

Geomorphological controls on the re-vegetation of erosion gullies in blanket peat: implications for bog restoration

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SUMMARY

This paper describes the natural re-vegetation of eroded blanket peat gullies in the Dark Peak National Park, Southern Pennines (UK). Sequences derived from the plant macrofossil records of nine peat cores indicate a two-phase process of re-vegetation consisting of (a) a primary (pioneer) phase of colonisation by *Eriophorum angustifolium* (common cottongrass), and (b) a secondary phase involving colonisation by up to six species, establishing to either wet bog or dry heath vegetation. The stratigraphy not only reveals temporal changes in the development of the plant communities, but also shows patterns in the upstream-downstream direction that give insights into how species spread from the initial re-vegetation zone. The locations where re-vegetation begins are hypothesised to be determined by local geomorphological controls that create zones of re-deposited peat offering favourable conditions for colonisation. Management intervention aiming to restore areas of blanket peatland affected by gully erosion should focus on mimicking these geomorphic controls to reinforce natural trajectories of recovery of the physical system. This would promote colonisation by naturally occurring species that are adapted to the specific local environment, and would thus maximise the probability of establishing self-sustaining restored peatland.

KEY WORDS: *Eriophorum angustifolium*, *Sphagnum*, palaeoecology, plant macrofossils, South Pennines.

INTRODUCTION

Northern peatlands play an important role in the global carbon (C) cycle, storing about 450 Gt C, which amounts to about 30% of the global soil carbon pool (Gorham 1991). Widespread gully erosion of upland blanket peat in the UK (Tallis 1997) has the effect of providing natural drainage and locally lowering the water table, enhancing losses of gaseous and dissolved carbon (Worrall *et al.* 2003). However, in actively eroding peatland, particulate carbon loss is potentially the largest single flux (Evans *et al.* 2006). Restoration of eroded blanket mire in the UK has focused on re-establishing vegetation cover by re-seeding and fertilising areas of bare peat (Tallis & Yaldon 1983). More recently, new approaches have been adopted which aim to restore the wider functioning of the peatland system. Since 2002, for example, a programme of artificial gully blocking in the South Pennines which aims to raise the local water table and encourage both infilling and re-vegetation of the gullies has been carried out by the UK National Trust (Trotter *et al.* 2005). Despite the severity of degradation, natural re-vegetation is widely observed in Pennine blanket peatland (Clements 2005, Crowe 2007). Natural re-vegetation of eroded peatland gullies has been shown to reduce

significantly the magnitude of the particulate flux (Evans & Warburton 2005) and can also initiate fresh peat growth, promoting recovery of the water table and the natural hydrological regime. Previous work (Wishart & Warburton 2001, Evans *et al.* 2005, Evans & Warburton 2005) has indicated that the geomorphological context is an important control on re-vegetation processes in eroded gully systems. Blocking of relatively narrow gullies by peat released through mass failure of their walls plays a potentially important role in initiating re-vegetation (Figure 1a). In broader, flat-floored gullies characteristic of the later stages of peat erosion, a different pattern of re-vegetation is hypothesised. In these wider gullies the flowing stream migrates across the gully floor and the process of channel migration causes deposition of peat on the insides of bends. The waterlogged re-deposited peat makes an ideal surface for colonisation by *Eriophorum angustifolium* (common cottongrass). In both types of gully re-vegetation the rapid spread of pioneer cottongrass species appears to increase surface roughness and promote further peat deposition and vegetation spread. Similar feedback patterns have been observed in anastomosing systems in Poland. (Gradzinski *et al.* 2003) and in semi-arid systems in Spain (Bochet *et al.* 2000).

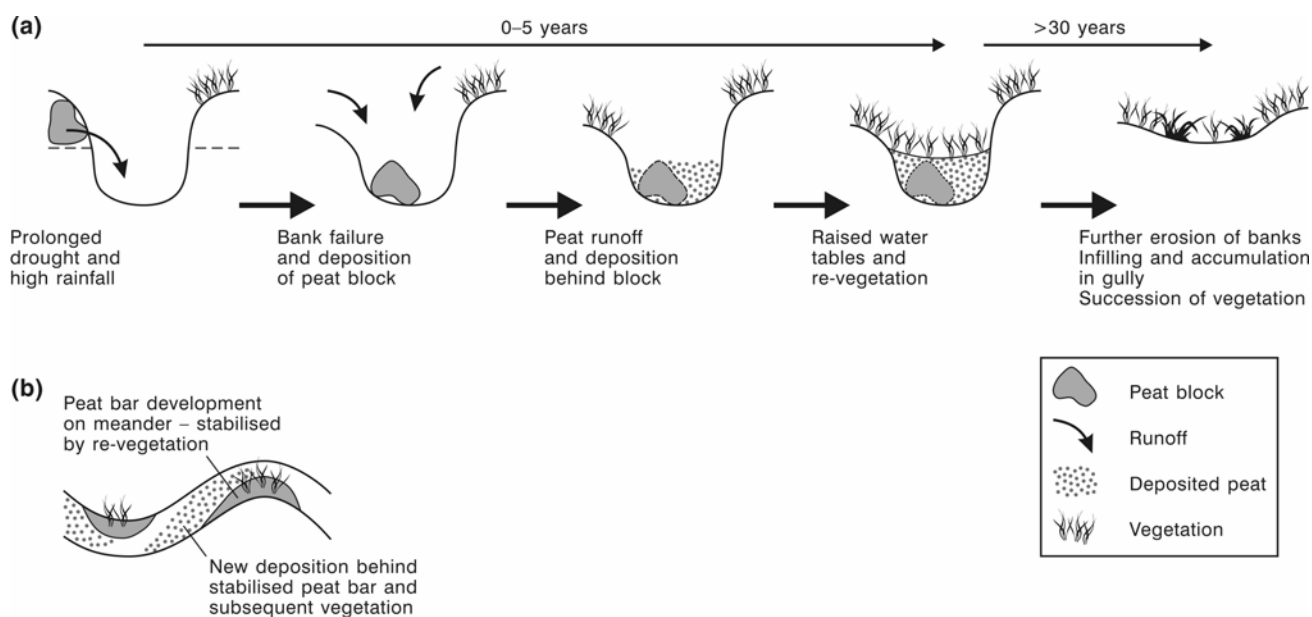


Figure 1. Hypothesised modes of re-vegetation in (a) narrow and (b) broad gullies in eroded blanket bog.

This paper aims for the first time to investigate gully re-vegetation processes in detail. The specific aims are:

- (1) to use stratigraphic evidence from peat cores extracted from re-vegetating gullies with distinct geomorphological contexts to determine the natural re-vegetation trajectories that can occur; and
- (2) to suggest how these sequences of re-vegetation can be used as natural templates for artificial restoration strategies.

METHODS

Study area and site selection

The Dark Peak is one of the summits within the 1,438 km² Peak District National Park in north-west England (UK). In the Dark Peak area, where the study sites are located, carboniferous mudstones and gritstones are overlain by ombrotrophic blanket peat up to three metres thick, the lower deposits dating to *ca.* 5,000–8,000 BP (Conway 1954). Much of this blanket peat has experienced two periods of erosion. The first phase began *ca.* 1450 AD (550 BP) and caused widespread desiccation and degradation. The second phase, commencing around 250 years ago, resulted in the formation of extensive gully systems and is clearly evident in the *Empetrum* pollen record (Tallis 1997).

The contemporary plant communities of the Dark Peak area are predominantly composed of two associations of the UK National Vegetation

Classification (NVC). This system provides a series of broad vegetation classes derived from a survey of major plant associations occurring within 10 km grid squares. Mire communities are indicated by the prefix 'M' (Rodwell 1991). At the study sites described in this paper, the vegetation of remaining intact mire belongs to the species-poor community *Eriophorum angustifolium* blanket bog (M20), and the *E. angustifolium* sub-community (M20a) is distinguished where some species have declined due to aerial pollution (Ferguson *et al.* 1978) and land management (Tallis 1981). Where the water table is relatively low at gully edges, the community changes locally to *Vaccinium* 'edge', a separate seral community which is characterised by *Vaccinium myrtillus* and *Empetrum nigrum* (Ritchie 1956).

Gully systems in which re-vegetation had taken place were identified initially by comparing air photographs taken in 1977 and 2000 (Figure 2). Their suitability was then checked by making field visits to ensure that re-vegetation was indeed occurring. In the field, geomorphological characteristics of the selected gullies were noted and locations with visually different species assemblages were chosen for individual cores.

Upper North Grain, at UK National Grid Reference SK 108938 and altitude 520 m a.s.l. is a headwater catchment containing both severely eroded gully systems and re-vegetated peat-floored and mineral-floored gullies. Doctor's Gate (SK 095931) is a headwater catchment at 500 m a.s.l.

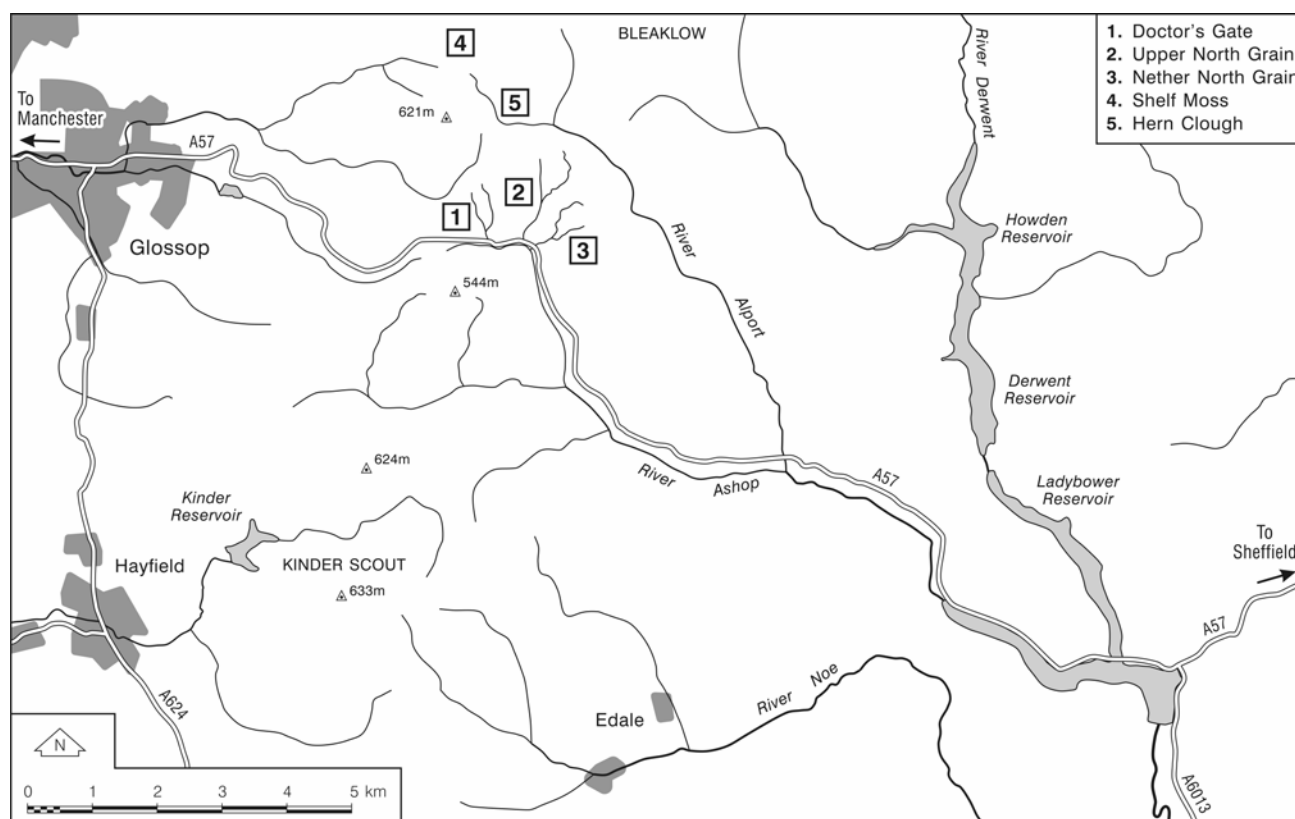


Figure 2. Locations of sites (catchments) identified from air photographs for the study of natural re-vegetation. Catchments 1–3 are clustered around latitude $53^{\circ} 26' 00''$ N, longitude $1^{\circ} 51' 00''$ W. Cores from Catchments 1, 2 and 4 are described in this paper.

with re-vegetated narrow V-shaped peat-floored gullies and a notable gully system with extensive re-vegetation by *Sphagnum* species. Shelf Moss (SK 088958, 580 m a.s.l.) contains large areas of sheet erosion as well as shallow but wide U-shaped peat-floored gullies with meandering drainage.

Collection and analysis of peat cores

Vertical peat cores were taken from re-vegetating gullies using a Russian corer. Three coring locations were selected within each of the study catchments, providing a total of nine peat cores. The cores ranged in length from 30 to 50 cm, and the core locations encompassed a range of geomorphological contexts (Table 1). To establish the species richness of contemporary plant communities at each site, the percentage cover of each species and non-vegetated gully floor substrate was estimated using a 1 m^2 quadrat sub-divided into 10 cm squares placed over the coring area.

Each core was divided into 4 cm sections and analysed for plant macrofossils, loss-on-ignition and moisture content.

A method adapted from Barber (1980) was used for plant macrofossil analysis. A 4 cm^3 sub-sample of peat was taken from each section and washed

through a $450 \mu\text{m}$ sieve into a 3 litre beaker. A $450 \mu\text{m}$ sieve was used instead of the standard $125 \mu\text{m}$ sieve because most of the plant macrofossils were $>1 \text{ mm}$ in diameter, and these were retained whilst the finer macrofossils and amorphous peat particles from the original intact peat were washed through. The retained macrofossils were then washed into a Petri dish, identified to species level where possible, and counted. The floras used were Stace (1997) for vascular plants and Smith (2004) for mosses. This technique was considered to be more sensitive than the Quadrat and Leaf count method (Barber 1980), which is commonly used in environments with a higher density of species. In addition it allowed macrofossils to be counted more rapidly than if the sub- $450 \mu\text{m}$ macrofossils were included. Although it is possible that the secondary peat deposits contained finer fossils, those observed in the waste were mainly small ericaceous fragments characteristic of the primary peat deposits. It is considered, therefore, that the loss of macrofossils from secondary peat was small.

Approximately 1g of each peat section was placed in a pre-weighed crucible and dried in an oven at 105°C for 24 hours. The samples were then re-weighed, placed in a muffle furnace for 3 hours at

Table 1. Locations and environmental contexts of gully cores.

Catchment	Environmental context
Upper North Grain (UNG) Cores: 1a, 2a, 3a	All core locations were in the broader, U shaped lower reaches (gully mouth); UNG1a and UNG2a in peat-floored gullies and UNG3a in a mineral-floored gully. Core locations were selected to represent the observed variation in plant communities.
Doctor's Gate (DG) Cores: 1a, 1b, 1c	Long linear V-shaped gullies terminating in a well vegetated central confluence/erosion zone. The three cores were taken to characterise the vegetation of both individual gullies and the confluence zone.
Shelf Moss (SM) Cores: 1a, 1b, 1c	Broad U-shaped and frequently interconnecting gullies with extensive colonisation by <i>Eriophorum angustifolium</i> and bare peat flats.

550°C, cooled and re-weighed. Ash free dry mass (g) and percentage organics were then calculated.

In order to evaluate the data, it was necessary to make a key distinction between primary peat (i.e. the remaining pre-erosion peat) and secondary peat (i.e. sediment deposition and peat growth following re-vegetation of the erosion surface). Reliable identification of this boundary (Figure 3) was essential. The boundary is associated with a significant change in sedimentary conditions, and its identification in each core was based on the consideration of four stratigraphic attributes: first, the level of decomposition of the material as assessed using the von Post Classification system (von Post & Granlund 1926, *op. cit.* Berglund 1986); second, the organic matter content of the peat; third the moisture content of the peat; and fourth, a visual assessment of peat texture.

Plant macrofossil and sediment stratigraphic data were plotted using C2 software[®] (Juggins 2007) to allow visual assessment.

RESULTS

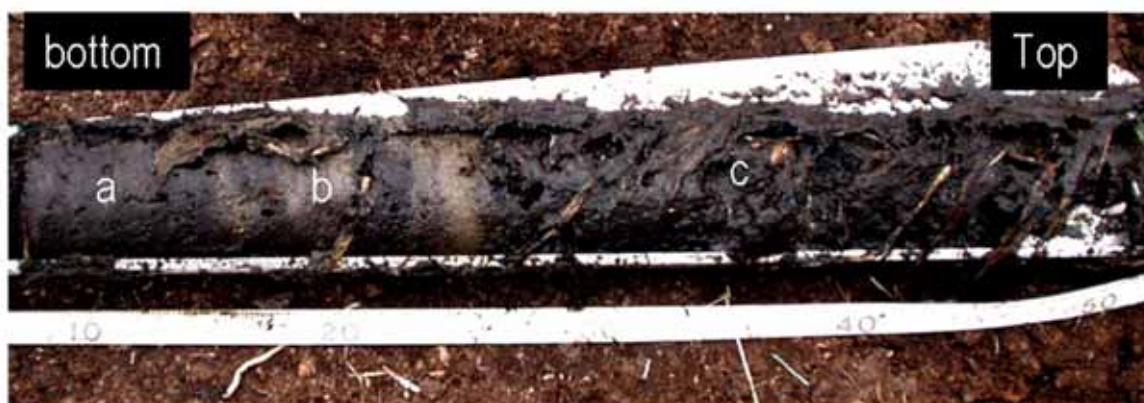
Stratigraphic macrofossil records

The macrofossil diagrams for the sediment cores (Figures 4–6) reveal initial phases of pioneer colonisation and subsequent phases of succession to different plant communities, which are also reflected in the recent plant communities at all sites (Table 2). They also show sediment organic content and have been qualitatively zoned on the basis of both the macrofossil and lithostratigraphic data. It should be noted that the macrofossil records presented here show the record of changes for both primary and secondary peat. The stratigraphic location interpreted as representing the onset of re-

vegetation, and hence of new peat formation, is marked on each diagram. The secondary peat in all cores is confined to the uppermost 20 cm, and the macrofossil records are species poor. Table 3 summarises the species identified in the plant macrofossil record and their individual frequencies.

Upper North Grain

The stratigraphy of the cores from Upper North Grain is shown in Figure 4. In Core UNG1a (Figure 4a) the boundary between primary and secondary peat is clearly defined by a zone of mineral deposition (Figure 3a) and disjunction in the macrofossil record. The core has a 10 cm lower section of well decomposed (H7) primary peat characterised by a high percentage of organic matter (which is also characteristic of the peat in the adjacent exposed gully walls) and contains *E. angustifolium*, *Eriophorum vaginatum* and *V. myrtillus*. These species disappear at 18 cm, where there is also a sharp decline in moisture and organics. No plant macrofossils are present in the zone of mineral sediments between 18 and 11 cm. This section reflects a period of changing surface conditions, with alternating layers of peat and fine mineral sediment. This is indicative of headwater instability with inwashes of mineral sediment from the gully floor and peat eroded from banks and the surrounding catchment. From 15 cm to the present surface the core record shows stabilisation and pioneer colonisation of the poorly decomposed (H1/H2) secondary peat surface. Pioneer colonisation is characterised by an increase in moisture and organic content to 80% and 90% respectively accompanied by a gradual increase in *E. angustifolium*. Core UNG2a (Figure 4b) shows evidence of a more advanced succession to *Eriophorum angustifolium*-*Sphagnum* bog with the



a - Primary peat: well consolidated, high organic content and contains a similar plant macrofossil assemblage to the exposed gully walls.

b - Alternating mineral/ peat layers indicative of upstream erosion.

c - Secondary peat: poorly consolidated, variable organic content and markedly different plant macrofossil assemblages to the exposed gully wall.



a - Primary peat with intruding rhizomes from the underlying secondary peat

b - Secondary peat: primary assemblage of *Eriophorum angustifolium*

c- Secondary peat: secondary assemblage of *Sphagnum*

Figure 3. Example peat cores UNG1a (upper photograph) and UNG2a (lower photograph) taken from re-vegetated gullies, showing their physical structure. Note the abrupt transition from the well consolidated primary peat at the bottom of each core to loose, crumbly secondary peat above.

Table 2. Summary of contemporary species assemblages at the nine coring sites. Nomenclature follows Stace (1997) for vascular plants and Smith (2004) for mosses.

Site	Contemporary species and cover (%)
UNG1a	<i>Eriophorum angustifolium</i> (100)
UNG2a	<i>Sphagnum cuspidatum</i> (100)
UNG3a	<i>Eriophorum angustifolium</i> (50); <i>Eriophorum vaginatum</i> (5); <i>Vaccinium myrtillus</i> (30); <i>Empetrum nigrum</i> (15)
DG1a	<i>Eriophorum angustifolium</i> (10); <i>Sphagnum cuspidatum</i> (60); <i>Sphagnum denticulatum</i> (10); <i>Juncus effusus</i> (20)
DG1b	<i>Sphagnum denticulatum</i> (20); <i>Juncus effusus</i> (80)
DG1c	<i>Eriophorum angustifolium</i> (100)
SM1a	<i>Eriophorum angustifolium</i> (55); bare peat (45)
SM1b	<i>Eriophorum angustifolium</i> (95); bare peat (5)
SM1c	<i>Eriophorum angustifolium</i> (100)

Table 3. Summary of species abundance and frequency in the plant macrofossil records. Species nomenclature as for Table 2.

Species	Maximum abundance of individual fragments observed	Number of cores with records
<i>Eriophorum angustifolium</i>	54	8
<i>Eriophorum vaginatum</i>	2	1
<i>Sphagnum cuspidatum</i>	480	2
<i>Sphagnum denticulatum</i>	180	2
<i>Polytrichum commune</i>	16	1
<i>Juncus effusus</i>	5	2
<i>Vaccinium myrtillus</i>	15	3
<i>Empetrum nigrum</i>	5	2

contemporary plant community consisting of wet *Juncus-Sphagnum* bog. The primary peat assemblage consists of *E. angustifolium*, *V. myrtillus* and *E. nigrum*, and as in Core UNG1a this zone has a high organic content (94%) and is well decomposed (H6 on the von Post scale). There is then an abrupt reduction in organic content indicating peat degradation. The boundary between primary and secondary peat is identified at 12 cm by an abrupt change in plant macrofossils, peat texture and organic content. From 12 cm to 8 cm depth, an increase in organic content (92%) signifies the process of secondary peat deposition. This layer also has a lower (H4) von Post classification and the peat is loosely bound, being clumped around the *E. angustifolium* rhizomes (Figure 3a). The appearance

of *Sphagnum cuspidatum* amongst the *E. angustifolium* at 8 cm marks the change to secondary peat assemblages and coincides with an increase in sediment organic content to a level similar to that in the primary peat (95%). Core UNG3a (Figure 4c) contains a different succession sequence. Unlike Core UNG2a, where re-vegetation occurred on a surface of primary peat and inwashed mineral sediment, Core UNG3a shows only mineral sediments in the basal zone. The bottom 15 cm of the core consists of loose mineral substrate and this overlies a deeper coarse mineral substrate. This indicates that erosion reached the sub-peat mineral deposits at this location, and re-vegetation and the accumulation of secondary peat has occurred directly onto this mineral substrate. At

approximately 12 cm there is an abrupt change to poorly decomposed (H2) peat and evidence of the early stages of pioneer *E. angustifolium* colonisation appears in the macrofossil record. There is then a further increase in *E. angustifolium* and *E. vaginatum*. *V. myrtillus* and *E. nigrum* also appear and increase in abundance, indicating a change to drier surface conditions and development of a dry heath community which is now well established in the contemporary gully vegetation (see Table 2).

Doctor's Gate

The plant community at DG1a, like its counterparts at Upper North Grain, is at an advanced stage of succession. Aerial photography indicated that this gully had no vegetation and was eroding in 1977, but that full vegetation cover had established by 2003. Core DG1a (Figure 5a) shows a re-vegetation sequence in three stages with moderately decomposed (H3/H4) peat throughout the core. The first stage begins at 28 cm depth with the *E. angustifolium* pioneer colonisation sequence. The organic content is already relatively high, rising in the lower stratigraphy to a peak of 98% at 24 cm depth. Although there is no clearly defined break in the macrofossil or lithostratigraphic data indicating a sharp boundary between primary and secondary peat, the sequence is consistent with a secondary peat succession. At 18 cm *E. angustifolium* is joined by *Sphagnum denticulatum* and *Polytrichum commune*, which gradually increase in abundance. Stage 2 commences at 16 cm, with a reduction in *E. angustifolium* and a gradual increase in *S. cuspidatum* accompanied by persistence of *S. denticulatum*. Both of these species remain at constant abundance until 12 cm, at which point there is a marked increase in organic content reflecting the onset of the third stage of re-vegetation. The increase in organic content here is accompanied by increases in *S. cuspidatum* and *S. denticulatum*, with the latter beginning to dominate the macrofossil assemblage. Both *Sphagnum* species continue to increase rapidly to 8 cm at which point *Juncus effusus* appears and, although the peak of this species is small, the associated slight decline in abundance of both *S. cuspidatum* and *S. denticulatum* is notable. All three species are found in the contemporary plant community. Core DG1b (Figure 5b) is upstream of DG1a and shows a different pattern of re-vegetation. It is unique amongst the study cores in having no initial stage of *E. angustifolium* colonisation. The depth range 48–8 cm contains primary peat characterised by a high density of *C. vulgaris* macrofossils, constant high organic content, the presence of charcoal layers and well decomposed (H7) peat. From 8 cm there is a

gradual increase in *J. effusus* and a very small increase in *S. denticulatum*, coincident with a further gradual increase in organic content continuing to the contemporary peat surface. Core DG1c (Figure 5c) was taken from near the headwaters of the gully and appears to show a less developed re-vegetation sequence. The lowermost 28 cm of the core consists of well decomposed (H7) primary peat with macrofossil assemblages dominated by *C. vulgaris* but with small amounts of *E. vaginatum*, *V. myrtillus* and *E. nigrum*. The boundary between primary and secondary peat is identified by a temporary decline in organic content at 12 cm. The abundance of *E. angustifolium* increases rapidly upwards from 6 cm to the present day peat surface, and this species provides complete cover in the contemporary vegetation (Table 2).

Shelf Moss

The Shelf Moss cores were taken from a reach of re-vegetating meandering channel (Table 1). Core SM1a (Figure 6a) indicates less well established re-vegetation in the lower half of the channel with the majority of the core (48–4 cm) being composed of macrofossil assemblages indicative of primary peat, in particular high abundance of *V. myrtillus*. The boundary between primary and secondary peat is less well defined in this core than in the cores from Upper North Grain and Doctor's Gate, although the disappearance of *Racomitrium* and the appearance and sharp increase in *E. angustifolium* at 4 cm are consistent with a primary–secondary transition. The middle reaches of the channel represented by Core SM1b have a higher percentage cover of *E. angustifolium* in contemporary vegetation than the area represented by Core SM1a (Table 2). The lowermost 32 cm of Core SM1b (Figure 6b) has *Racomitrium lanuginosum*, *C. vulgaris* and *Sphagnum* spp. macrofossils characteristic of primary peat. At 12 cm the re-vegetation surface and secondary peat development are identified by the reappearance of *E. angustifolium* and, as in Core SM1a, this species increases rapidly in the plant macrofossil record between 12 cm and 4 cm depth. The site farthest upstream, SM1c (Figure 6c), has 100% cover of *E. angustifolium* (Table 2). The lowermost 16 cm of Core SM1c is composed of primary peat with *C. vulgaris* macrofossils. As in both SM1a and SM1b there is no discernable variation in its organic content, which remains above 90%. The transition to secondary peat is marked by a sudden decline in *C. vulgaris* macrofossils and the appearance and rapid increase of *E. angustifolium* plant fragments between 24 cm and 20 cm. *E. angustifolium* continues in the stratigraphic record up to the surface.

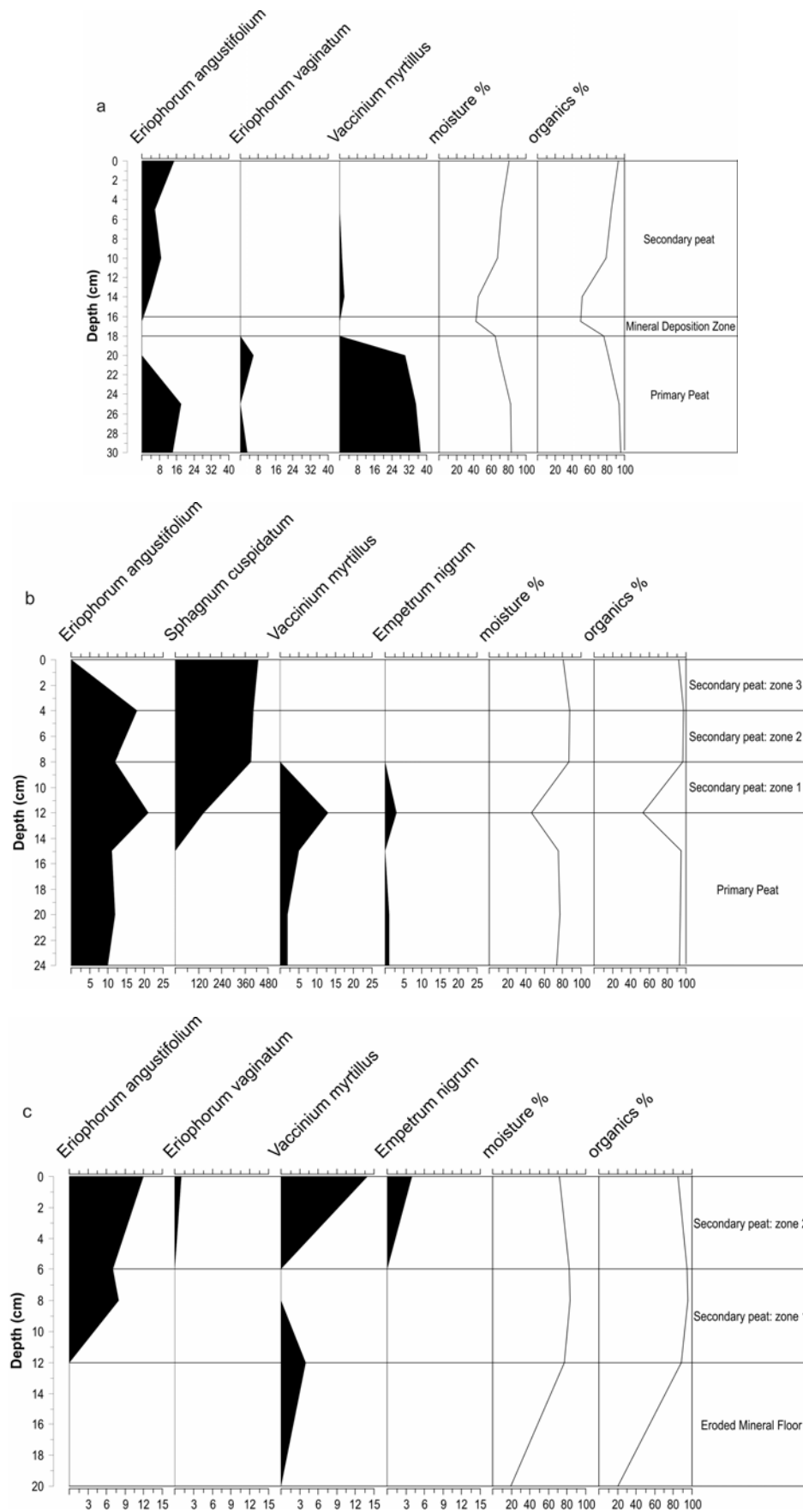


Figure 4. Summary plant macrofossil, moisture and organic content data for peat cores from gullies in the Upper North Grain catchment. (a) Core UNG1a; (b) Core UNG2a; (c) Core UNG3a.

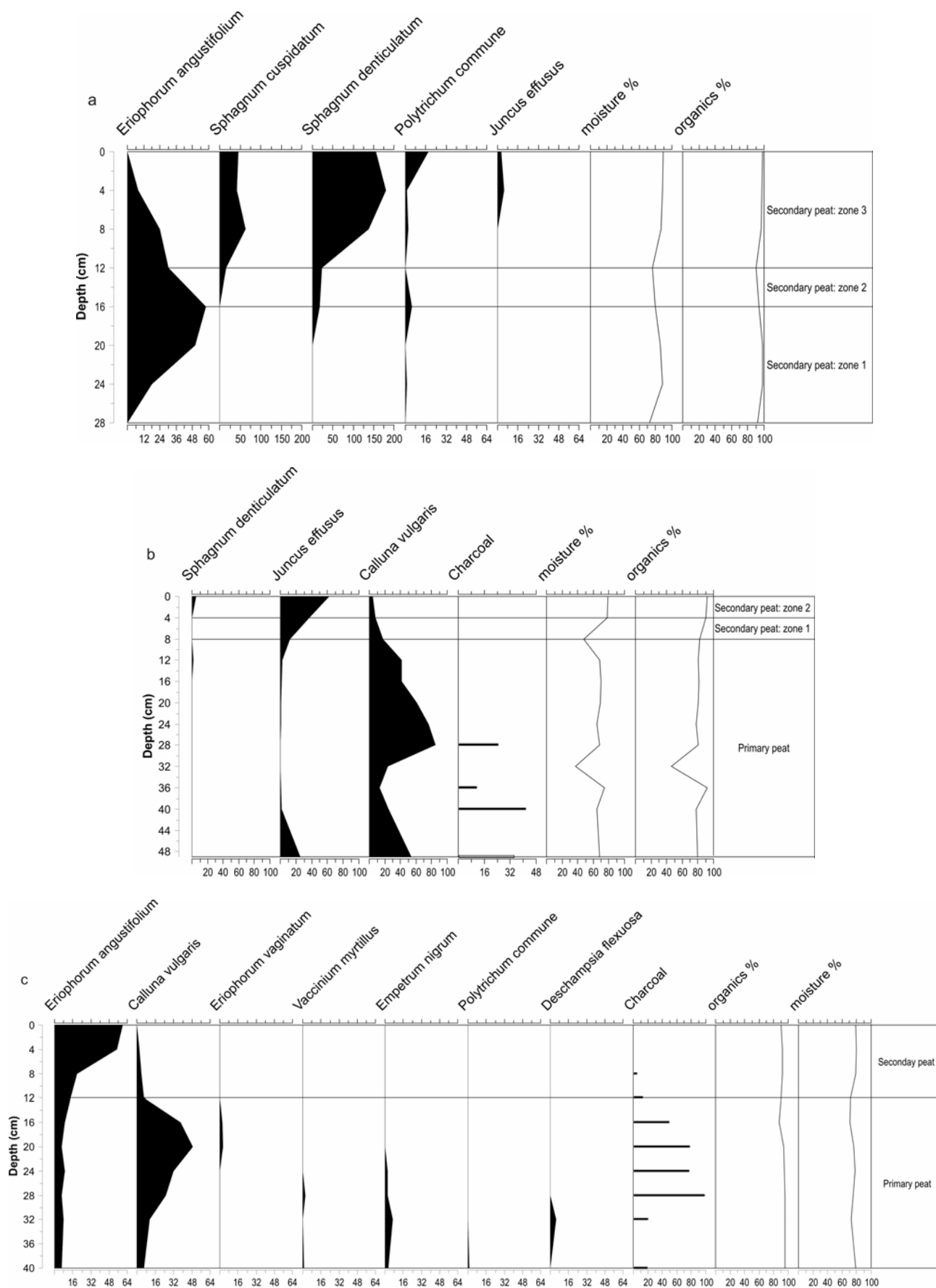


Figure 5. Summary plant macrofossil, moisture and organic content data for peat cores from gullies in the Doctor's Gate catchment. (a) Core DG1a (downstream); (b) Core DG1b; (c) Core DG1c (upstream).

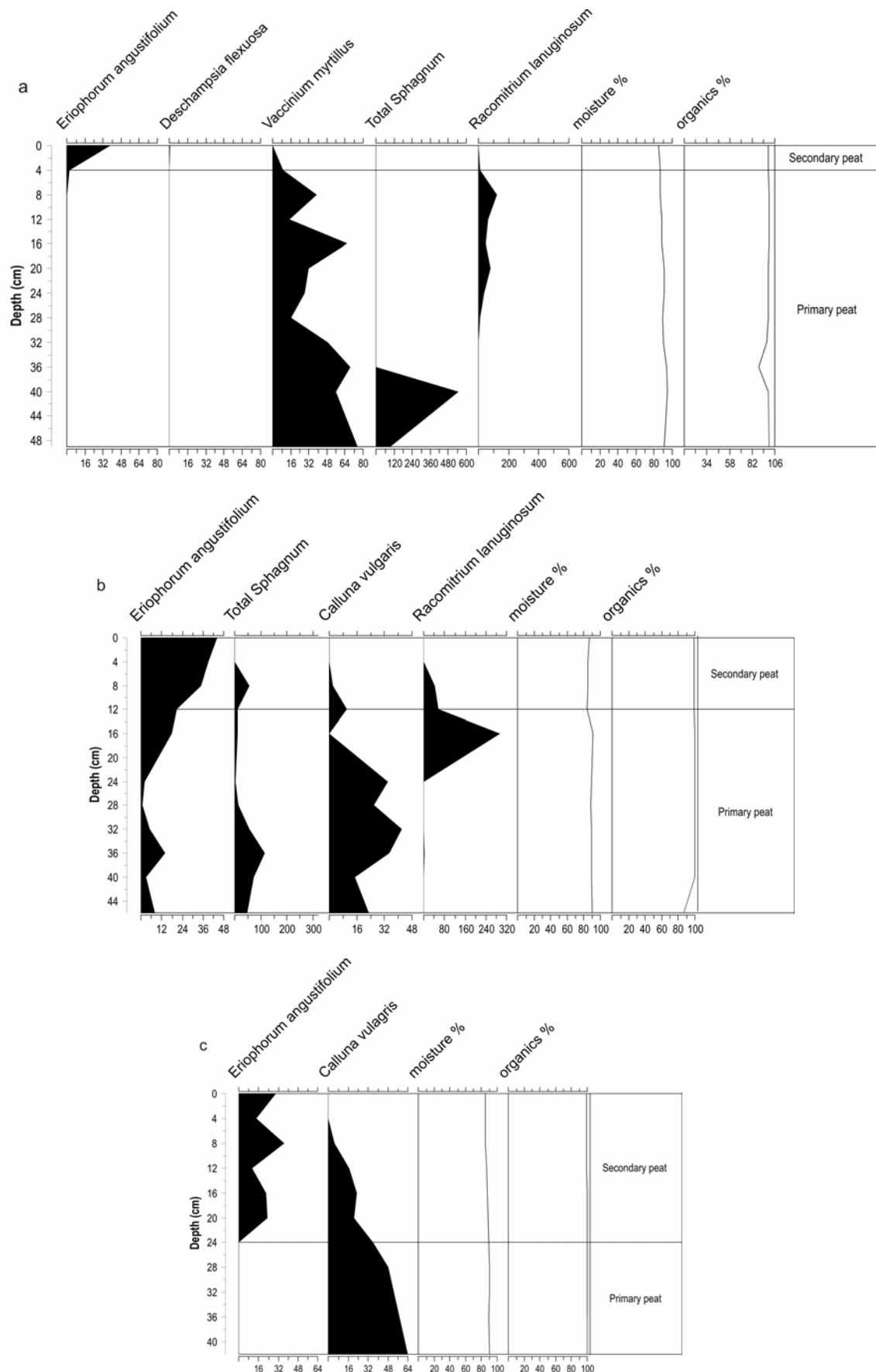


Figure 6 Summary plant macrofossil, moisture and organic content data for peat cores from gullies in the Shelf Moss catchment. (a) Core SM1a (downstream); (b) Core SM1b; (c) Core SM1c (upstream).

DISCUSSION

Hypothesised re-vegetation sequence

The stratigraphic data from all nine cores reveal broadly similar sequences of gully re-vegetation. In particular, re-vegetation is initiated by the pioneer coloniser *E. angustifolium*, a species known to colonise re-deposited peat and described by Phillips (1954) as being characteristic of seral communities or those sites that have had a history of peat degradation. The exception to this pattern is found in core DG1b, in which primary colonisation is by *S. denticulatum* and *J. effusus*, a colonisation association that has also been recorded by Farrell & Doyle (2003). Relatively little has been published on the importance of *E. angustifolium* as a pioneer coloniser, in contrast to *E. vaginatum* (Rocheftort *et al.* 2002) and *Sphagnum* (Grosvernier *et al.* 1997, Rocheftort 2000). However the results reported here suggest that it is a key species in the re-vegetation and regeneration of blanket peat gullies and also in mitigating the effects of further erosion. Phillips (1954) provided a concise description of the autecology of *E. angustifolium* and reported it amongst the seral communities which frequently colonise re-deposited peat pools. Nearly four decades on, Wheeler (1995) noted its importance in peatland restoration projects, indicating that, along with ericaceous shrubs, it was frequently the first species to colonise abandoned drainage ditches in peat.

Following colonisation by *Eriophorum* species, there are two main trajectories that can be identified from the plant macrofossil records. The first is to wet *Sphagnum* bog, as occurred at DG1a and UNG2a. This trajectory is associated with continuously waterlogged conditions on the gully floor and a nearby source of colonists. In contrast, other sites follow a trajectory to dry heath assemblages characterised by *V. myrtilus* and *E. nigrum* (e.g. UNG3a). This second trajectory is possibly the result of drier gully floor conditions during the re-vegetation process.

An encouraging aspect of the macrofossil records is the prominence of *Sphagnum* regeneration. *Sphagnum* was considered to have been almost eradicated from the Dark Peak by the 1970s due to atmospheric deposition from industrial pollution (Ferguson *et al.* 1978), and it was expected that high levels of sulphur in the surface peat would make recovery of *Sphagnum* difficult (Tallis 1995). What is apparent from both the macrofossil and the contemporary plant record is that *Sphagnum* recovery is controlled by more than just the chemical condition of the surface peat. Contemporary plant surveys reveal localised patches

where the most resilient species such as *S. cuspidatum* have persisted and where other species such as *S. palustre* and *S. denticulatum* have reappeared. This has created a localised spore bank for gully re-colonisation, and the appearance of these species in the plant macrofossil record close to spore banks suggests that propagule availability rather than the residual sulphur levels in peat may be the main factor limiting *Sphagnum* recovery. The reduction of annual sulphur dioxide emissions from 3.2 million tonnes in 1970 to 0.6 million tonnes in 1999 has brought deposition in most rural areas of the UK below critical loads (NEG-TAP 2001). With this reduction in sulphur, it is accelerated climate change that will now become the greatest challenge in re-establishing *Sphagnum*-rich blanket bog. This study reveals two main trajectories of re-vegetation; to a wet bog assemblage typical of waterlogged, high water table peatland and to a dry heath assemblage typical of establishment on mineral substrate or on peat with low water table. It should be noted however, that the latest climate scenarios for the UK (Hulme *et al.* 2002) predict prolonged dry summers. These predictions could have major implications for the sustainability of the wet bog communities already established and for the colonisation of remaining bare peat, especially as the climate of the Southern Pennines is already marginal for blanket peat (Tallis 1995). The macrofossil record from Core UNG3a shows succession to a dry heath community composed of *E. vaginatum*, *E. nigrum* and *V. myrtilus*, which are characteristic species for the plant community of the surrounding catchment. It is possible that the predicted drier summers and resulting lower water tables could lead to the dominance of this trajectory of re-vegetation, and even to the replacement of the regenerated *Eriophorum-Sphagnum* communities by *Vaccinium-Empetrum* communities as observed in longer palaeoecological records during previous shifts from wet to dry climates (Ellis & Tallis 2001).

This paper presents a relatively small dataset, but nevertheless the stratigraphic and macrofossil data offer some preliminary support for the hypothesis that the re-vegetation process is subject to geomorphological control (Figure 1). Clear spatial patterns in re-vegetation and secondary peat growth can be seen in the data for both Doctor's Gate and Shelf Moss catchments, where cores were taken along the lengths of individual gullies. In the relatively narrow gullies at Doctor's Gate, both the thickness of secondary peat and the richness of contemporary vegetation decline in the upstream direction (Figure 5 and Table 2). This is consistent with a process initiated by establishment of vegetation on waterlogged peat deposited upstream

of an obstruction. Once vegetation has become established on the peat surface, it acts both as a trap for eroded peat particles and as a source of colonists for the newly deposited peat. The process of colonisation and peat deposition thus creates a spatially distinct pattern of gully floor re-vegetation advancing upstream (Evans *et al.* 2005). In contrast, the highest percentage cover of contemporary re-vegetation on Shelf Moss is found at the upstream sampling location. In the broad shallow gullies of this catchment it is possible that an initial patch of re-vegetation could propagate both upstream and downstream because the lower hydraulic gradients mean that downstream transport of peat is sluggish even in the absence of physical blockages. Peat that is mobilised is subsequently deposited on meander bends in an analogous process to the creation of gravel bars in rivers (Laronne & Duncan 1992). As with gravel bars, any deposited peat that remains undisturbed will eventually re-vegetate and begin to obstruct the channel, promoting further peat deposition and re-vegetation.

Implications for restoration of blanket peatland

The work presented here has important implications for blanket peat re-vegetation, and particularly for current and on-going restoration work in the South Pennines and other parts of the UK (Trotter *et al.* 2005, Scottish Natural Heritage 2005). In addition to re-seeding bare peat flats, restoration strategies increasingly involve blocking narrow gullies with dams of plastic sheet piling, wood, stone or wool-wire. The stated aim of this new approach is to more fully restore peatland functions, principally by raising the water table (Evans *et al.* 2005, Trotter *et al.* 2005). The results presented here generally endorse this approach, as it seems analogous to natural re-vegetation processes in narrow gullies. However the differences revealed between the physical mechanisms controlling re-vegetation in narrow and broad gullies indicate that, for maximum effect, restoration techniques need to take account of the specific geomorphological context of the erosion that is to be repaired. In broad anastomosing gully systems, the use of baffles to promote meandering flow may be more appropriate than dam construction on the basis that it mimics more closely the natural processes supporting re-vegetation. Overall, the importance of the geomorphological controls on re-vegetation dynamics illustrated here is such that indiscriminate re-seeding of eroded peat may not be the optimal approach in all contexts. Recent literature reflects a large revival of interest in restoration ethics and practice, and emphasises the need for reconnaissance surveys of damaged areas (Hobbs & Harris 2001, Suding *et al.* 2003). Where

the physical system has been degraded or altered (e.g. by soil loss or hydrological change), the focus should be on restoring the physical system and allowing the ecological system to recover in its own time. The results of this work indicate that such an approach is applicable to degraded peatland systems.

CONCLUSIONS

- Palaeoecological analysis of sediments in naturally re-vegetating peatland gully systems demonstrates the importance of *Eriophorum angustifolium* as a keystone species for re-vegetation of eroded gullies, acting as a precursor to more diverse plant communities including those containing *Sphagnum* species.
- The geomorphological context significantly influences the pattern and trajectory of re-vegetation. In narrow steep gullies, re-vegetation propagates upstream from local blockages. In broad shallow gullies, re-vegetation may propagate in either direction from the initial location.
- These results provide support for the artificial gully blocking approach to moorland restoration. Blocking of narrow gullies and planting with *Eriophorum angustifolium* has the potential to accelerate natural processes of re-vegetation.

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