 24 565.5 ha. In total, the volume of soil lost from the uplands equals 0.284 km³. This eroded area represents 2.46% of the total upland area surveyed in 1999. Unfortunately, there are no published estimates of erosion extent with which these values can be compared. Previous works on erosion extent have either been more localised (Phillips *et al.*, 1981), or have determined the relative importance of different erosion features within an area (Grieve *et al.*, 1994). There has been considerable research into erosion on agricultural land (Boardman *et al.*, 1990; Boardman, 1994; Evans, 1996). Although Evans (1990a) implied that no upland soil associations were at very high risk of erosion, no attempt has been made to determine the actual extent of erosion within upland England and Wales.

Of the total extent of erosion measured, bare and vegetated eroded ground accounted for almost equal areas, at 12 463 ha and 12 102.5 ha respectively. Again, these values were obtained from the 50 m field survey.

7.5.3 Distribution of erosion within the uplands

From both 10 m and 50 m data, it was clear that eroded sites were concentrated along the length of the Pennines. Within the Pennine range, erosion was particularly predominant in the Peak District and in Teesdale and Weardale. Erosion was not confined to these regions, however: eroded field sites in smaller numbers occurred in South, Mid and North Wales, in SW England and in the Lake District. No significant part of the uplands escaped erosion, although there were fewer eroded field sites within the North York Moors or the Cheviots.

It is clear that the most intense erosion occurred where peat was the predominant soil cover and where, certainly in the case of the Peak District, recreational pressure

is concentrated. Occupying an area of 1,436 km², The North York Moors receive approximately 7.8 million visits each year (North York Moors National Park, 2000). This figure is almost certainly surpassed by the numbers visiting the Peak District, which at 1 438 km², is almost identical in area but is within 60 miles of 17 million people (Peak District National Park, 2000).

In addition to these factors, the Peak District is situated at the heart of the former industrial centre of Britain. There, erosion has been attributed to several causes, including the retreat of endotelmic streams, variable climatic conditions such as the Little Climatic optimum (1150-1300 AD), sheep grazing, grouse rearing and air pollution (Tallis, 1994). While current agricultural intensity may be assumed reasonably uniform throughout the uplands today, this may not have been so in the past. Due to its positioning between high populations, it is also reasonable to assume that, historically, land pressures in the Peak District have exceeded those experienced elsewhere in the uplands. In combination, these factors may be responsible for the current pronounced erosion extent measured in this region.

Erosion in Weardale and Teesdale in the North Pennines is more difficult to explain as, until recently, recreational use has been slight and the degree of industrialisation was also limited. However, in common with the Peak District, these are landscapes dominated by blanket peat, the degradation of which may be similarly attributed to stream retreat, changes in climate and landuse practices.

Erosion was also marked where peat is not pervasive but where recreation is an important landuse. In contrast, regions that largely escaped extensive erosion are associated with low amenity use. There is therefore a link between the current and historical intensity of upland use and the contemporary extent of erosion. Recreational pressure on Dartmoor may exceed that on the Cheviots or in the North York Moors although these latter regions also experience peak influxes of both summer and winter visitors. On Dartmoor, the pressures of recreation and agriculture are added to by the military presence on the moors. While recreational pressure certainly plays a role in determining erosion extent, management practices may also influence the extent, or lack, of erosion measured there. Causes of degradation in different regions are discussed in the next section.

7.5.4 Causes of erosion

Analysis of the causes of erosion showed that, in 1999, water erosion accounted for greater volumes and areas of erosion than either biotic factors or wind (Section 7.3.4). Wind erosion was identified on only two out of 399 field sites, and was not an important factor in the uplands. While biotic erosion lacked the extent of water-induced degradation, it nonetheless occurred on a greater number of field sites. This is particularly relevant when the changes in erosion between 1997 and 1999 are discussed.

Illustrations of erosion distribution revealed that, in the Lake District, Dartmoor and Snowdon National Parks, in the NE Pennines (Wolsingham area) and the Cheviot Hills, erosion was almost exclusively due to humans and animals. In the Peak District and other regions where water erosion was dominant, human erosion was present but not marked. This result may reflect human pressure in previously and naturally uneroded areas. In regions predisposed to water erosion such as the Peak District and NW Pennines, the effects of humans are not pronounced. Where water erosion is not an important issue, however, biotic degradation is the dominant form of erosion. This suggests that the high incidence and generally large areas of water erosion may exhibit a masking effect over other erosion forms, and may effectively reduce the areas of damage due to other factors.

These results have highlighted the fact that in areas of peat degradation, it is easy to miss or to negate the effects of humans in favour of the overwhelming evidence of water erosion. However, in places where water erosion does not mask the dominance of biotic erosion, it is clear that widespread erosion may be attributed to the activities of humans and animals in the uplands. The effects of humans, and in particular grazing sheep, are not confined to the eroded regions mentioned above. It may be assumed, therefore, that their effects are present, if not obvious, throughout the remainder of the uplands, and that, as a cause of erosion and in particular of erosion in recent times, they are more important than water.

7.5.5 Changes in erosion between 1997 and 1999

Overall, erosion increased by 518.32 ha between 1997 and 1999. In the same period, 1 333 397 m³ of soil were lost from 50 m field sites. Biotic factors were responsible for 99.9% of the increase in eroded area and 91.4% of the increased volume of soil lost.

In spite of the large area of land it covers, water erosion increased in extent by less than half a hectare between 1997 and 1999. Volumetrically, however, it increased by an estimated 113 996 m³ on only four field sites while biotic erosion, which had increased on 55 field sites, was responsible for an increase of 1 219 383 m³. Continued water erosion therefore accounts for a relatively greater proportion of soil loss than biotic erosion.

In terms of its areal coverage peat erosion represents an extensive and long-established but relatively inactive form of erosion when compared with biotic erosion, which is developing as a small-scale but insidious feature. Currently, the areal extent of biotic erosion is considerably less than that of water erosion: at the current rate of development, however, it could equal the area of water erosion within 70 years.

Volumetrically, soil was lost to biotic erosion at a rate over ten times that of water erosion in spite of the small and localised nature of typical biotic erosion. Again, this reflects the stabilised nature of water erosion, much of which is peat degradation, and highlights the importance of continued erosion initiated by grazing animals and humans.

7.6 CONCLUSIONS

As a first assessment of erosion extent in the uplands of England and Wales, the 1997 and 1999 field surveys represent a statistically robust baseline studies of soil degradation.

An ideal field site size on which erosion surveys should be based has not been established. There is an argument however for the use of sites of at least one hectare, if not greater: a circular site of one hectare area would extend to almost 60 m radius. The extra area of coverage would generate more comprehensive measurements of the erosion and deposition cycle, and facilitate improved derivations of regional and national erosion extents. An amendment to field site size, however, does not require alteration to the sampling strategy outlined in Chapter 3. As stated above, the systematic way in which the work was conducted has ensured this reliable and objective assessment of erosion extent within England and Wales.

This chapter confirms that upland erosion in England and Wales is most severe on peat soils and that their degradation accounts for a huge total area and volume of

degraded soil. The progression of biotic erosion is confirmation, however, of a widely held but, until now, unproven belief that contemporary upland erosion is attributable to the activities of humans and animals. The rate of this increase, established from a statistically robust sample of 399 field sites, suggests that within a single century, the extent of biotic erosion could equal, if not exceed, that of peat erosion. Currently, agricultural and recreational uses of the uplands show little signs of abating and instead may be intensifying. It is therefore expected that this rate of erosion will increase unless effective measures are taken to control the forces driving erosion processes.

The study also revealed that most water erosion is not actively eroding at a rate that was observable over the two-year survey period and therefore cannot be compared with that of biotic erosion.

Future research is required to distinguish the different forms of biotic erosion and to determine the contributions of grazing animals, farmers, hunters, recreational upland users and others to erosion extent. Until then, however, this study has highlighted a disturbing rate of erosion attributed to the general group. Immediate intervention is suggested to minimise the further creation of scars, tracks, footpaths and poached areas within the uplands.

Chapter 8

Discussion and conclusions

8.1 INTRODUCTION

This thesis has described fundamental research into the extent and causes of upland soil erosion in England and Wales. Here, the results from this study are interpreted in terms of their assessment of the current condition of the upland environment and their implications for its continued management of that environment. The advantages and disadvantages of the different methodologies used are also determined. Finally, proposals are made for continued research into upland erosion and for the remediation of existing degraded soil within the uplands.

8.2 RESULTS IN BRIEF

This research sought to answer three questions about soil erosion in the uplands:

- What is the extent of eroded soil?
- What has caused the erosion?
- At what rate is erosion progressing?

In total, nearly 25 000 ha, or 2.58%, of the uplands of England and Wales was estimated to be currently eroded. Almost 50% of the total area of eroded ground has revegetated: the balance remains as bare soil exposed to the elements. The total volume of soil currently eroded from the uplands is 0.284 km³.

The greatest area and volume of erosion, at 72% of the total, is due to water erosion of, principally, blanket peat. Biotic erosion, however, was the single greatest contributor to erosion initiation and exacerbation between 1946 and 1989. In contrast, and over the same period, the majority of over 700 observations of peat erosion indicated no continued erosion or erosion revegetation.

Between 1997 and 1999, erosion was estimated to increase by over 500 ha and by 0.0011 km³. Biotic factors were responsible for 99.9% of this increase. At this rate, the extent of biotic erosion will equal that of water erosion within a century.

8.3 RESULTS IN DETAIL

Information on upland erosion was gathered in several different ways in this research, as summarised in the following.

8.3.1 Field survey

The extent of degraded soil, causes of erosion and the degree of erosion revegetation were determined through repeated visits to 399 field sites located throughout upland England and Wales. The presence of erosion was related to various environmental and management features of the field sites.

Soil erosion was most prevalent on peat soils and on wet mineral soils, on field sites located at high altitudes and on gentle slopes. Of the total extent of erosion, erosion that remained unvegetated was principally due to biotic factors.

Grazing pressure as quantified in this work showed no relation to erosion, in spite of numerous previous studies that have conclusively linked the two processes. As the survey was based upon a statistically robust sampling period and sample size, it was therefore concluded that grazing pressure was an insufficiently assessed parameter in this work. A more comprehensive assessment, where indicators of recent and historical grazing pressures are based upon vegetation susceptibility, current sward height and evidence of dunging (Welch, 1984a and b) is required.

Within the field survey, erosion was measured within circles of 10 m and 50 m radius. Comparisons of data from the field sites revealed that erosion measurements from the 50 m dataset were the more statistically significant. However, in terms of the forms of erosion, each field site size had its advantages. In particular, 10 m field sites were adequate for the measurement of large-scale water erosion, while 50 m field sites were better adapted to records of the individually smaller and more irregularly scattered biotic erosion features.

The field survey represented a first attempt at the systematic assessment of upland erosion over both England and Wales, and provided the basis for much of the information contained in this thesis. As an exercise it was logistically challenging: it

required prolonged periods in often difficult terrain and adverse weather conditions. However, the many advantages of the work compensated for these difficulties.

Importantly, the survey was both extensive and statistically sound: it did not rely on subjective choices of field site locations or size. The objectivity of the work was compromised, however, in the initial field survey, in which additional surveyors were recruited to aid progress. Then, the field protocol relied upon an estimate of erosion extent for the field site (Appendix 2). Subsequent comparison of field sheets revealed that erosion extents assessed on the same field site varied by as much as an order of magnitude. Immediately, the protocol was amended so that later surveys, and the remainder of the 1997 survey, entailed the dimensional recording of individual erosion features, and thus eliminated surveyor bias (Appendix 3).

A further advantage of the field protocol was that it objectively sampled a representative population. Current research indicates that, for surveys of many soil mineral elements, sampling on a 10 km grid sufficiently reflects regional variation (Scholz *et al.*, 1998). There is confidence, therefore, that this also applies to soil processes and that the upland environment was adequately represented by the field survey.

Degraded soil was prevalent on vulnerable peat soils and under heath and bog vegetation, which are both sensitive to disturbance and both aesthetically and economically valuable. As it is essential to prevent further soil disruption and loss from these areas, there is obviously a need for the protection of this vegetation and for the remediation of currently eroded areas.

8.4.2 Traverses

Traverses were detailed measurements completed across eroded linear gullies to determine rates of soil loss or revegetation over the period of the field survey. Overall, it was clear that two years presented an insufficient period over which to detect statistically significant changes in gully erosion. Nonetheless, it was possible to determine trends in gully erosion.

Rates of erosion were greater when traverses, and hence gullies, were located at higher altitudes, on steep slopes, on convex slopes, on peat or wet mineral soils or

under heather or bog vegetation communities. Erosion rates were, therefore, greater under wetter conditions, whether they resulted from higher precipitation, greater runoff or from the inherent wetness of the soil.

Within gullies, mean erosion was also assessed on different gully substrata. Soil loss was greatest at the lichen-covered overhanging edge, which was unsupported due to the erosion of soil from the gully wall. Overall decreases in gully depth were recorded on surfaces that were prone to redeposition of material, such as on fine earth and redeposited peat substrata.

Finally, differences in rates of soil loss were established for different facets of the gully cross-section. The gully wall experienced a mean increase in depth, corresponding to continued erosion, over the survey period. The greatest changes in depth, however, were negative and occurred on the gully floor. There was no appreciable change in depth at the gully footslope.

Overall, the traverse procedure was successful in all its aspects. As a previously untried basis for relocating field sites for measurement repetition, galvanised nails, which were buried at the traverse ends and found using a metal detector and careful photography, were economical, easily transported, positioned and relocated, and were unobtrusive. They are fully endorsed, therefore, for future work in which it is similarly essential to fulfil those criteria. Erosion pins, in comparison, are obvious, may be tampered with and sometimes move within the soil they are buried in (Bridges and Harding, 1971). While nails may not be used as markers of the movement of soil over time, they are the better way to mark the location of measurements for future visits.

The traverse procedure itself was also a novel approach to the problem of objectively measuring erosion within specific, randomly-distributed areas. Recommendations for improvements to the process refer only to the traverse technique. As the results indicate the need to complete traverses over a longer time period, it is essential that traverse details are rigorously recorded and photographed. Experience has shown that the most useful relocation photographs are those taken from the start point and that overlook the entire traverse, as in Plate 8.1. In such photos, vegetation on both gully banks are recorded as extra aids to relocation.

In addition, a larger database would be advantageous. In this study, traverses were limited by the need for objectivity, and were situated only on eroded field sites. Now that it has been proven as a reliable and useful field research tool, the traverse procedure could be adopted to investigate the rates of soil loss within any gullies not located within NSI or CS2000 field sites. Traverses could also be located subjectively to allow information on soil loss and deposition within different hillslope or catchment regions to be determined.

The erosion of stream and riverbanks and beds could also be determined using the same procedure. The technique is limited by depth, however, as, with increasing depth, vertical measurements are difficult to achieve accurately and have larger experimental errors.

8.3.3 Erosion and sub-catchment morphology

This study was completed to determine if the area of land that contributed hydrologically to individual field sites also influenced field site erosion. OS maps were used to describe the shape, aspect and length of field site sub-catchments.

Results indicated a threshold effect of the sub-catchment length on the extent of erosion. With increasing distance to the watershed, the extent of erosion declined. Similarly, there was less erosion above a threshold slope angle of 7-11°. It was not possible to link field site erosion to sub-catchment morphology, but there was clearly greater erosion on S and SW-facing sub-catchments.

Overall, it was clear that examining the link between erosion and the sub-catchment was a valuable exercise, which shed light onto the relationship between erosion and environment. Its completion through the interpretation of OS maps, however, was not optimal. Important information, such as that on soils and vegetation, was not available as the sub-catchments were very small and it was not possible to derive robust soils information from the 1:250 000 Soil Maps of England and Wales (Mackney *et al.*, 1983). Details on inherent landscape variation were also not available directly from OS maps, and descriptions of sub-catchments therefore reflected gross morphology only.

It is suggested that to link the incidence of soil erosion adequately to the landscape, it is necessary to use stereoscopic aerial photographs, in which a true image of the landscape is obtained. In combination with ground verification, it would be possible to produce a detailed map, which could then be parametrically described and related to the location, extent and cause of erosion within the sub-catchment. An alternative is to complete detailed morphological mapping in the field, using an established technique such as that pioneered by Savigear (1965). This process would then require quantitative interpretation.

This study focussed on field sites of limited extent, which effectively represented single points within the catchment. Because of the correspondingly small sub-catchments defined for field sites and the presence of draining streams and rivers that further confused sub-catchment boundaries, it was not possible to measure sub-catchment area accurately. As the extent of ground contributing water to a field site is a critical determinant of erosion (Morgan, 1995), there is a strong case for scaling this study up to examine erosion within entire catchments.

8.3.4 Aerial photographs and changes in erosion extent

Changes in individual erosion features were examined using archived aerial photographs taken between 1946 and 1989. Because of the difficulties associated with the scales and exposures of aerial photographs, differences in eroded areas were not measured. Instead, erosion processes were established in terms of changes in numbers and morphology of individual features. Thus, the disappearance of hags, revegetation of bare soil and the exposure of mineral substrate were interpreted as changes in the state of erosion, counted and expressed in terms of erosion recovery, stability or deterioration.

Results indicated that the area of both peat and mineral soil erosion not directly attributable to humans or animals had changed little over forty-four years. In many instances, both peat and mineral erosion showed obvious signs of stabilisation or recovery due to revegetation.

In contrast, the number of erosion features caused by the activities of humans and animals had clearly risen over the same period. Existing scars also experienced increases in extent and exposure over the same period. Changes were most

obvious as paths, tracks and as poached and rutted areas. In general, individual sheep scars were not obvious on small scale images, but where the photograph scale permitted their observation, there were clear increases in their numbers. Neither the increases in biotic erosion nor the sustained extents of peat and mineral erosion were confined to particular periods within the 44 years of interest.

The technique used in aerial photographic interpretation was successful: it was possible to distinguish between erosion features, and to discern often tiny changes in their form or exposure between photographs. It would be advantageous nonetheless to confirm the results above by accessing aerial photographs for a greater number of eroded field sites.

Access to more up-to-date photographs than those used in this work would benefit the survey by confirming the findings above. As quality has improved with time, it should be easier to distinguish erosion forms from recent aerial photographs. It is essential also to establish if the patterns of erosion development determined between 1946 and 1989 have changed between 1990 and the present. Alternatively, satellite imagery may provide a useful source of information.

8.3 EXTENT, STATE AND RATES OF UPLAND SOIL EROSION

In Chapter 7, data from the 1997 and 1999 field surveys were used to determine the national extent of upland soil erosion and the rate at which it proceeded over the survey period. Information on the causes of erosion allowed the identification of their contributions to the extent of degradation and the rate of soil loss.

8.3.1 Field site size

Investigation of the variation in both field site datasets revealed that the standard deviation of the 50 m dataset was consistently lower than that of the 10 m dataset. Although it is clear that 50 m field site data are preferable, however, it is argued that a field site size that does not require a correction factor to achieve erosion extent per unit area is desirable. Circular field sites of 56.42 m radius, which may be enlarged to 60 m for simplicity, represent one hectare, and are recommended for future research.

8.3.2 Extent and distribution

Overall, 2.58% of the upland area of England and Wales was classified as eroded within this survey: this represents an area of over 25 000 ha. Approximately half of this area was recorded as revegetated in 1999: over 12 500 ha of soil therefore remained bare and was subject to further deterioration and soil loss through weathering and traffic.

Erosion was clearly concentrated in the S Pennines and in the NW Pennines, but also occurred in S, Mid and N Wales, in SW England and in the Lake District. There was appreciably less erosion in the North York Moors and in the Cheviot Hills.

The prevalence of erosion on field sites in the Peak District, Teesdale and Weardale was explained in terms of air pollution caused by the Industrial Revolution combined with intensive amenity and agricultural use. The most important factor controlling erosion, however, was the presence of blanket peat, which has a greater overall susceptibility to erosion. Where blanket peat occurs but erosion is less evident, this is surmised to be because of its less extensive development and because it has not been subject to the pressures imposed on peat in areas such as the Peak District. Thus the extent of peat and management conditions appear to combine to create conditions in which erosion is particularly exacerbated.

This finding is supported by the information on causes of erosion. In the Lake District, Dartmoor and Snowdon National Parks, in the NE Pennines and in the Cheviots, erosion was almost exclusively due to the actions of humans and animals. In the Peak District and NW Pennines, meanwhile, erosion, as expected, was almost entirely water-induced. While this may reflect a masking effect of water-induced erosion over biotic erosion, it is also likely that the sheer scale of water erosion, where it occurs, is sufficient to diminish the relative contribution of any biotic erosion. Consequently, biotic erosion either does not exist in these localities, or is sufficiently undeveloped in area and volume to be noticeable above water erosion.

8.3.3 Change in erosion extent and cause

Because of the changes applied to the field survey protocol in the middle of the 1997 field season, only 40% of field sites could be directly compared. Using these field sites, the area of erosion in upland England and Wales was calculated to have

increased by over 500 ha between 1997 and 1999. Of this erosion, 99.9% was due to biotic activity. The volume of erosion was similarly calculated to have increased by 0.0011 km³, 91.4% of which was due to humans and animals. It was determined from the annual rate of increase in biotic erosion that its area could attain that of water erosion within one century.

8.4 RECOMMENDATIONS FOR FURTHER RESEARCH

This project has established substantial evidence of the extent and severity of erosion, and answered many elementary questions on degradation in the upland environment. As the first study of its kind, however, it has identified several key issues of erosion that should be addressed urgently.

Overall, it is important to establish contemporary rates of erosion. This could be done remotely, through the interpretation of aerial photographs taken within the last twenty years. It would also be advantageous to continue to use the NSI field sites, which have now been visited up to four times and are described by a wealth of information of use in erosion surveys or to any research interested in changes in the upland environment over time.

The quality of field procedures, including the systematic sampling technique and field protocols also merit their further use. It is advised, however, that field sites of at least one hectare would be more useful and statistically sound than smaller sites. A beneficial future study could also determine the ideal sampling interval for field erosion studies. In this work, field sites were positioned at 5 km intervals: research indicates however that such intense sample grids are not necessary for certain soil mineral elements (Scholz *et al.*, 1998). A similar statistical test that investigates the variation in erosion distribution could determine if smaller numbers of field sites are a feasible option for the continued monitoring of upland erosion.

The further interpretation of aerial photographs would also be a valuable exercise, not only in the further elucidation of information on erosion, but on vegetation and landuse changes over time. Currently, the loss of sensitive vegetation communities through overgrazing, military use, forestry and other activities is unquantified although research has identified these practices as a threat (Thompson *et al.*, 1995).

The Code of Good Upland Management (MAFF, 1996) does not specify particular care or restraint to be applied to the creation of tracks within farm or moorland. In Plate 8.2, however, it is clear that, even without accelerated soil disturbance, erosion and runoff, moorland tracks detract aesthetically from open upland landscapes. Currently, the land suitability system that operates for camp and caravan sites and for footpaths does not apply to horse-riding or four-wheel drive access (George and Jarvis, 1979; Morgan, 1995). Although the means for testing environmental sustainability currently exist, alternative assessments may provide different results (Hanley *et al.*, 1999). A system that may be widely and successfully implemented is therefore required.

Remeasurement of field site traverses is recommended, perhaps within five to ten years of the initial measurements. Within shorter intervals, the rate of erosion measured may not exceed the experimental error of the procedure, while over longer intervals, there is a risk of excessive soil loss or nail disturbance. After several visits, when the rate of soil erosion has been determined in different soils and localities, a sampling strategy based on that information could be developed.

8.4.1 Tolerance Standards for upland erosion

Previous to this study, impressions of erosion relied upon remote assessment of erosion risk (Evans, 1990a). By investigating the actual extent of erosion, this work has shown that erosion is concentrated in some regions more than in others. An important and logical next step in the issue of upland erosion is concerned with what should be done about eroded regions. The creation of Tolerance Standards, their applications and the benefits to the uplands of their implementation are discussed in the following.

8.4.1.1 Introduction

In Chapter 2 it was proposed that a system of erosion performance standards applied to the uplands would be better than the assignation of economic values to ecological or natural resources (Scott *et al.*, 1998). The following theory proposes measures that ask upland users to define their own erosion standards for the uplands. These Tolerance Standards could then be used to define whether the areas of interest are acceptably or unacceptably eroded. Obviously, unacceptably eroded localities require immediate financing to aid remedial work. Acceptable levels

of erosion would mean, however, that remedial work is not currently required and that efforts may be concentrated in more eroded localities. It is therefore proposed that Tolerance Standards be used to distinguish between sites that require immediate attention, those where erosion may be effectively ignored at present and locations where erosion is not of concern.

8.4.1.2 The determination of Tolerance Standards

Tolerance Standards could be achieved by asking different user groups to quantify their impressions of erosion. One way to achieve this is via detailed questionnaires and survey forms. Individuals could be presented with photos of a range of erosion features and asked to quantify their impressions on a scale between complete tolerance (zero) and complete unacceptability (minus 10).

Using the measured area and volume of erosion per unit area represented by the photos, it would be possible to derive threshold levels of acceptable erosion for different upland user groups, for various stages of soil degradation and for representative vegetation communities. The Tolerance Standards achieved would then be widely applicable.

Hypothetical Tolerance Standards are provided in Table 8.1 for a selection upland user groups. In their calculation, certain assumptions have been made:

- visitors and residents are interested in aesthetics but residents, with daily exposure and lower expectations from a locality, are less “disappointed” by erosion
- water authorities are concerned only with the potential sediment delivery from erosion and therefore have higher thresholds
- agricultural, military and forestry user groups are unconcerned with landscape appearance and are affected by erosion only when it impedes their activities.

In Table 8.1, a zero reflects an erosion state that elicits no positive or negative feelings while decreasing negative values reflect growing intolerance of an eroded condition. Positive values reflect situations where the perceived erosion is actually of benefit to the user group: for example, more tracks are advantageous to farmers even if they represent sources of sediment or runoff. It is clear that, in this theoretical situation, different user groups are more or less sensitive to different

forms of erosion. These sensitivities could be used to deal with specific eroded situations, as described in the next section.

Table 8.1 Hypothetical impacts of erosion on different upland users.

Erosion feature	Extent	Impact on...					
		Visitors	Residents	Farmers	Water authority	Military	Forestry
Sheep scars	Low	0	0	0	0	0	0
	Medium	-1	-1	0	-1	0	0
	High	-4	-3	-1	-5	0	0
Tracks	Low	-1	0	+2	-1	+1	+1
	Medium	-3	-1	+4	-2	+2	+2
	High	-5	-3	+6	-3	+3	+4
Footpaths	Low	-5	-3	0	-1	0	0
	High	-10	-5	-2	-2	0	0
Peat erosion	Limited	-3	-3	-2	-5	0	0
	Extensive	-10	-5	-5	-10	-10	0
Slope failures	Few and small	-1	0	0	-1	0	0
	Few and large	-3	-1	-2	-2	0	0
	Many and large	-5	-3	-6	-5	0	0

8.4.1.3 The application of Tolerance Standards

Most upland regions involve more than one of the user groups mentioned above. National Parks, for example, provide homes, incomes and amenity, may provide sources of water for reservoirs and, as on Dartmoor, a valuable military exercise training area. Tolerance Standards need to represent the concerns of all of those groups, but in the assessment of any particular situation, the concerns of the most sensitive user group i.e. the user group with the lowest Tolerance Score, should be incorporated. Although this may mean the views of visitors are prioritised over those of residents, the end result should appeal to all sectors of a community.

Once the Tolerance Standards are applied, it should become clear whether the current state of erosion is acceptable or unacceptable. Erosion could be assessed on any scale within catchments, although the use of small areas and individual hills may be easier. Standards may also be applied to specific features, such as long distance footpaths like the Pennine Way. In that case, the priority concerns of walkers would be applied to determine how acceptable footpath erosion is. In

addition, however, the Tolerance Standards of environmentalists and ecologists, whose concerns may focus on additional issues of plant disturbance and the loss of fragile communities, must be applied to achieve a balanced perspective. Tolerance Standards maps produced for different areas from the information gained could become valuable tools in planning and land management.

This approach permits an acceptance that some erosion is inevitable and provides a means of establishing exactly how much is tolerable before remediation measures must be applied. As the physical costs of remediation are easy to quantify, erosion-repair authorities that are financially constrained can make informed decisions regarding the best employment of their resources. Once Tolerance Standards are established and remediation has been implemented on excessively eroded regions, it would be possible to concentrate resources on regions that are not prioritised on the Tolerance Scale. Similarly, it would be beneficial to concentrate sympathetic management in such areas while carrying out remediation on eroded ground.

The remedial actions that could be applied where erosion exceeds acceptable levels are described in the following.

8.5 THE REMEDIATION OF ERODED GROUND

It is imperative to reduce the area of bare ground in, and hence the amount of soil lost from, upland catchments. Various measures exist to do this, as described below. Erosion prevention and remediation are delicate and expensive operations, however, which require considerable forethought and planning as failed attempts are both frustrating and time- and money-consuming (Ciubotaru, 1998). Specific forms of erosion also require different treatments, as described in the following where remediation measures are considered in terms of the degree of intervention required.

8.5.1 Promoting revegetation

An important first step in the rehabilitation of eroded soil must be the fencing of the affected area. The exclusion of humans and of grazing animals in particular confers several advantages to the eroded area as further soil disturbance and loss through biotic factors is prevented. The cessation of grazing allows seedlings time to grow and achieve maturity. It reduces the competitive advantage given to grasses in

favour of heather through defoliation and the nutrification of the soil through urine and dung deposition. It is also proposed that the closing of footpaths, particularly across such badly eroded peat as that at Bleaklow Stones (Plate 8.3), would aid revegetation by preventing the further disruption of the potentially mobile, bare peat.

Restoration and reclamation of eroded recreation areas has also been accomplished by closing the land to visitors and replanting shrubs, trees and grasses (Morgan, 1995) or applying seed and fertiliser (Anderson *et al.*, 1997).

Once the fence is removed, care must be taken however to avoid a return to the original eroded state, effectively negating the work accomplished. It is therefore necessary to limit grazing sheep numbers to the current accepted rate of a single sheep per hectare (Phillips *et al.*, 1981), although this value changes on different soils (Evans, 1998). The creation of footpaths across newly restored ground should also be monitored to prevent the development of more than a single path, and to prevent excessive wear on that path.

Where fencing is insufficient to promote natural revegetation of eroded land, reseeding and the use of mats to maintain soil cover should be considered. The success of these techniques has been shown in the Peak District (Anderson *et al.*, 1997).

Geotextiles are a permeable textile in mat, sheet, grid or web form available in rolls as commercial products for erosion control. Some are biodegradable. They are designed to be unrolled over the surface of eroded areas to allow the establishment of vegetation cover. Burying artificial fibres also reinforces the soil and gives permanent protection to a slope (Morgan, 1995). Surface-laid mats of natural fibres reduce soil detachment because they absorb raindrop impact, allow water ponding and provide soil cover (Rickson, 1988; 1990). Although surface mats do not reduce runoff, they do reduce erosion through runoff, because of their roughness. Buried mats, in contrast, cannot prevent soil detachment at the surface but do help reduce erosion.

8.5.2 Active erosion repair

Above all, it is crucial that eroded soil is allowed to revegetate: in many instances, the simple exclusion of traffic will allow that revegetation to take place. Intervention is required to deal with footpath erosion on steep inclines and on footpaths where the exclusion of walkers is not an option. In both situations, expensive footpath repair is the only certain means of limiting erosion and maintaining safe and enjoyable conditions for walkers. Footpath restoration involves planting trampling-resistant vegetation that is compatible with the physical environment, but may also require the use of gravel, steps or flags, designed to reduce further erosion (Davies *et al.*, 1996; Morgan, 1995; Pearcehiggins and Yalden, 1997).

Footpath paving encourages walkers to remain in single file and helps to limit lateral development of paths. It also allows degraded soil and vegetation around paths to recover, thus reducing runoff from paths. Once in place, experience has proved that walkers will use the maintained footpath, allowing the extended and eroded path to recover: on the Pennine Way, 3.8% of walkers strayed from the restored path, compared with over 30% of walkers before path resurfacing (Pearcehiggins and Yalden, 1997). With maintenance, repaired footpaths will continue indefinitely to prevent soil degradation, and therefore represent better value for money than the initial outlay required would suggest.

8.5.3 Removal of the erosive agent

Biotic erosion has been identified as a major source of continued erosion in the field survey, although the responsibility rests entirely with humans, as they control the concentrations of grazing animals in the uplands. However, while hill farmers physically position animals and are responsible for their maintenance, it is the current system of headage payments that controls stocking densities in the uplands. Modification of this system is therefore required before it can be reasonably expected that the numbers of sheep grazing the uplands will be reduced. Options such as Environmentally Sensitive Areas and cross-compliance schemes are aimed at the reduction of stocking numbers but their current level of uptake by the farming community is far less than that required to have a significant beneficial effect on the upland environment (Evans, 1996).

The other form of biotic erosion is that caused by landusers themselves and includes wheel rutting and poaching, and the creation and maintenance of tracks. While the former may represent ephemeral erosion, tracks, particularly those engineered to enable access to moorland, are frequently large-scale and permanent. While these are necessary in some situations, it may be desirable to regulate the creation of additional tracks in favour of the preservation of undisturbed tracts of moorland.

In summary, therefore, it is proposed that future use of the uplands should be guided towards the remediation and recovery of eroded ground and the preservation of currently uneroded areas. Guidelines may be required for where tracks are necessary and where they should be avoided, such as on grouse moors. There should be encouragement and promotion of reduced sheep numbers: even where they are not causing erosion, sheep remove vegetation, reduce biodiversity and prepare the soil for erosion. A reduction in sheep numbers is necessary now: while overgrazing damage to soil may be sustainable in the short term, the state of vegetation compromise and loss may eventually peak for the country as a whole and result in severe and widespread erosion.

Catchment management is the only permanent solution to excessive reservoir sedimentation, and managing catchments to reduce erosion has a mutually beneficial effect in reducing water colour. An holistic approach to the management of catchments was therefore proposed by White *et al.* (1996). Erosion remediation measures are expensive, however, either in terms of the equipment and material used, such as when geotextiles are employed, or in the restrictions placed upon land management practices. These expenses will determine which, if any, of the measures suggested above are used.

8.5.4 The consequences of erosion control

Erosion remediation should not limit potentially damaging but essential activities. In many cases, actions that cause erosion can still be used as long as soil and landscape considerations are taken into account. Ploughing for afforestation, for example, should be acceptable on deep peat soils as long as the underlying substrate is not exposed (Carling *et al.*, 1997). Penetration resistance, which forms the basis of hydraulic thresholds of erosion, is a good indicator of peat humification

(Carling *et al.*, 1997) and could be used by designers of preafforestation drainage networks to aid forestry management.

Similarly, it is not proposed that all sheep currently grazing in the uplands are removed or that the activities of farmers are limited to prevent the exposure of bare soil. It is imperative that measures used to limit erosion also take into account the finely balanced economic and social environment of the uplands. It is equally essential, however, that sustainability is achieved.

This thesis cannot comment on the reforms needed to achieve a turn-around in current philosophy regarding the uplands. It is necessary for all upland users to realise that the uplands represent a limited resource and that their own activities impact upon that resource. Careful and considered actions will enable the full potential of the uplands to be realised, just as careless misuse will detract from the uplands, and ultimately destroy the very qualities that make the uplands special.

Nonetheless, it is clear that certain changes would contribute to a healthier upland environment in which erosion is no longer promoted. The current system of state subsidies could be amended. Proposals have included the management of environmentally sensitive areas (ESA) to prescribed stocking rates and practices of winter feeding and fertiliser with greater compensation for the implementation of more rigorous husbandry standards (Weaver *et al.*, 1998). Alternatively, compliance with environmental standards could be assigned to CAP support payments, thus discouraging overgrazing, as suggested by RCEP (1996).

A reduction in the numbers of sheep grazing in the uplands is essential but should not be conducted in such a way as to threaten the livelihoods of upland farmers. As the managers of a landscape that is so admired, it is essential to maintain communities living and working in the uplands. Currently it appears that one of the greatest threats to upland communities is the absence of a domestic market for their produce. Through the promotion of such a market with the simultaneous gradual withdrawal of subsidies, the upland economic system may rebalance. Flock sizes would be reduced as the current system of subsidy reliance is replaced by market-driven economics, in which farmers are paid for the produce they sell, rather than the produce they can accommodate. Alternatively, it may be necessary to implement

schemes whereby farmers are subsidised for sensitive land management. Such reforms would benefit upland farmers and the population as a whole, and would go some way towards redressing the damage currently being done to the upland ecosystem. As the current CAP system faces reform, it is essential to impose such advance measures for the sustainable protection of the uplands and its populations.

8.6 CONCLUSIONS

The current overall extent of erosion represents 2.58% of the uplands of England and Wales. Between 1997 and 1999, the areal extent of erosion increased by over 500 ha. Most of the contemporary area and volume of current erosion is water caused, and due to the degradation of blanket peat. Biotic factors are becoming increasingly important as the cause of new and continued erosion and already occur on more field sites than water erosion. The current rate of development of biotic erosion also far exceeds that of water erosion. While water erosion has remained virtually unchanged over time, biotic erosion has continued to increase in numbers and severity.

Upland erosion is a serious issue within England and Wales, emphasised by its rate of increase. The dependence of the population on the uplands for livelihoods and pleasure mean it is necessary to use the information presented here to protect the upland environment from further deterioration and to promote the rehabilitation of damaged area.

For many years, the issue of soil erosion within the uplands has been dismissed. Firstly, it was not perceived to be a problem, and later insufficient fundamental information was used as an excuse for indifference and inactivity. This work has shown the very real extent of the problem and has confirmed many of the suspicions of earlier workers: that the uplands are at risk of erosion and that that erosion is predominantly due to the activities of landusers. Perhaps more worrying, however, is the potential for erosion to become very much more prevalent in the next few decades. It is essential, therefore, for remedial and preventive action to begin now.



Plate 8.1 Traverse photograph, showing details of eroded wall for relocation (Northumberland).



Plate 8.2 Distant view of moorland track created between 1997 and 1999 field visits (NW Pennines).



Plate 8.3 Peat erosion near Bleaklow Stones, across which a public-access track runs (Peak District).

Appendix 1

Table I National Soil Inventory field sites, used in the 1999 field survey.

NT60/6010	NY77/1060	NZ70/6010	SE05/6060	SH82/1060	SN72/6010	SO11/1010
NT70/1010	NY77/6010	NZ71/1010	SE06/6060	SH82/600125	SN75/1010	SO11/1060
NT70/1060	NY78/1060	NZ71/6010	SE07/1010	SH82/6060	SN75/1060	SO11/6060
NT80/1010	NY79/1010	NZ80/6010	SE07/6010	SH83/1010	SN75/6010	SO12/6060
NT82/6060	NY79/1060	NZ90/6010	SE07/6060	SH83/1060	SN75/6060	SO14/1060
NT83/6010	NY79/6010	SD18/6060	SE08/6010	SH83/6060	SN76/6010	SO15/1010
NT90/1010	NY79/6060	SD19/6010	SE08/6060	SH84/1010	SN77/6010	SO15/6010
NT91/1060	NY80/1010	SD19/6060	SE09/1060	SH84/1060	SN77/6060	SO15/6060
NT91/6010	NY80/6060	SD28/6060	SE09/6060	SH84/6060	SN78/1010	SO16/1010
NT93/1010	NY81/6060	SD29/6010	SE10/1010	SH90/1010	SN78/1060	SO20/1009
NU00/6060	NY82/1010	SD29/6060	SE10/6010	SH91/1060	SN78/6010	SO20/1060
NU12/1010	NY82/1060	SD39/1010	SE14/1060	SH91/6010	SN78/6060	SO21/1010
NU12/1060	NY82/6060	SD55/6010	SE15/1010	SH92/1060	SN79/1010	SO21/6010
NY10/6010	NY83/1110	SD64/1060	SE15/1060	SH92/6010	SN79/6010	SO22/1010
NY11/1010	NY83/1060	SD64/6010	SE15/6010	SH92/6060	SN79/6060	SO22/1060
NY11/6010	NY83/6060	SD65/1010	SE15/6060	SH93/6010	SN80/1060	SO23/1010
NY11/6060	NY84/1010	SD65/0955	SE16/1010	SH94/605100	SN81/1060	SO23/6060
NY12/1010	NY84/1060	SD65/6256	SE16/1060	SH95/1010	SN82/1010	SO25/6060
NY20/1058	NY85/1010	SD66/1010	SE17/1060	SH95/1060	SN82/1060	SO26/6060
NY20/6010	NY85/6010	SD68/6060	SE17/6010	SH96/1010	SN82/6010	SO32/1060
NY21/6010	NY88/1060	SD69/1010	SE17/6060	SJ00/1010	SN84/1060	SO39/1060
NY22/1010	NY88/6060	SD69/6060	SE18/1010	SJ02/1010	SN85/6060	SO49/1010
NY22/1060	NY89/1060	SD72/6010	SE59/1060	SJ02/1060	SN86/1060	SO49/1060
NY23/6010	NY89/6011	SD76/1010	SE69/1060	SJ03/1010	SN86/6010	SS59/1110
NY31/6010	NY89/6060	SD76/6010	SE79/1010	SJ03/6010	SN86/6060	SS73/6060
NY31/6060	NY90/1010	SD77/1060	SE79/1060	SJ03/6060	SN87/1010	SS74/1060
NY32/1060	NY90/1060	SD77/6060	SE79/6060	SJ13/1060	SN87/1060	SS74/6060
NY32/6010	NY90/6010	SD78/1010	SE89/6060	SJ13/6060	SN87/6010	SS83/1010

Table I (cont.d) National Soil Inventory field sites, used in the 1999 field survey.

NY33/1010	NY90/6060	SD78/6011	SH54/1060	SJ14/1010	SN87/6060	SS84/1010
NY33/1060	NY91/1010	SD79/1060	SH55/6060	SJ14/6010	SN88/1010	SS84/6060
NY33/6010	NY91/1060	SD79/6010	SH60/6010	SJ14/6060	SN88/1060	SS89/6059
NY41/1010	NY91/6060	SD79/6060	SH61/1010	SJ16/6010	SN89/1010	SS98/6060
NY41/1060	NY93/1010	SD87/1160	SH61/1460	SJ26/1010	SN89/6010	SS99/6010
NY41/6010	NY93/6010	SD87/6010	SH61/6010	SJ98/6010	SN89/6060	ST09/1010
NY41/6060	NY93/6060	SD89/1010	SH62/1010	SK06/5959	SN90/6011	ST29/6060
NY42/1010	NY94/1060	SD89/1060	SH63/6010	SK07/1010	SN91/1060	SX06/1110
NY42/6010	NY94/6010	SD89/6060	SH63/6060	SK08/6060	SN91/6010	SX18/6010
NY50/1060	NY94/6060	SD91/6010	SH65/1010	SK09/6010	SN91/6060	SX27/1010
NY50/6060	NY95/1010	SD91/6060	SH65/1060	SK09/6060	SN92/1010	SX56/6060
NY51/1010	NY96/6060	SD92/6210	SH65/6060	SK18/1060	SN92/6010	SX57/6011
NY58/6010	NY98/6060	SD93/1060	SH66/1010	SK19/1060	SN93/1060	SX57/6060
NY60/6010	NY99/6010	SD93/6060	SH66/6010	SK19/6060	SN93/6060	SX58/6010
NY64/6010	NY99/6060	SD94/6010	SH66/6060	SK27/6060	SN95/1060	SX58/6060
NY64/6060	NZ00/1010	SD95/6060	SH70/1060	SK28/1010	SN96/1010	SX66/1060
NY65/1010	NZ00/6060	SD97/1060	SH71/6061	SK28/1060	SN96/6010	SX66/6010
NY65/1060	NZ01/1010	SD98/1010	SH72/1060	SK28/6010	SN97/1010	SX66/6060
NY67/6060	NZ03/1010	SD99/1060	SH73/6010	SK28/6060	SN97/6010	SX67/1010
NY68/1010	NZ03/1060	SE00/1010	SH74/1059	SK29/1010	SN98/1060	SX67/1060
NY68/6010	NZ03/6010	SE00/6010	SH74/6010	SK29/1060	SN98/1060	SX67/6010
NY70/1010	NZ04/1010	SE00/6060	SH74/6060	SK39/1061	SO01/1060	SX68/1010
NY70/6010	NZ04/1060	SE01/1010	SH75/1010	SN03/6010	SO01/6060	SX68/1060
NY72/6060	NZ05/1010	SE01/6010	SH75/6060	SN60/6060	SO02/1009	SX68/6010
NY73/1010	NZ09/1060	SE02/1010	SH76/1060	SN61/6060	SO02/6010	SX68/6060
NY73/1060	NZ60/1014	SE03/1010	SH76/6060	SN65/1060	SO04/6010	SX69/1010
NY73/6010	NZ60/1060	SE03/1060	SH77/1010	SN65/6010	SO09/6010	SX77/1060
NY73/6060	NZ60/6010	SE05/1010	SH81/1060	SN71/1060	SO10/1110	SX77/6060
NY74/1010	NZ70/1010	SE05/1060	SH81/6060	SN71/6060	SO10/0960	SX78/1010

Table II Countryside Survey 2000 field sites included in the 1999 field survey.

NY10/2525	NZ60/2525	SD87/7525	SH62/7525	SJ16/2576	SO21/7575
NY12/2525	NZ70/7525	SD88/7555	SH65/7525	SK09/2575	SO23/7525
NY23/7525	SD75/2575	SE01/2525	SH82/2525	SK19/7575	
NY73/2525	SD77/2525	SE05/2575	SH83/2575	SN81/2575	
NZ04/2575	SD80/7525	SH60/7575	SH90/7525	SN86/2525	

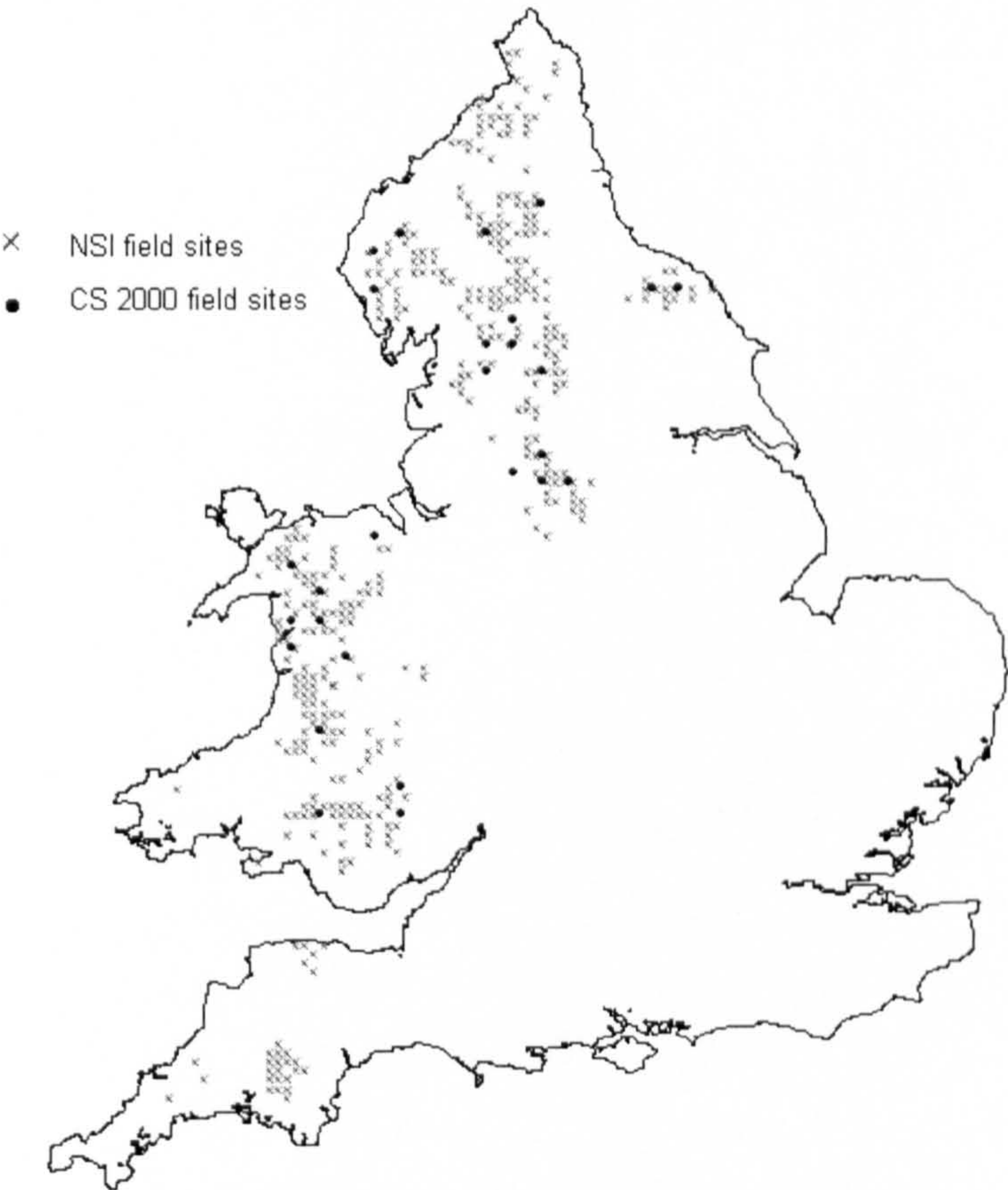


Plate I The distribution of NSI and CS 2000 field sites across the uplands of England and Wales.

Table III Grid references for field sites on which traverses were completed in 1997 and in 1999

NT91/1060	NY80/6060	SD66/1010	SE00/1010	SH90/7525	SK29/1010
NU12/1060	NY83/1060	SD76/1010	SE00/6060	SH95/1010	SN75/1060
NY73/1010	NY84/1010	SD79/6010	SE01/1010	SK07/1010	SN81/2575
NY73/1060	NY93/6010	SD79/6060	SE07/6010	SK09/2575	SN88/1010
NY73/2525	SD 76/6010	SD87/7525	SH 84/1060	SK09/6010	SN88/1060
NY73/6010	SD65/1010	SD93/6060	SH71/6061	SK19/1060	SN91/6060
NY77/1060	SD65/6060	SD98/1010	SH82/6012	SK19/7575	SX 66/1060

Appendix 2

SSLRC UPLAND SOIL EROSION/RUNOFF RE-SURVEY AT NSI SITES 1997

The purpose of this survey is to get a reasonably precise and clear measurement of the amount and form of soil erosion and deposition occurring within the specified boundaries; 10 m and 50 m from NSI node, respectively. An indication of change in the amount of soil erosion occurring at the site can be calculated by comparing data from the previous site visit with data from this re-survey. Please address this on page 2, 'Erosion Details'. This is only valid for sites that have had a previous visit (NB: You will need the form and photos from 1995 with you for this), questions marked with an '' may therefore not need completing. To maintain consistency, all units are expressed in metres.*

Please ensure that each field (i.e all shaded boxes) has an appropriate entry, (encircled if italicised or written on the lined space provided) and that any manuscript is readily legible to those unfamiliar with your own fair hand. Please refrain from making notes on the form - any points of interest or observations not covered can be added in the 'Observations / Points of interest' field on page 4 .

SITE: ____/____

DATE: ____/____/ 97

OBSERVER: ____

SLOPE ANGLE: ____°

SLOPE SHAPE: Concave Convex Rectilinear

ASPECT: _____

GPS USED?: Yes / No

VEGETATION: Upland grass Heath Bog Montane Other (specify): _____

ACCESS

NAME: _____

TEL NO: _____

ADDRESS: _____

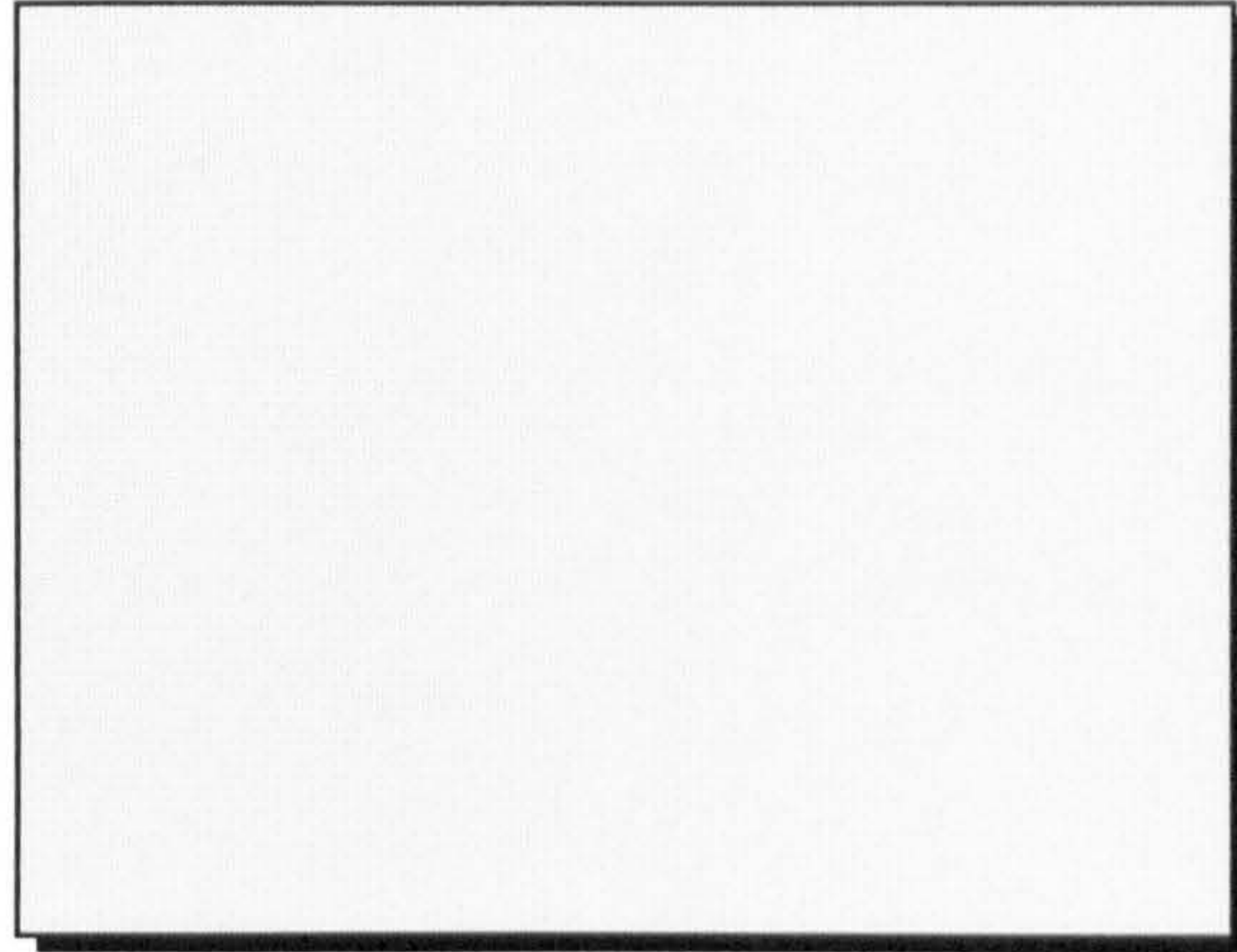
GENERAL - Where to park, shortcuts to site
or notes on relocation of site:

SOIL EROSION POTENTIAL - CONTRIBUTORY FACTORS

Note any degradation of vegetation or activity likely to affect erosion, e.g. burning, stocking, foot or other traffic:

FEATURES**SKETCH: →****1) Position at site of:**

- NSI node (X)
- 10m boundary
- 50m boundary
- erosion
- deposition
- runoff

2) Approx. extent / dimensions of features**3) Position of traverses (detailed overleaf)****EROSION / DEPOSITION / RUNOFF** (Please circle)

	EROSION	DEPOSITION	RUNOFF
WITHIN 10m OF NSI NODE:	<i>Water Wind None</i>	<i>Water Wind None</i>	<i>Yes / No</i>
WITHIN 50m OF NSI NODE:	<i>Water Wind None</i>	<i>Water Wind None</i>	<i>Yes / No</i>

NB: If 'wind', describe under 'Observations' (Page 4) and photograph.**EROSION DETAILS****WITHIN 10m OF NSI NODE****Area involved:** _____ %**Volume of eroded soil:** _____ m³***How much more soil erosion
has occurred since last visit?:** _____ m³***Comments on how the form of erosion
has changed since last visit:**

WITHIN 50m OF NSI NODE**Area involved:** _____ %**Volume of eroded soil:** _____ m³***How much more soil erosion
has occurred since last visit?:** _____ m³***Comments on how the form of erosion
has changed since last visit:**

WATER EROSION

	WITHIN 10m		WITHIN 50m	
	MEAN	UPPER EXTREME	MEAN	UPPER EXTREME
CHANNEL				
- DEPTH (m):				
- WIDTH (m):				
- X-SECTION SHAPE:				
- LENGTH (m):				

PATTERNS OF EROSION

	WITHIN 10m	WITHIN 50m	
ACTIVITY			
- GROUND AFFECTED:	_____%	_____%	
- ACTIVELY ERODING:	_____%	_____%	
- ERODED BUT STABLE:	_____%	_____%	
- PLANT COVER ON			
CHANNEL FLOOR / WALLS			
- VASCULAR:	_____%	_____%	
- NON-VASCULAR:	_____%	_____%	
NETWORK SHAPE:			
Linear	Rectilinear	Dendritic	Other (specify):_____

DEPOSITION DETAILS

WITHIN 10m OF NSI NODE

Area involved: _____%

Volume of deposited soil: _____m³

*How much more deposition has occurred since last visit?: _____m³

*Comments on how the form of deposition has changed since last visit:

WITHIN 50m OF NSI NODE

Area involved: _____%

Volume of deposited soil: _____m³

*How much more deposition has occurred since last visit?: _____m³

*Comments on how the form of deposition has changed since last visit:

PATTERNS OF DEPOSITION *(Please circle)*

Form / Composition:	<i>Laminated</i>	<i>Dispersed and separated soil</i>	<i>Peat</i>	<i>Mineral soil</i>	<i>Stones</i>
	<i>V. small (2-6mm)</i>	<i>Small (6mm-2cm)</i>	<i>Medium (2-6cm)</i>	<i>Large (6-20cm)</i>	<i>V. Large (20-60cm)</i>
Rolled aggregates - size	✓	✓	✓	✓	✓
Stones - size:	✓	✓	✓	✓	✓

OBSERVATIONS / POINTS OF INTEREST

EROSION / DEPOSITION FEATURES

If there is any erosion or deposition, record a few traverses at representative and readily identifiable sites, indicating channel depth measurements and spacings of significant changes in wall / floor configuration.

EXAMPLE

Traverse No.1 - start at foot of white boulder, heading ESE

0.5 m	- gully starts;
0.75m	- 0.35m deep, freshly eroded, no vegetation;
0.9m	- 0.53m deep, active erosion in parts, 60% moss cover;
1.4m	- 1.2m deep, stable, complete grass cover;
2.6m	- 0.8m deep, 60% actively eroding, bare with 10% <i>Calluna</i>
3.5m	- gully ends.

TRAVERSE No. 1

TRAVERSE No. 2

TRAVERSE No. 3

TRAVERSE No. 4

Please now check that all items have an entry if appropriate.

Appendix 3

SOIL SURVEY AND LAND RESEARCH CENTRE
UPLAND SOIL EROSION (JF 4118) 1999

SITE :
MAP:
SLOPE ANGLE:
VEGETATION:
DOMINANT PLANT SPECIES:

/

DATE:

/

1999

OBSERVER:

GPS ?:

Yes / No

ASPECT:

SLOPE SHAPE:

Concave

Convex

Linear

Upland grass

Heath

Bog

Montane

Other (specify):

ACCESS

NAME:

TEL NO:

ADDRESS:

GENERAL - Where to park, shortcuts to site
or notes on relocation of site:

SOIL EROSION POTENTIAL - CONTRIBUTORY FACTORS

Note any degradation of vegetation or activity likely to affect erosion, e.g. burning, stocking, foot or other traffic:

Assess grazing pressure (low-high, 0-5)

	EROSION	DEPOSITION	RUNOFF
WITHIN 10m:	Water Wind Biotic None	Water Wind Biotic None	Yes / No
WITHIN 50m:	Water Wind Biotic None	Water Wind Biotic None	Yes / No

EROSION DETAILS**WITHIN 10m OF NSI NODE**

Total area involved: _____%

Total volume of eroded soil: _____m³**ACTIVE erosion:** **INACTIVE erosion:**

Area _____%

Area _____%

Volume _____m³Volume _____m³*How much more soil erosion
has occurred since last visit?: _____m³*Comments on how the form of erosion
has changed since last visit:

WITHIN 50m OF NSI NODE

Total area involved: _____%

Total volume of eroded soil: _____m³**ACTIVE erosion:** **INACTIVE erosion:**

Area _____%

Area _____%

Volume _____m³Volume _____m³*How much more soil erosion
has occurred since last visit?: _____m³Comments on how the form of erosion
has changed since last visit:

WATER EROSION

	<u>WITHIN 10m</u>		<u>WITHIN 50m</u>	
	MEAN	MAXIMUM	MEAN	MAXIMUM
<u>CHANNEL</u>				
- DEPTH (m):	_____	_____	_____	_____
- WIDTH (m):	_____	_____	_____	_____
- X-SECTION SHAPE:	_____	_____	_____	_____
- LENGTH (m):	_____	_____	_____	_____

PATTERNS OF EROSION

<u>WITHIN 10m</u>	<u>WITHIN 50m</u>	
<u>ACTIVITY</u>		
- GROUND AFFECTED:	_____%	_____%
- ACTIVELY ERODING:	_____%	_____%
- ERODED BUT STABLE:	_____%	_____%
- PLANT COVER ON		
CHANNEL FLOOR / WALLS		
- VASCULAR:	_____%	_____%
- NON-VASCULAR:	_____%	_____%
<u>NETWORK SHAPE:</u>	<i>Linear</i>	<i>Dendritic</i>
		<i>Other (specify):</i> _____

DEPOSITION DETAILS

WITHIN 10m

Area involved: _____ %

Volume of deposited soil: _____ m³

***How much more deposition has occurred since last visit?:** _____ m³

***Comments on how the form of deposition has changed since last visit:**

WITHIN 50m

Area involved: _____ %

Volume of deposited soil: _____ m³

***How much more deposition has occurred since last visit?:** _____ m³

***Comments on how the form of deposition has changed since last visit:**

PATTERNS OF DEPOSITION *(Please circle)*

Form:	<i>Laminated</i>	<i>Dispersed and separated soil</i>	<i>Peat</i>	<i>Mineral soil</i>	<i>Stones</i>
	<i>V. small (2-6mm)</i>	<i>Small (6mm-2cm)</i>	<i>Medium (2-6cm)</i>	<i>Large (6-20cm)</i>	<i>V. Large (20-60cm)</i>
Rolled aggregates - size:	✓	✓	✓	✓	✓
Stones - size:	✓	✓	✓	✓	✓

OBSERVATIONS / POINTS OF INTEREST (Number and location of photos taken)

SITE MEASUREMENTS: GULLIES

TRAVERSE No. 1

Distance from node (m):

Bearing from node (O):

Bearing of traverse (O):

Information to aid relocation

Distance (m)	Depth (m)	Substrate
-----------------	--------------	-----------

[illegible]

TRAVERSE No. 2

Distance from node (m):

Bearing from node (O):

Bearing of traverse (O):

Information to aid relocation

Distance (m)	Depth (m)	Substrate
-----------------	--------------	-----------

[illegible]

TRAVERSE No. 3

Distance from node (m):

Bearing from node (O):

Bearing of traverse (O):

Information to aid relocation

Distance (m)	Depth (m)	Substrate
-----------------	--------------	-----------

[illegible]

SITE MEASUREMENTS: OTHER FEATURES

Feature name: _____
Cause: _____
Location within site: _____
Length (m): _____
Depth (m): _____
Width (m): _____
Photographed? *Yes / No*

Feature name: _____
Cause: _____
Location within site: _____
Length (m): _____
Depth (m): _____
Width (m): _____
Photographed? *Yes / No*

Feature name: _____
Cause: _____
Location within site: _____
Length (m): _____
Depth (m): _____
Width (m): _____
Photographed? *Yes / No*

Feature name: _____
Cause: _____
Location within site: _____
Length (m): _____
Depth (m): _____
Width (m): _____
Photographed? *Yes / No*

Feature name: _____
Cause: _____
Location within site: _____
Length (m): _____
Depth (m): _____
Width (m): _____
Photographed? *Yes / No*

Feature name: _____
Cause: _____
Location within site: _____
Length (m): _____
Depth (m): _____
Width (m): _____
Photographed? *Yes / No*

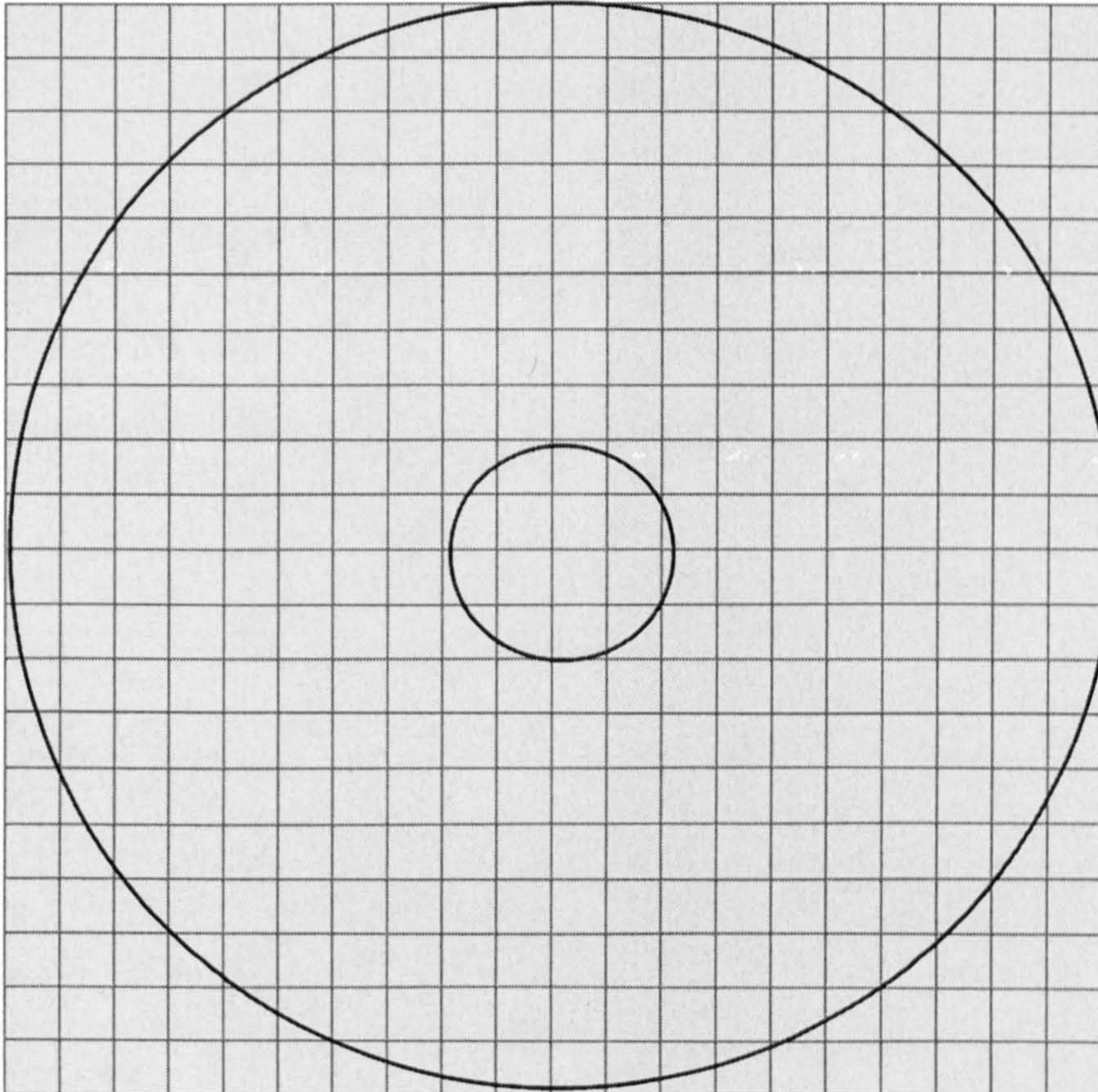
Feature name: _____
Cause: _____
Location within site: _____
Length (m): _____
Depth (m): _____
Width (m): _____
Photographed? *Yes / No*

Feature name: _____
Cause: _____
Location within site: _____
Length (m): _____
Depth (m): _____
Width (m): _____
Photographed? *Yes / No*

Field site sketch

Include

- principal features of field sites for relocation
- locations and approximate size of erosion features
- positions of gully traverses, if any



Appendix 4

Descriptions of statistical tests used in this thesis (from Sokal and Rohlf, 1995; Payne *et al.*, 1987).

Linear regression fits a linear model to represent the relationship between a response (or y-) variate, and an explanatory (or x-) variate. The test prepares a relationship between the response variate (erosion) and a known constant, and examines the change on this linear relationship that results from the addition of the continuous variable.

To further the output from this powerful statistical tool, a number of more advanced regression analyses may be used. The simplest of these is **Simple Linear Regression with Groups (SLRG)** which fits a sequence of models to data values that are classified into groups. It is therefore ideal for combining factors such as grazing, aspect, site morphology and vegetation, with the variables altitude and slope.

In SLRG, the first model to be fitted is a simple linear regression ignoring the groups. Next, the model is extended to include a different intercept for each group, i.e. a parallel relationship between the factor and erosion is drawn. The final model combines the factor with the variable and creates an entirely new regression linking this combination with erosion. This latter test is the most powerful and, as well as indicating whether there is interaction between the two variates being tested, also assesses the significance, or lack of, of the new erosion – combined variates relationship.

The main problem with this test is that a linear relationship between factors is assumed, although this may not be the case. However, in terms of providing a first and useful indication of the sense of relationships between response and explanatory variates, linear regression is a valuable tool.

In the same way as for simple linear regressions, **Multiple Linear Regression** also fits a linear model to represent the relationship between a response (or y-) variate, and several explanatory (or x-) variates. **Multiple Linear Regression with Groups** also fits a sequence of models to data values that are classified into groups and specified as factors (MLRG).

In both SLRG and MLRG, graphs and further output display information from the final (full) model. The Accumulated display setting is particularly useful as it produces an accumulated analysis of variance that allows you to assess whether there is evidence of non-parallelism for each explanatory variate. If there is no evidence of non-parallelism, the line for the main effect of the groups factor assesses whether different intercepts are needed. In the summary tables that follow, parallel regressions are indicated by "+" while non-parallel, and hence interactive, regressions are denoted by "x".

ANOVA analysis of variance provides a structured approach to the analysis of classified data and tests the null hypothesis that there are no differences between the groups. The advantage of such factorial analysis is that both the overall effect of the factor and the individual effects of factor levels are assessed. In this thesis, only one-way analyses were necessary.

Table I Output from statistical analyses of the data on total erosion recorded within 10 m field sites.

Statistical test	Variable	Group	Area		Volume	
			F pr	R ²	F pr	R ²
Simple Linear Regression	Altitude		0.181		0.004	9.7
	Slope		0.101		0.079	2.9
	Altitude	+ aspect	0.906		0.638	
	"	x aspect	0.284		0.524	
	"	+ grazing	0.779		0.438	
	"	x grazing	0.045	7.4	0.023	20.3
	"	+ vegetation	0.197		0.044	17
	"	x vegetation	0.973		0.470	
	"	+ morphology	0.313		0.275	
	"	x morphology	0.218		0.265	
Simple Linear Regression with Groups	"	+ soil	0.040	8.4	0.010	19.9
	"	x soil	0.837		0.533	
	Slope	+ aspect	0.951		0.714	
	"	x aspect	0.999		0.696	
	"	+ grazing	0.814		0.689	
	"	x grazing	0.284		0.419	
	"	+ vegetation	0.200		0.037	11.3
	"	x vegetation	0.743		0.780	
	"	+ morphology	0.338		0.203	
	"	x morphology	0.038	9.0	0.101	8.2
Multiple Linear Regression	"	+ soil	0.019	11.7	0.001	19.5
	"	x soil	0.812		0.672	
	Altitude + Slope		0.136		0.006	11.2
	Altitude + Slope	+ aspect	0.949		0.670	
	"	x aspect	0.106		0.085	21.3
	"	+ grazing	0.817		0.605	
	"	x grazing	0.170		0.139	
	"	+ vegetation	0.281		0.075	16.9
	"	x vegetation	0.620		0.159	
	"	+ morphology	0.414		0.404	
Multiple Linear Regression with Groups	"	x morphology	0.108		0.147	
	"	+ soil	0.036	10.4	0.015	20.5
	"	x soil	0.919		0.801	
		Aspect	0.910		0.711	
		Grazing	0.786		0.508	
		Vegetation	0.119		0.016	
		Morphology	0.214		0.096	
		Soil	0.017		<0.001	
Analysis of Variance						

Table II Summary of statistical output from analyses performed on erosion recorded within 50 m field sites.

Statistical test	Variable	Factor	Area		Volume	
			F pr	R ²	F pr	R ²
Simple Linear Regression	Altitude		<0.001	5.7	<0.001	10.2
	Slope		0.073	1.1	0.033	1.7
	Altitude	+ aspect	0.562		0.403	
	"	x aspect	0.926		0.361	
	"	+ grazing	0.044	9.4	0.024	13.6
	"	x grazing	0.587		0.193	
	"	+ vegetation	0.003	11.9	<0.001	18.6
	"	x vegetation	0.572		0.823	
	"	+ morphology	0.003	10.2	0.024	12.6
	"	x morphology			0.668	
	"	+ soil	0.047	8.0	0.005	14.4
	"	x soil	0.070	9.9	0.020	17.3
Simple Linear Regression with Groups	Slope	+ aspect	0.795		0.757	
	"	x aspect	0.749		0.693	
	"	+ grazing	0.033	4.6	0.033	5.2
	"	x grazing	0.345		0.270	
	"	+ vegetation	0.002	8.4	<0.001	11.9
	"	x vegetation	0.529		0.518	
	"	+ morphology	0.004	5.5	0.028	
	"	x morphology	0.806		0.839	
	"	+ soil	0.006	5.6	<0.001	9.7
	"	x soil	0.448		0.368	
Multiple Linear Regression	Altitude + Slope		<0.001	6.5	<0.001	11.4
	Altitude + Slope	+ aspect	0.753		0.521	
Multiple Linear Regression with Groups	"	x aspect	0.931		0.358	
	"	+ grazing	0.026	9.9	0.046	14.2
	"	x grazing	0.356		0.104	16.8
	"	+ vegetation	0.005	12.1	<0.001	18.7
	"	x vegetation	0.628		0.658	
	"	+ morphology	0.004	10.3	0.046	13.2
	"	x morphology	0.384		0.943	
	"	+ soil	0.109	7.7	0.015	
	"	x soil	0.164		0.049	17.5
Analysis of Variance		Aspect	0.703		0.681	
		Grazing	0.018		0.014	
		Vegetation	<0.001		<0.001	
		Morphology	0.002		0.010	
		Soil	0.002		<0.001	

Table III Output from statistical analysis of erosion on 10 m field sites. Peat soils have been omitted.

Statistical test	Variable	Factor	Area		Volume	
			F pr	R ²	F pr	R ²
Simple Linear Regression	Altitude		0.504		0.250	
	Slope		0.915		0.913	
	Altitude	+ aspect	0.965		0.972	
	"	x aspect	0.136		0.379	
	"	+ grazing	0.589		0.386	
	"	x grazing	0.328		0.460	
	"	+ vegetation	0.862		0.373	
	"	x vegetation	0.354		0.119	
	"	+ morphology	0.835		0.377	
	"	x morphology	0.577		0.916	
Simple Linear Regression with Groups	"	+ soil	0.162		0.056	
	"	x soil	0.692		0.518	
	Slope	+ aspect	0.971		0.944	
	"	x aspect	0.925		0.625	
	"	+ grazing	0.494		0.320	
	"	x grazing	0.266		0.346	
	"	+ vegetation	0.799		0.375	
	"	x vegetation	0.297		0.128	
	"	+ morphology	0.798		0.388	
	"	x morphology	0.572		0.303	
Multiple Linear Regression	"	+ soil	0.126		0.039	10.4
	"	x soil	0.969		0.903	
	Altitude + Slope		0.797		0.516	
	Altitude + Slope	+ aspect	0.969		0.974	
	"	x aspect	0.084	15	0.048	24.7
	"	+ grazing	0.557		0.395	
	"	x grazing	0.409		0.794	
	"	+ vegetation	0.66		0.379	
	"	x vegetation	0.324		0.119	
	"	+ morphology	0.834		0.373	
Multiple Linear Regression with Groups	"	x morphology	0.813		0.700	
	"	+ soil	0.162		0.062	9.1
	"	x soil	0.949		0.855	
		Aspect	0.968		0.941	
		Grazing	0.523		0.310	
		Vegetation	0.792		0.365	
		Morphology	0.794		0.385	
		Soil	0.127		0.035	
Analysis of Variance						

Table IV Output from statistical analysis of erosion on 50 m field sites, minus peat soils.

Statistical test	Variable	Factor	Eroded area		Eroded volume	
			<i>F pr</i>	<i>R</i> ²	<i>F pr</i>	<i>R</i> ²
Simple Linear Regression	Altitude		0.461		0.196	
	Slope		0.682		0.556	
	Altitude	+ aspect	0.687		0.529	
	"	x aspect	0.949		0.281	
	"	+ grazing	0.573		0.881	
	"	x grazing	0.236		0.835	
	"	+ vegetation	0.070	4.8	0.092	5.1
	"	x vegetation	0.189		0.242	
	"	+ morphology	0.012	5.7	0.072	3.6
	"	x morphology	0.207		0.570	
Simple Linear Regression with Groups	"	+ soil	0.143		0.037	4.7
	"	x soil	0.472		0.361	
	Slope	+ aspect	0.747		0.710	
	"	x aspect	0.669		0.709	
	"	+ grazing	0.650		0.937	
	"	x grazing	0.492		0.517	
	"	+ vegetation	0.075	4.3	0.103	
	"	x vegetation	0.372		0.424	
	"	+ morphology	0.012	5.4	0.074	2.4
	"	x morphology	0.792		0.459	
Multiple Linear Regression	"	+ soil	0.142		0.036	3.6
	"	x soil	0.600		0.522	
	Altitude + Slope		0.693		0.354	
	Altitude + Slope	+ aspect	0.713		0.567	
	"	x aspect	0.973	15	0.405	
	"	+ grazing	0.589		0.882	
	"	x grazing	0.194		0.556	
	"	+ vegetation	0.077	3.9	0.106	
	"	x vegetation	0.532		0.608	
	"	+ morphology	0.014	4.8	0.086	2.7
Multiple Linear Regression with Groups	"	x morphology	0.436		0.707	
	"	+ soil	0.160		0.047	3.8
	"	x soil	0.637		0.477	
		Aspect	0.724		0.677	
		Grazing	0.633		0.933	
		Vegetation	0.068		0.090	
		Morphology	0.011		0.062	
		Soil	0.129		0.030	
Analysis of Varlance						

Table V Output from analyses of bare and vegetated eroded area recorded on 50 m field sites.

Statistical test	Variable	Factor	Bare area		Vegetated area	
			<i>F pr</i>	<i>R</i> ²	<i>F pr</i>	<i>R</i> ²
Simple Linear Regression	Altitude		0.004	3.7	<0.001	12.8
	Slope		0.166		0.048	3.6
Simple Linear Regression with Groups	Altitude	+ aspect	0.754		0.654	
	"	x aspect	0.903		0.467	
	"	+ grazing	0.093	5.9	0.188	
	"	x grazing	0.653		0.755	
	"	+ vegetation	0.042		0.070	
	"	x vegetation	0.356		0.896	
	"	+ morphology	<0.001		0.789	
	"	x morphology	0.382		0.183	
	"	+ soil	0.088		0.074	17.1
	"	x soil	0.324		0.080	21.2
	Slope	+ aspect	0.913		0.700	
	"	x aspect	0.984		0.684	
	"	+ grazing	0.093	2.7	0.383	
	"	x grazing	0.433		0.441	
	"	+ vegetation	0.028	4.6	0.091	8.4
	"	x vegetation	0.377		0.903	
	"	+ morphology	<0.001		0.803	
	"	x morphology	0.820		0.580	
	"	+ soil	0.015	4.2	0.026	11
	"	x soil	0.064	6.4	0.869	
Multiple Linear Regression	Altitude + Slope		0.007	4	<0.001	17.5
Multiple Linear Regression with Groups	Altitude + Slope	+ aspect	0.843		0.487	
	"	x aspect	0.974		0.554	
	"	+ grazing	0.117		0.243	
	"	x grazing	0.422		0.617	
	"	+ vegetation	0.062	6.9	0.188	
	"	x vegetation	0.474		0.919	
	"	+ morphology	0.002	9.2	0.739	
	"	x morphology	0.584		0.450	
	"	+ soil	0.125		0.213	
	"	x soil	0.123		0.279	
Analysis of Variance		Aspect	0.838		0.773	
		Grazing	0.068		0.254	
		Vegetation	0.015		0.033	
		Morphology	<0.001		0.689	
		Soil	0.009		0.012	

Table VI Statistical analyses on changes in erosion recorded on 10 m field sites between 1997 and 1999.

Statistical test	Variate	Factor	10 m area		10 m volume	
			<i>F pr</i>	<i>R</i> ²	<i>F pr</i>	<i>R</i> ²
Simple Linear Regression	Altitude		0.204		0.921	
	Slope		0.267		0.640	
	Altitude	+ aspect	0.505		0.932	
	"	* aspect	0.154		0.362	
	"	+ grazing	0.834		0.925	
	"	* grazing	0.577		0.917	
	"	+ vegetation	0.784		0.851	
	"	* vegetation	0.943		0.279	
	"	+ morphology	0.645		0.877	
	"	* morphology	0.832		0.377	
	"	+ soil	0.251		0.337	
	"	* soil	0.584		0.092	39.5
	Slope	+ aspect	0.461		0.941	
	"	* aspect	0.451		0.716	
Simple Linear Regression with Groups	"	+ grazing	0.511		0.926	
	"	* grazing	0.629		0.950	
	"	+ vegetation	0.983		0.902	
	"	* vegetation	0.038	41.1	0.002	78.2
	"	+ morphology	0.946		0.857	
	"	* morphology	0.821		0.409	
	"	+ soil	0.226		0.343	
	"	* soil	0.885		0.195	
Multiple Linear Regression	Altitude + Slope		0.284		0.901	
Multiple Linear Regression with Groups	Altitude + Slope	+ aspect	0.623		0.897	
	"	* aspect	0.308		0.546	
	"	+ grazing	0.608		0.937	
	"	* grazing	0.848		0.956	
	"	+ vegetation	0.932		0.900	
	"	* vegetation	0.003	83.2	0.004	77.1
	"	+ morphology	0.703		0.849	
	"	* morphology	0.963		0.470	
	"	+ soil	0.330		0.398	
	"	* soil	0.557		0.215	
Analysis of variance		Aspect	0.333		0.972	
		Grazing	0.760		0.911	
		Vegetation	0.921		0.862	
		Morphology	0.846		0.904	
		Soil	0.147		0.288	

Table VII Statistical analyses on changes in erosion recorded on 50 m field sites between 1997 and 1999.

Statistical test	Variate	Factor	50 m area		50 m volume	
			<i>F pr</i>	<i>R²</i>	<i>F pr</i>	<i>R²</i>
Simple Linear Regression	Altitude		0.092	3.2	0.551	
	Slope		0.283		0.814	
	Altitude	+ aspect	0.355		0.893	
	"	* aspect	0.194		0.242	
	"	+ grazing	0.333		0.802	
	"	* grazing	0.206		0.460	
	"	+ vegetation	0.748		0.548	
	"	* vegetation	0.398		0.303	
	"	+ morphology	0.204		0.029	7.7
	"	* morphology	0.161		0.180	
	"	+ soil	0.141		0.100	4.7
	"	* soil	0.665		0.456	
Simple Linear Regression with Groups	Slope	+ aspect	0.616		0.871	
	"	* aspect	0.602		0.815	
	"	+ grazing	0.315		0.802	
	"	* grazing	0.969		0.926	
	"	+ vegetation	0.668		0.509	
	"	* vegetation	0.073	6.2	0.021	12.1
	"	+ morphology	0.240		0.034	6.7
	"	* morphology	0.506		0.670	
	"	+ soil	0.059	8.0	0.073	5.5
	"	* soil	0.633		0.215	
Multiple Linear Regression	Altitude + Slope		0.163		0.800	
Multiple Linear Regression with Groups	Altitude + Slope	+ aspect	0.425		0.905	
	"	* aspect	0.414		0.772	
	"	+ grazing	0.324		0.802	
	"	* grazing	0.597		0.750	
	"	+ vegetation	0.765		0.533	
	"	* vegetation	0.187		0.097	6.9
	"	+ morphology	0.278		0.031	6.2
	"	* morphology	0.468		0.468	
	"	+ soil	0.126		0.070	4.8
	"	* soil	0.537		0.381	
Analysis of variance		Aspect	0.525		0.861	
		Grazing	0.317		0.802	
		Vegetation	0.584		0.534	
		Morphology	0.164		0.034	
		Soil	0.058		0.105	

Appendix 5

Table I Soil deposition on 10 m field sites, related to altitude

Altitude	Count	Total area	Total volume	Mean area	Mean volume
≤200	0	0.0	0.0	0.0	0.0
201-300	1	8.0	0.5	8.0	0.5
301-400	2	5.1	3.3	2.6	1.7
401-500	2	3.6	1.7	1.8	0.9
501-600	3	32.5	21.2	10.8	7.1
601-700	4	5.9	2.6	1.5	0.7
≥700	2	91.0	28.6	45.5	14.3
Total	14	146.1	57.9	70.2	25.0

Table II Soil deposition on 50 m field sites, related to altitude

Altitude	Count	Total area	Total volume	Mean area	Mean volume
≤200	0	0.0	0.0	0.0	0.0
201-300	3	2.3	12.8	0.8	4.3
301-400	9	5.4	35.5	0.6	3.9
401-500	7	10.3	38.7	1.5	5.5
501-600	9	18.1	113.0	2.0	12.6
601-700	11	7.5	18.1	0.7	1.6
≥700	2	46.1	386.0	23.1	193.0
Total	41	89.7	604.1	28.6	220.9

Table III Soil deposition on 10 m field sites, related to slope

Slope	Count	Total area	Total volume	Mean area	Mean volume
<3	2	3.1	0.4	1.6	0.2
4-7	5	10.4	3.4	2.1	0.7
8-11	0	0.0	0.0	0.0	0.0
12-15	1	25.0	20.0	25.0	20.0
16-25	1	3.3	1.6	3.3	1.6
≥25	5	104.0	32.5	20.8	6.5
Total	14	145.8	57.9	52.7	29.0

Table IV Soil deposition on 50 m field sites, related to slope

Slope	Count	Total area	Total volume	Mean area	Mean volume
<3	4	2.5	9.3	0.6	2.3
4-7	17	29.5	135.0	1.7	7.9
8-11	6	2.4	10.2	0.4	1.7
12-15	3	1.3	20.3	0.4	6.8
16-25	5	3.4	25.2	0.7	5.0
≥25	6	50.8	425.0	8.5	70.8
Total	41	89.9	625.0	12.3	94.6

Table V Soil deposition on 10 m field sites, related to aspect

Aspect	Count	Total area	Total volume	Mean area	Mean volume
NE	2	40.3	12.7	20.2	6.4
E	0	0.0	0.0	0.0	0.0
SE	2	2.8	2.2	1.4	1.1
S	3	76.1	36.0	25.4	12.0
SW	0	0.0	0.0	0.0	0.0
W	3	9.1	5.0	3.0	1.7
NW	1	6.7	1.1	6.7	1.1
N	2	9.5	0.6	4.8	0.3
Total	13	144.5	57.6	61.4	22.5

Table VI Soil deposition on 50 m field sites, related to aspect

Aspect	Count	Total area	Total volume	Mean area	Mean volume
NE	7	41.6	324	5.9	46.3
E	4	13.2	51	3.3	12.8
SE	3	0.6	4.6	0.2	1.5
S	9	13.7	194	1.5	21.6
SW	2	1.6	3.3	0.8	1.7
W	6	2.4	27.9	0.4	4.7
NW	2	12.6	6.1	6.3	3.1
N	7	2.5	7.0	0.4	1.0
Total	40	88.2	618	18.8	92.5

Table VII Soil deposition on 10 m field sites, related to field site morphology

Shape	Count	Total area	Total volume	Mean area	Mean volume
Concave	1	6.7	1.1	6.7	1.1
Linear	9	104.0	35.0	11.6	3.9
Convex	4	35.3	21.9	8.8	5.5
Total	14	146.0	58.0	27.1	10.5

Table VIII Soil deposition on 50 m field sites, related to field site morphology

Shape	Count	Total area	Total volume	Mean area	Mean volume
Concave	7	25.5	54.1	3.6	7.7
Linear	18	57.6	532.0	3.2	29.6
Convex	16	6.5	38.9	0.4	2.4
Total	41	89.6	625.0	7.2	39.7

Table IX Soil deposition on 10 m field sites, related to soil class

Soil class	Count	Total area	Total volume	Mean area	Mean volume
Dry mineral	3	48.1	13.1	16.0	4.4
Wet mineral	3	59.3	20.9	19.8	7
Wet peaty mineral	0	0	0	0	0
Peat	8	38.7	23.9	4.8	3
Total	14	146.1	57.9	40.6	14.3

Table X Soil deposition on 50 m field sites, related to soil class

Soil class	Count	Total area	Total volume	Mean area	Mean volume
Dry mineral	6	44.8	343	7.5	57.2
Wet mineral	5	8.9	100	1.8	20
Wet peaty mineral	8	7.5	110	0.9	13.8
Peat	22	28.4	72.4	1.3	3.3
<i>Total</i>	<i>41</i>	<i>89.6</i>	<i>625</i>	<i>11.5</i>	<i>94.2</i>

Table XI Soil deposition on 10 m field sites, related to vegetation

Vegetation	Count	Total area	Total volume	Mean area	Mean volume
Scrub	0	0	0	0	0
Bracken	0	0	0	0	0
Upland grass	9	134	55	14.9	6.1
UG/H	1	0.1	0	0.1	0
Upland heath	3	5.3	1.8	1.8	0.6
H/B	1	6.7	1.1	6.7	1.1
Bog	0	0	0	0	0
<i>Total</i>	<i>14</i>	<i>146.1</i>	<i>57.9</i>	<i>23.5</i>	<i>7.8</i>

Table XII Soil deposition on 50 m field sites, related to vegetation

Vegetation	Count	Total area	Total volume	Mean area	Mean volume
Scrub	0	0.0	0.0	0.0	0.0
Bracken	1	0.5	0.3	0.5	0.3
Upland grass	21	58.1	556.0	2.8	26.5
UG/H	5	0.4	1.9	0.1	0.4
Upland heath	12	18.0	54.0	1.5	4.5
H/B	2	12.7	12.5	6.4	6.3
Bog	0	0.0	0.0	0.0	0.0
<i>Total</i>	<i>41</i>	<i>89.7</i>	<i>624.7</i>	<i>11.2</i>	<i>37.9</i>

Table XIII Soil deposition on 10 m field sites, related to grazing pressure

Grazing	Count	Total area	Total volume	Mean area	Mean volume
0	1	1.5	0.1	1.5	0.1
1	0	0.0	0.0	0.0	0.0
2	5	11.6	3.0	2.3	0.6
3	3	8.7	1.3	2.9	0.4
4	4	73.3	37.5	18.3	9.4
5	1	51.0	16.0	51.0	16.0
<i>Total</i>	<i>14</i>	<i>146</i>	<i>57.9</i>	<i>76.0</i>	<i>26.5</i>

Table XIV Soil deposition on 50 m field sites, related to grazing pressure

Grazing	Count	Total area	Total volume	Mean area	Mean volume
0	2	0.3	1.1	0.2	0.6
1	6	9.7	21.6	1.6	3.6
2	15	22.6	61.8	1.5	4.1
3	9	5.3	31.5	0.6	3.5
4	8	45.6	436.0	5.7	54.5
5	1	6.1	72.0	6.1	72.0
<i>Total</i>	<i>41</i>	<i>89.6</i>	<i>624</i>	<i>15.7</i>	<i>138</i>

Appendix 6

Table 1 Comparison of 1997 and 1999 traverses for significant differences using Student's t –test (3 traverses per site, a, b and c). One and two tailed tests assess differences between population means at one and at both ends of the distribution respectively.

P(T<=t)	One tail	Two tail	P(T<=t)	One tail	Two tail
NT91/1060a	0.47	0.93	SD79/6060a	0.42	0.84
NT91/1060b	0.17	0.33	SD79/6060b	0.46	0.93
NT91/1060c	0.36	0.71	SD79/6060c	0.30	0.59
NU12/1060a	0.48	0.96	SD98/1010a	0.41	0.82
NU12/1060b	0.47	0.93	SD98/1010b	0.50	1.00
NU12/1060c	0.46	0.91	SD98/1010c	0.50	0.99
NY73/1010a	0.48	0.95	SE00/1010a	0.47	0.94
NY73/1010b	0.48	0.95	SE00/1010b	0.46	0.91
NY73/1010c	0.37	0.74	SE00/1010c	0.19	0.38
NY73/1060a	0.47	0.94	SE01/1010a	0.24	0.49
NY73/1060b	0.50	1.00	SE01/1010b	0.04	0.09
NY73/1060c	0.48	0.95	SE01/1010c	0.12	0.25
NY73/2525a	0.42	0.85	SE07/6010a	0.47	0.94
NY73/2525b	0.30	0.61	SE07/6010b	0.47	0.94
NY73/2525c	0.45	0.90	SE07/6010c	0.47	0.94
NY73/6010a	0.41	0.83	SH71/6061a	0.44	0.88
NY73/6010b	0.35	0.70	SH71/6061b	0.47	0.94
NY73/6010c	0.43	0.87	SH71/6061c	0.48	0.96
NY77/1060a	0.48	0.97	SH82/6012a	0.43	0.87
NY77/1060b	0.48	0.96	SH82/6012b	0.43	0.86
NY77/1060c	0.23	0.46	SH82/6012c	0.39	0.78
NY80/6060a	0.44	0.87	SH95/1010a	0.49	0.98
NY80/6060b	0.49	0.98	SH95/1010b	0.22	0.44
NY80/6060c	0.46	0.93	SH95/1010c	0.42	0.84
NY83/1060a	0.45	0.90	SK07/1010a	0.12	0.22
NY83/1060b	0.43	0.87	SK07/1010b	0.44	0.87
NY83/1060c	0.46	0.91	SK09/2575a	0.46	0.92
NY84/1010a	0.36	0.73	SK09/2575b	0.34	0.68
NY84/1010b	0.37	0.74	SK09/2575c	0.48	0.95
NY84/1010c	0.20	0.40	SK19/1060a	0.39	0.77
NY93/6010a	0.17	0.33	SK19/1060b	0.48	0.97
NY93/6010b	0.48	0.96	SK19/1060c	0.34	0.68
NY93/6010c	0.39	0.78	SN75/1060a	0.46	0.93
SD65/6060a	0.42	0.83	SN75/1060b	0.48	0.97
SD65/6060b	0.39	0.78	SN75/1060c	0.42	0.85
SD65/6060c	0.45	0.90	SN88/1060a	0.44	0.88
SD79/6010a	0.37	0.75	SN88/1060b	0.34	0.69
SD79/6010b	0.22	0.43	SN88/1060c	0.34	0.68
SD79/6010c	0.46	0.91	SN91/6060a	0.42	0.84
			SN91/6060b	0.37	0.74
			SN91/6060c	0.27	0.53

Table II Examples of gully traverses remeasured to assess experimental error. The third column provides the differences between point measurements, which were then averaged for individual traverses. All mean differences were less than 1 cm.

Depth measurements		
Original	Repeat	Difference
0	0	0
7	6	1
34	34	0
39	39	0
47	48	1
40	40	0
37	36	1
36	35	1
29	30	1
20	20	0
4.5	4.5	0
0	0	0
Mean difference		0.42
0	0	0
16	15	1
25	25	0
38	36	2
49	48	1
61	61.5	0.5
70	71	1
67	67	0
53	52	1
47	46	1
40	40	0
22	22	0
2	2.5	0.5
0	0	0
Mean difference		0.57

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