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CONTROLS OF SOIL PIPE FREQUENCY IN UPLAND BLANKET PEAT

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Abstract

Soil pipes were surveyed in 160 British blanket peat catchments using consistent application of ground penetrating radar. Soil pipes were found in all catchments. The mean frequency of piping was 69 per kilometer of surveyed transect. Land management (moorland gripping) appears to exert the most important control on hillslope pipe frequency in blanket peats. Management practice in peatlands may therefore induce more rapid subsurface erosion, carbon loss and landform denudation via enhanced preferential flow. Topographic position is also important, with topslopes having greater pipe frequencies than footslopes, followed by midslopes with lowest frequencies. Slope gradient, however, is not a significant factor in controlling blanket peat pipe frequency. I propose that peat structural properties inherited from the way a blanket peat develops on a hillslope strongly control pipe network development. This is manifested in the way slope position appears to control pipe frequency. Aspect appears not to influence frequency in blanket peats except that it does play a weak role in catchments with annual precipitation less than 1500 mm. Here southwesterly-facing slopes tend to have more frequent piping.

Keywords

Soil pipes, peatlands, wetlands, topography, moorland gripping, geomorphology, runoff

1. Introduction

Soil pipes are important hillslope hydrological and geomorphological agents in many parts of the world [e.g. *Zhu et al*., 2002; *Elsenbeer*, 2001; *Carey and Woo*, 2000; *Gutierrez et al*., 1997; *Crouch et al.,* 1986; *Drew*, 1982; *Harvey,* 1982; *Jones*, 1981; *Baillie*, 1975] and particularly in humid temperate regions [*Holden and Burt,* 2002a; *Uchida et al*., 1999; *Jones,* 1997a; *Jones*, 1990; *Jones,* 1981]. In the shallow peaty podzol soils at Maesnant, mid-Wales, for example, pipes contributed 49 % to stream stormflow and 46 % to baseflow [*Jones and Crane*, 1984]. *Holden and Burt* [2002a] found that 10 % of stream discharge was produced by pipes in a deep peat catchment in northern England. *Jones* [1994b; 2004] showed that piping can play an important role in landscape development in some regions. *Zhu et al.* [2002] found that pipes delivered 57 % of basin sediment production in a catchment of the hilly loess region of North China. Piping is involved in channel extension through roof collapse, gully development, and mass movements [*Higgins*, 1990; *Jones*, 1994a; 1994b; 2004].

Jones et al. [1997] suggested that 30 % of Britain was susceptible to piping, with pipes more likely in upland peats and podzols. *Bower* [1961)], *Radley* [1962], *Anderson and Burt* [1990], *Jones et al.* [1997] and *Holden and Burt* [2003b] noted that blanket peats commonly have soil pipes. Peat is the accumulation of partially decomposed remains of dead plants that forms in a waterlogged environment. Blanket peats develop on gentle slopes of upland plateaux, ridges and benches and are primarily ombrogenous. That is, they are believed to be hydrologically disconnected from the underlying mineral layer such that they receive almost all of their water and nutrients in the form of precipitation. These peats often extend upwards from initial development on hill toes due to increased upslope waterlogging caused by the peat

[*Hobbs,* 1986]. Blanket peats also tend to develop on hilltops and then extend downslope due to the waterlogging caused by their effluent waters. This water also causes further waterlogging at the base of the slope, encouraging further peat development and allowing a blanket of peat to cover the slope. On very gentle slopes the lack of drainage encourages micropools to develop and a patchy and mosaic-like vegetation community colonizes [*Ingram*, 1983] with specialist plants adopting different positions within the local microtopography. This then enhances the microtopography, often manifest in larger features such as hummock-pool topography [*Hobbs,* 1986; *Holden and Burt*, 2003b; 2003c]. Since the peat itself therefore consists of plant remains, different phases of surface colonization or local pool development result in a peat of variable properties throughout its profile [*Beckwith et al.,* 2003]. Thus, some parts of peat hillslopes may be more likely to inherit a heterogeneous peat structure than others depending on local plant or pool occurrences and local drainage.

Piping can transcend the traditional two-layered hydrological model for peats which suggests that almost all of the water, nutrient and sediment movements are at, or very close to the surface [*Holden and Burt*, 2003b]. Saturation-excess overland flow and near surface throughflow dominate runoff in blanket peats [*Evans et al*., 1999; *Holden and Burt*, 2003b]. The lower peat layers are generally considered to be hydrologically inactive in that, despite being saturated, the hydraulic conductivity is so small that they transmit very little water to the stream. Pipes, however, may couple (hydrochemically and sedimentologically) deep and shallow layers of the soil profile. Given that 15 % of Britain is covered with blanket peat [*Tallis et al*., 1998], and this peat cover is mainly in upland headwaters, it is likely that pipes play an important role in many British catchments. Blanket peats are important stores of terrestrial carbon [*Turetsky et al.,* 2002] and Britain holds around 15 % of the global blanket peat resource [*Tallis et al.,* 1998]. However, soil pipes have not been considered in carbon budgets for blanket peat catchments [e.g. *Worrall et al*., 2003] and they may be an important subsurface agent of carbon removal from peatlands. Pipes may therefore result in losses of carbon through increased dissolved and particulate organic carbon loss. Few studies of pipe sediment yields in peats or peaty soils exist. However, weekly sampling on the peaty podzols of the Maesnant catchment suggested 15 % of annual stream sediment yield came from the pipes [*Jones and Crane*, 1984], and *Jones* [1990] speculated that this value was more likely to be 25 % when the unmonitored pipes are taken into account. Jones [2004] showed that for Maesnant the areas of piping yielded more sediment to the stream than the areas without piping. Therefore, because research has demonstrated that pipes are important hydrological and geomorphological agents in peat catchments, and that they could be important in carbon budgets, it is important to examine the frequency of soil piping in blanket peat catchments and to examine the controls on pipe frequency and distribution.

Relatively little is known about the number and extent of soil pipes in most peatland (or any other) environments. Often pipes are only reported where they issue onto streambanks or where their roofs have collapsed. *Jones et al.* [1997] reported the frequency of pipe outlets and the mean cross-sectional area of soil pipe outlets per km of streambank. However, as *Jones et al.* [1997] noted, many hillslope pipes are not directly connected to streambanks. Furthermore, *Holden et al.* [2002] and *Holden and Burt* [2002a] and *Terajima et al.* [2000] showed that soil pipe dimensions and depths could be very different just a few meters upslope. Soil pipes are often not just formed as a single conduit but can form complex drainage networks with branching tributaries [*Holden et al.*, 2002]. The main difficulty with collecting data in order to examine pipe distribution has been the lack of appropriate techniques for detecting and mapping subsurface soil pipes. *Bryan and Jones* [1997] noted that new techniques were urgently needed for surveying pipe networks and measuring subsurface catchments. Recently, *Holden et al.* [2002] reported on the successful application of ground penetrating radar (GPR) for identifying soil pipes and their hydrological connectivity [*Holden*, 2004]. This technique allows soil pipes to be identified from the ground surface without disturbance. These earlier two papers reported solely on technical developments. However, these technical developments now provide an opportunity for a more adequate assessment of soil pipe occurrence and the potential controls on soil piping in blanket peat catchments. This provides the focus of this paper.

Several factors that might control pipe distribution in blanket peatlands have been suggested. These include topographic position, slope gradient, aspect and land management. Many authors, such as *Jones* [1981] and *Gutierrez et al.* [1997], have suggested that piping is more common on steeper slopes and that flatter slopes (such as hilltops) with limited drainage area per unit contour length are less susceptible to soil piping [*Jones et al.*, 1997]. This is because steeper hydraulic gradients and greater volumes of water flow are more likely to result in pipe formation (with greater shear stresses on macropore and pipe walls). Based on an initial field survey, however, *Holden et al.* (2002) suggested that, in blanket peat catchments, soil pipe densities may be much greater on more gentle slopes (such as valley floors and hill tops) but they had very limited data with which to back up this hypothesis. Indeed, in *Conacher* *and Dalrymple*'s [1977] nine unit landsurface classification they indicate that piping is likely on unit 2 which is the area downslope from the interfluve area (unit 1). In unit 2 they suggest that mechanical and chemical eluviation by lateral subsurface water movement dominates. In addition, *Jones* [1990] used a survey of worldwide literature and suggested that piping was generally common on unit 2 but the highest frequency of piping was found on toeslopes (units 6 and 7). Of course, it is therefore important to distinguish between slope gradient in general and slopes in their topographic context. For example we need to distinguish between steep slopes (based on gradient) and midslopes which are slopes on the hillside between more gently sloping topslopes and footslopes. Surface erosion features in blanket peats tend to have a hillslope topographic context. For example, gully networks are branching and dense on flatter hilltops but they feed into straighter, unbranching gullies on steeper midslopes [*Bower*, 1960; 1961]. However, the effect of slope position, and slope gradient on soil pipe density has never been fully tested in peat catchments.

In the overview of British soil piping presented by *Jones et al*. [1997] they examined data for 74 catchments that contained active soil pipes (mainly peats and peaty podzols). They found that 19 of these catchments faced south. This was a significant number since aspect was split into 8 categories in their analysis. Upland peats are often subject to shrinkage cracking during dry summer periods [e.g. *Holden and Burt*, 2002b; *Holden and Burt*, 2002c], higher annual precipitation totals than the national average, and suffer from impeded drainage with large changes in hydraulic conductivity over very short vertical and lateral distances [*Holden and Burt*, 2003a]. Thus, *Jones et al*. [1997] suggested that while high rainfall areas are associated with piping, there was also an important role for desiccation cracking in initiating pipes in

Britain. There is therefore a proposed two-way control here; sufficient water surplus is required to form the pipe networks and for them to remain open, and sufficient warm dry periods are required in which cracking can be induced. However, the aspect control assessment performed by *Jones et al.* [1997] is based on a limited number of reported catchments which contain soil piping. A systematic survey of catchments, using a consistent pipe detection method, has never been performed to test whether there is a genuine aspect control on soil piping occurrence. In particular there have been no large-scale intensive surveys to examine intra-basin pipe intensity variations and the role of aspect in controlling such variation.

Many blanket peats in Britain have been artificially drained by moorland gripping. This consists of open ditches approximately 50 cm wide by 50 cm deep cut into the peat during the mid 20th century [*Holden et al.*, 2004]. The aim of gripping was to drain the peat in order to 'improve' the land for pasture and bird shooting. However, *Holden et al.* [2004] suggested that this practice may promote the shrinkage and cracking of the peat [*Egglesmann et al.,* 1993; *Holden and Burt*, 2002b], resulting in enhanced macropore and pipe development. However, there have been no surveys to compare piping in drained peats versus intact peats making it difficult to establish whether this is the case.

This paper reports on a survey of 160 British catchments dominated by blanket peat. The sample survey was carried out using the same GPR technique throughout, in order to provide a standard to allow fair comparison between catchments and in order to assess, for the first time, the relative roles of aspect, slope, topographic position and moorland gripping. The paper aims to:

i) Determine the extent to which piping is found in blanket peats (is it ubiquitous, what is its mean frequency, and how variable is it?)

ii) Examine the relative roles of topographic position, slope, aspect (and precipitation) and moorland gripping on pipe frequency.

iii) Suggest process-mechanisms associated with controls on pipe frequency that can be examined by further research.

2. Methods

i) Fieldwork

A total of 160 upland blanket peat catchments between 0.8 km^2 and 4.2 km^2 across Britain were surveyed (Figure 1). The small range in catchment size was used in order to minimize any potential scaling errors. The catchments were chosen systematically so that areas of British blanket peat were representatively sampled. Hence the greatest number of survey catchments occurred in northern Scotland which represents the largest blanket peat deposit in Britain. However, catchments in Exmoor, Dartmoor, Wales, North York Moors, South Pennines, North Pennines, Grampian and Cairngorms, Caithness and Sutherland, Dumfries and Galloway and the Isle of Skye formed part of the survey. Afforested catchments were not part of this survey. Figure 1b highlights those survey catchments with mean annual precipitation greater and less than 1500 mm. Figure 2 shows the distribution of catchment altitude (mean of the maximum and minimum altitude), mean stream slope and mean annual precipitation among the sampled catchments. Blanket peat catchments tend to be relatively shallow sloping in nature with high annual precipitation totals.

Hillslope piping was surveyed using GPR. In each catchment two hillslopes were surveyed with three plots on each hillslope. Typically the two survey hillslopes in each catchment were facing each other so that they had opposite aspects. In order to minimize scaling errors each hillslope was chosen so that its total length from the divide to streambank was between 200 and 500 m. On each hillslope one plot was located on the flatter topslope near the summit, one on the hillslope toe and one on the steeper midslope section midway between the top and footslope plots. There were therefore 960 hillslope pipe density surveys, each performed using the same technique and thus allowing comparison between catchments. Each plot consisted of six 20 m transects running transverse across the slope with each transect 10 m apart upslope. Thus, each plot was 50 m x 20 m and a total of 115.2 km of GPR survey took place. The GPR was traversed across each transect using 100 and 200 MHz antennae (depending on peat depth) with standard separation distances of 1 m and 0.5 m respectively. As *Holden et al*. [2002] provide details of the technique, only a summary is provided here. Signals were emitted at 10 cm intervals along the transect. Because GPR transmits energy through the ground in wide beam, the antennae are therefore not detecting reflections from directly vertically below, but also to the front, back and sides. The GPR should therefore be able to detect features (such as soil pipe cavities) that are between the 10 cm sampling interval. The number of pipes identified on the radargrams was then counted and the density of piping was calculated as the number of pipes per km of survey transect for each plot. Unfortunately as GPR cannot provide information on pipe diameters, no information about the relative size of pipes on different parts of the hillslope could be obtained.

Aspect, slope, and the presence (or lack) of moorland gripping was noted at each site. The topographic (*a/s)* index was calculated for the midpoint of each plot (the ratio of the area drained per unit contour length, *a*, and the slope, *s*, [*Carson and Kirkby*, 1972] as an indicator of the topographic concentration of drainage. This index was calculated from ground survey which is known to be a more reliable method than using maps which suffer from scale problems [*Jones*, 1986; *Jones*, 1997b]. Data on peat depth were also collected for each plot using coring rods. In addition, for eight hillslopes (hence 24 plots), values of saturated hydraulic conductivity (*k*) and dry bulk density (DBD) were measured at 10 cm vertical intervals down through the peat profile using the technique described in *Holden and Burt* [2003a] and *Warburton et al*. [2004]. This allowed some indication as to whether differences in pipe intensity were related to local peat properties.

In addition to hillslope piping, the intensity of streambank piping was also surveyed. This was done by walking up the main channel of each catchment and measuring the depth and diameter of each pipe. In one catchment (in the Dee headwaters around Mar Lodge, in the Grampians) this was not possible as the main channel had a wide alluvial floodplain consisting of coarse gravels so that hillslope pipes were not directly coupled to the stream channel.

ii) Analytical techniques

It is hillslope piping which forms the focus of this paper and as such the unit of replication is the hillslope plot (n=960). Individual transects within plots are not considered separately. Data were tested for normality and square root transformations were found to improve distributions, making them less skewed and more importantly providing more constant variability within topographic position, aspect and gripping presence categories. Despite ANOVA (single one-way and general linear model (GLM)) being quite robust to non-normal data it is more reliable when data are normally distributed or are close to normal and hence it was felt that data transformations were justified. Both categorical data (e.g. presence of gripping, aspect, topographic position) and continuous data (e.g. precipitation) were used in the GLMs. Aspect was categorized into eight groups (N, NE, E, SE, S, SW, W, NW).

3. Results

Soil pipes were detected in all 160 catchments with a mean of 69.2 per km of GPR transect (standard error = 2.1) and a maximum of 466.7 km^{-1}. No pipes were found below fifty of the plots. Table 1 provides results of a single one-way ANOVA based on square root transformed data for the number of pipes per km of GPR survey. Topographic position (topslope, midslope, footslope) appears to be an important control on soil pipe intensity. The differences between the slope positions are shown on Figure 3. Footslopes and topslopes have significantly greater pipe intensities than midslopes. Indeed topslopes have significantly more soil pipes than both footslopes and midslopes (p <0.001).

Given that there is a need to distinguish between topographic context and slope angle I decided to examine the role of slope both overall and for each topographic position separately. Figure 4 shows that there was no significant relationship between pipe intensity and slope angle. Hence slope is not considered any further in the following analysis. Similarly there were no significant relationships between the topographic index (ln *a*/*s*) and pipe intensity, although Figure 5 shows that there is a tendency for the greatest pipe intensities to be found where the topographic index is between -2 and 2.

Table 2 provides results of a GLM in which I investigated what variables control the variation in soil pipe intensity. Interactions among variables are also considered. Slope position and the presence or absence of gripping exerts the strongest control while mean annual precipitation had a minor effect (significant at $p = 0.059$). Aspect does not significantly control pipe frequency. Of the interactions between variables, only aspect x gripping was significant.

The GLM used continuous data for precipitation but there is considerable scatter and when these data are unpacked by grouping precipitation into four classes a clearer picture of the response emerges (Figure 6). It is the wettest catchments (with mean annual precipitation greater than 2000 mm) that have significantly more hillslope soil pipes per survey length than catchments with precipitation below 2000 mm per year. Noteably, no significant differences in pipe frequency exist between the three classes below 2000 mm. When the catchments with precipitation greater than 2000 mm are taken out of the GLM presented in Table 2, precipitation was not found to be a significant factor controlling piping at the 90 % confidence level. Thus, precipitation appears to be a dominant control in the very wettest peat catchments. However, when the wettest catchments were removed from the analysis, aspect became a significant factor ($p = 0.003$). This being the case, I decided to examine the roles of aspect in drier and wetter catchments. Aspect exerts a significant control on pipe density where mean annual precipitation is less than 1500 mm (Figure 7; see also Figure 1). In Figure 7 I plot mean soil pipe frequency with standard errors for ‘dry’ catchments by aspect showing that there is a tendency for greater pipe densities on hillslopes facing southwest and west.

Gripped hillslope plots (n = 171) had significantly more soil pipes than non-gripped plots (n = 789) at $p<0.001$, with a mean of 127.4 pipes km^{-1} (standard error = 6.2) for gripped sites and 56.6 pipes km^{-1} (standard error = 2.0) for non-gripped sites. It is often assumed that moorland gripping in peats took place on wetter sites (although there is no evidence to support this and most UK gripping was *ad hoc* due to readily available grant aids during the 1970s; *Holden et al*., 2004). However, in order to test whether the result obtained above was not simply a function of gripping taking place where piping was already very intense (i.e. in wet areas), further analyses were performed. Two cases were explored. I compared apparent gripping effects in very wet catchments (mean annual precipitation greater than 2000 mm) and in the drier catchments. Gripping was found in catchments throughout the full precipitation range. In all cases (four precipitation groups as above) gripped plots had significantly more pipes than non-gripped plots ($p<0.001$). In a second approach I used the topographic index as an indicator of 'wetter' areas. It would be expected that sites with a low topographic index would be subject to more prolonged saturation than those areas with a higher topographic index. Gripping was found across almost the full range of topographic index values surveyed (Figure 8). When sites were grouped into topographic index classes (n = 240 in each class; classes equivalent to <0.49 km, 0.49 to 1.35, 1.36 to 4.49 and > 4.50 km), gripped plots had significantly higher soil pipe intensities than non-gripped plots in all cases. The impact of gripping is therefore independent of wetness.

I also tested for the impact of peat depth on pipe frequency. Deeper peats may be liable to have more pipes (and larger pipes) per GPR transect than shallow peats because there is a greater volume of peat within which pipes can develop. Peat depth was weakly positively correlated with pipe frequency ($p = 0.035$; $c = 0.16$); deeper peats tended to have slightly greater densities of soil pipes. In addition, topslopes and footslopes tended to have deeper peat than midslopes providing one reason why topographic position may exert significant control on pipe frequency. I note that the influence is weak and not enough to explain the magnitude of the differences observed.

Unfortunately, GPR does not provide information on pipe dimensions. However, data from streambanks on peat depth and pipe diameter was available. The mean number of pipes per km of streambank was 19.7 (geometric mean 13.9) with a standard error of 1.29, a minimum of 0.5 and maximum of 95.6. The mean cross-sectional area of pipes per km of streambank was 0.556 $m^2 km^{-1}$ (geometric mean, 0.088) with a standard error of 0.136 $m^2 km^{-1}$. Mean pipe diameter and peat depth at the streambank were positively correlated ($c = 0.41$, $p < 0.001$). Based on data for each pipe there were too many data points to allow clear plotting of this relationship; for clarity I plot in Figure 9 the mean streambank peat depth and mean pipe diameter for each catchment.

As in other reports [e.g. *Holden and Burt*, 2002a; 2003b], soil pipes were found not just within the peat itself but also at the interface between the peat and the underlying substrate and within the substrate itself. Of the soil pipe outlets at streambanks, 36 %

had their floors entirely within peat, 56 % at the interface between the peat and underlying substrate, and 8 % were entirely within the underlying substrate.

The analysis above has demonstrated that land management (gripping) and topographic position are dominating controls on hillslope pipe frequency in blanket peats. Gripping results in increased drying of the peat and enhanced crack development [*Holden et al*., 2004] and thus promotes conditions conducive to pipe development. However, it is less obvious why the topographic position is so important. A minor influence from peat depth has already been mentioned. Data presented in Figure 10 illustrates the variability of k and dry bulk density (DBD) on one of the survey hillslopes. There is a much greater variability in k and DBD on the topslope and footslope parts of this hillslope than in the midslope section. Table 3 shows that this trend is consistent across the eight survey hillslopes on which k and DBD where measured. The standard deviation of k for midslope plots is only 6.5×10^{-6} cm s^{-1}, compared to 20.4 and 16.2×10^{-6} cm s^{-1} for top and footslope plots. In addition, the average of k is slightly higher on the midslopes. This is indicative of better and more uniform drainage through the midslope parts of the hillslope. DBD varies less in the midslope regions. Peatland piping may therefore be a function of inherent soil properties on different parts of the hillslope. Topslope peats appear to be more susceptible to piping because the structure of the peat itself is more variable and is thus more conducive to wandering pipe development. Midslope peats tend to have a more uniform peat structure which is reflected in k being much less variable.

4. Discussion

Piping appears to be ubiquitous in blanket peats. The results above have demonstrated some important controls on pipe frequency within blanket peat catchments. Topographic position is important whereas slope gradient and topographic index are not significant. One of the reasons that slope may not be an important factor here is that blanket peats do not readily form on slopes greater than 15°, due to the need for waterlogged conditions. Unlike the sites reported by *Jones* [1981] and *Gutierrez et al.* [1997] the full range of slope gradients was not covered by this blanket peat survey. In Gutierrez *et al*. (1997), for example, steep arid zone piping occurred on slopes of typically 18-60°.

The dominance of the topographic control suggests that piping and landform development are intimately related. Some models simply propose that pipes result in landform change (e.g., topographic depressions or gullying) [e.g., *Pearsall*, 1950; *Jones*, 1990; 1994a; 1994b; 1997b] or that existing topography promotes enhanced flow in concentrated areas of hillslopes which promotes piping [*Anderson and Burt*, 1982]. However, I propose that the nature of the underlying topography (and its associated drainage conditions) promotes differential build up of the peat deposits. This occurs because of the development of micro pools and larger bog pool systems on hilltops and toes which are colonized by a mosaic of plants with specialist positions within the microtopography. The remains of these plants are then incorporated into the peat as it thickens, resulting in a peat of variable properties throughout its profile. In addition, bog pool development tends to be a cyclic process; pools disappear from one spot in a peatland while new ones form elsewhere as differential plant growth in pools and hummocks interacts with an ever-changing local topography while the peat deposit thickens [e.g. *Weber*, 1902; *Clymo*, 1991; *Glaser*, 1998; *Belyea and Clymo*, 1998]. This means that the peat in certain parts of hillslopes (tops and toes) is inherently more susceptible to preferential flow and piping. In essence this has many similarities to the general *Conacher and Dalrymple* [1977] nine unit landsurface classification, which in the case of piping, has until now been very difficult to test [*Jones,* 1990]. On hilltops and hill toes, results above suggest that the peat is more heterogeneous (e.g., highly variable DBD and *k*). *Holden and Burt* [2003a] showed that shallow throughflow dominated as the runoff process on blanket peat midslopes. This compares to footslopes and topslopes where saturation-excess overland flow dominated and there was more switching between overland flow and throughflow dependent on antecedent conditions. Better drained midslopes therefore have a more uniform structure, less variable *k,* and more uniform (spatially and temporally) runoff production. The associated midslope plant formations tend to be more homogeneous. Midslopes are therefore less susceptible to wandering and branching pipe networks. This homogeneity combined with gradient will allow pipe branching to be at a minimum on midslopes.

Jones [1981] noted that pipes are common where hydraulic conductivity changes abruptly. Results in this paper and in *Holden and Burt* [2003a] suggest that there can be up to two orders of magnitude variation in *k,* vertically and laterally, over just 10 cm of peat. This is particularly prominent on top and footslopes. Noteably, these are also sites where the change in hydraulic gradient is greatest. On convexo-concave hillslopes the hydraulic gradient increases towards the midslope from the topslope, and then decreases from the midslope to the footslope. Thus greater changes in hydraulic gradients and peat heterogeneity combine on hillslope toes and tops to increase the propensity for wandering preferential flow and pipe formation. In addition as peat depths are often greater on hilltops and toes, more (and larger) pipes can form. *Holden* [2004], for example, showed that pipe networks could overlap each other vertically in the soil profile and yet not be hydrologically connected. This is less likely in a shallower peat because the pipes are more likely to connect to form one pipe.

The slope position control outlined above for piping is strikingly similar to many surface erosion features seen in blanket peatlands and suggests that both processes are linked. *Bower* [1960] described two types of gully erosion in blanket peats. *Type 1*, consisting of a close network of freely and intricately branching gullies, occurred on hill tops of deep peat (>1.5 m). In contrast more open, linear gully systems with less branching (*Type 2*) were more common on midslopes where gullies form sub-parallel trenches running downslope.

The influence of precipitation in controlling soil pipe frequency in blanket peat is minor (although there is a requirement for a water surplus to maintain the presence of blanket peat). Only the very wettest peat catchments, with mean annual precipitation greater than 2000 mm, had higher pipe frequencies than other peats. However, it was only in the drier peatlands that aspect became a significant control. Blanket peats typically have water tables that are within a few centimeters of the surface [*Evans et al.,* 1999; *Holden and Burt* 2003b]. Drier peatlands will more frequently experience water table lowering during dry summer periods. This promotes shrinkage and cracking [*Gilman and Newson*, 1980] and thus the more frequent initiation of macropore networks that may then enlarge to form pipe networks [*Crouch et al.*, 1986; *Jones*, 1990]. Southwesterly facing slopes, which ought to receive the most summer insolation in the UK, tended to have more intense soil piping than slopes with other aspects in catchments where mean annual precipitation was less than 1500 mm.

The land management practice of moorland gripping was found to have the most influence on pipe frequency. Grips expose a bare peat surface to summer sunshine, resulting in increased desiccation cracking [*Holden et al*., 2004], and to enhanced winter needle ice formation, which also disturbs the peat structure [Francis, 1990]. In addition the grips reduce the downslope saturation of the hillslope (by redirecting flow along the contour to the stream and preventing water from following its natural course downslope), thereby inducing cracking further away from the grip walls and floors. *Holden et al.* [2001] showed that macropore flow was an important feature of blanket peat hydrology and *Holden and Burt* [2002b] showed that drought on peats could permanently increase macroporosity, the amount of infiltration, the amount of throughflow and the amount of macropore flow. One would expect that gripping would have the same effect, although this has never been properly tested. Once cracks open up and a peat surface dries, it often fails to fully resaturate (it can become partly hydrophobic). In other words, the peat can no longer hold as much water as its structure is permanently altered [*Hobbs,* 1986; *Egglesmann et al*., 1993]. This promotes conditions conducive to pipe network development across gripped hillslopes. While it is not possible to verify that pipe densities were not already high on plots before they were gripped, data presented here strongly suggests that this was not the case. Gripped plots were compared to hydrologically similar ungripped plots (same topographic index and same precipitation groups).

Many wetland restoration schemes attempt to place small dams into ditch (grip) networks in order to block them. This study suggests that those interested in wetland restoration may need to consider the changes to peatland structure and hydrological routing since the grips were installed. This re-routing of water through subsurface pipe networks may be fundamental to future peatland and landscape development. Most undisturbed blanket peats are dominated by overland flow and shallow throughflow within the top few centimeters of the peat mass [*Holden and Burt*, 2003b; 2003c] while typically only 10-30 % of the runoff may move through a subsurface pipe network to the stream channel [*Holden and Burt,* 2002a]. Following gripping, far more water may move through subsurface bypassing routes.

5. Conclusions

This paper has served to provide, for the first time, a comparative survey of hillslope soil pipe frequency in a range of blanket peat catchments. Soil pipes were found in all 160 survey catchments. Piping appears to be ubiquitous in British blanket peats. The analysis has shown that i) land management (gripping) is the most important control on hillslope pipe frequency in blanket peats; there are more pipes where land drainage has occurred; ii) topographic position is also an important factor with topslopes having greater pipe frequencies than footslopes which have greater pipe frequencies than midslopes; iii) slope gradient is not a significant factor in blanket peat piping; iv) while aspect is not a significant factor in general but there is an important interaction with precipitation such that the very wettest catchments have more pipes; aspect is only a control in the drier catchments where southwesterly facing slopes tend to have more piping. The result is that while there is less water available to develop and keep open pipe networks (and hence there is less piping than in the very wettest catchments) there are probably more pipes in the drier catchments than would otherwise be the case. Nevertheless, aspect is a minor secondary control.

I propose that inherent peat structural properties associated with peatland development exert important controls on pipe network development. Further work is required to test this hypothesis. Hill tops and toes with more heterogeneous peats are also sites where hydraulic gradients change significantly. These two factors combined result in a more wandering and branching pipe network on hill tops and toes, and more linear simple pipe systems on midslopes. Similar surface gully landforms have been observed in blanket peats. While this would suggest that midslope pipes are likely to be larger than those elsewhere, unfortunately GPR does not provide information on pipe geometry. Further work is required to contest this. It should also be noted that as GPR run at these frequencies does not tend to detect pipes that are smaller than 10 cm in diameter, there could be many smaller but important pipes that have not been detected by this survey.

It is important that land management has been shown to exert the largest influence (of all the factors investigated) on soil pipe frequency. It is well known that land management can inadvertently change the dominant runoff production processes within a catchment. Moorland gripping appears to promote the role of subsurface preferential flow through piping, resulting in accelerated subsurface erosion. Given that peatlands are a fundamental terrestrial carbon store, land management practices that can promote carbon loss should be avoided. While grip blocking practices in the UK and in many other countries with artificial peatland drainage are already underway [*Holden et al.*, 2004], further research is required to examine whether these wetland restoration strategies are able to cope with enhanced piping and to ensure that piping is adequately taken into account when developing blanket peat management plans.

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Figure captions

Figure 1. Location of survey catchments; a) areas of blanket peat in Britain; b) study catchments grouped by those with mean annual precipitation greater or less than 1500 mm.

Figure 2. Frequency distributions showing the characteristics of the 160 survey catchments; a) catchment altitude, m above mean sea level (mean of the maximum and minimum altitude of the surveyed catchment); b) mean stream slope, m m^{-1}; c) mean annual precipitation, mm.

Figure 3. Box plots showing the effects of topographic position on soil pipe frequency, units of pipes km^{-1}. The boxes show the interquartile range (quartile 1 (Q1) and Q3), with the median indicated within the boxes. The whiskers indicate the lowest and highest values that are still within the range: [Q1 – 1.5*(Q3-Q1)] and [Q3 + 1.5*(Q3-Q1)]

Figure 4. Scatter graphs plotting slope and pipe frequency (square root data) by topographic position; a) topslope sites; b) midslope sites; c) footslope sites.

Figure 5. Scatter graph plotting pipe frequency and topographic index for the 960 survey plots.

Figure 6. Box plots showing the role of mean annual precipitation group on soil pipe frequency. Catchment Group A < 1000 mm; Group B 1000 to 1499 mm, Group C 1500 to 1999 mm; Group D > 1999 mm. The boxes show the interquartile range, with

the median indicated within the boxes. The whiskers indicate the lowest and highest values that are still within the range: [Q1 – 1.5*(Q3-Q1)] and [Q3 + 1.5*(Q3-Q1)]

Figure 7. Means and plus one standard error for hillslope pipe frequency, km^{-1}, by aspect for catchments with a mean annual precipitation less than 1500 mm.

Figure 8. Frequency distribution of hillslope plots with and without the presence of gripping by topographic index.

Figure 9. Mean streambank pipe diameter and streambank peat depth for each of the survey catchments.

Figure 10. Saturated hydraulic conductivity and dry bulk density profiles for a peatland hillslope by slope position; a) topslope; b) midslope; c) footslope

Tables.

Table 1. Single one-way analysis of variance of the role of topographic position on pipe frequency per km of survey transect, square root transformed data.

Source of variation	Degrees of freedom	Mean square	*F* ratio	Probability
Topographic position	2	777.0	55.6	<0.001
Residual	957	13.6		
Total	959			

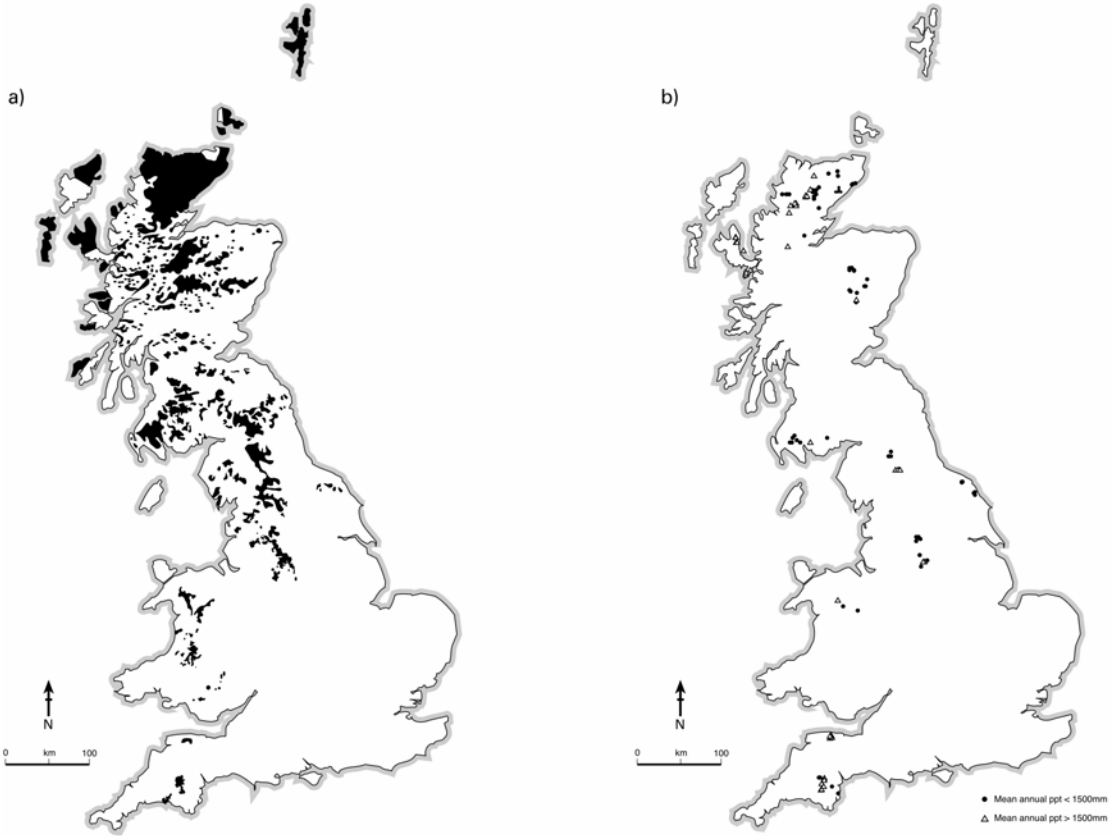
Table 2. ANOVA GLM of pipe intensity

Source of variation	Degrees of freedom	Mean square	*F* ratio	Probability
Slope position	2	63.8	5.8	0.003
Aspect	7	16.9	1.5	0.156
Gripping	1	211.9	19.1	<0.001
Precipitation	1	39.6	3.6	0.059
Slope position x aspect	14	2.6	0.2	0.998
Slope position x gripping	2	22.1	2.0	0.136
Slope position x precipitation	2	1.2	0.1	0.895
Aspect x gripping	7	48.4	4.4	<0.001
Aspect x precipitation	7	7.1	0.6	0.725
Gripping x precipitation	1	8.1	0.7	0.392
Slope position x aspect x gripping	14	4.4	0.4	0.977
Residual	901	11.1		
Total	959			

Table 3. Mean and standard deviation of peat depth, *k* (x 10^{-6} cm s^{-1}) and dry bulk density (g cm^{-3}) by slope position based on vertical sampling at 10 cm soil depth intervals.

Slope position	Mean peat depth, cm	Mean *k*	Standard deviation *k*	Mean dry bulk density	Standard deviation *k*
topslope	164	10.9	20.4	0.16	0.08
midslope	158	14.3	6.5	0.15	0.03
footslope	171	9.4	16.2	0.17	0.06

Figure 1: Location of survey catchments; a) areas of blanket peat in Britain;
b) study catchments grouped by those with mean annual precipitation
greater or less than 1500mm.



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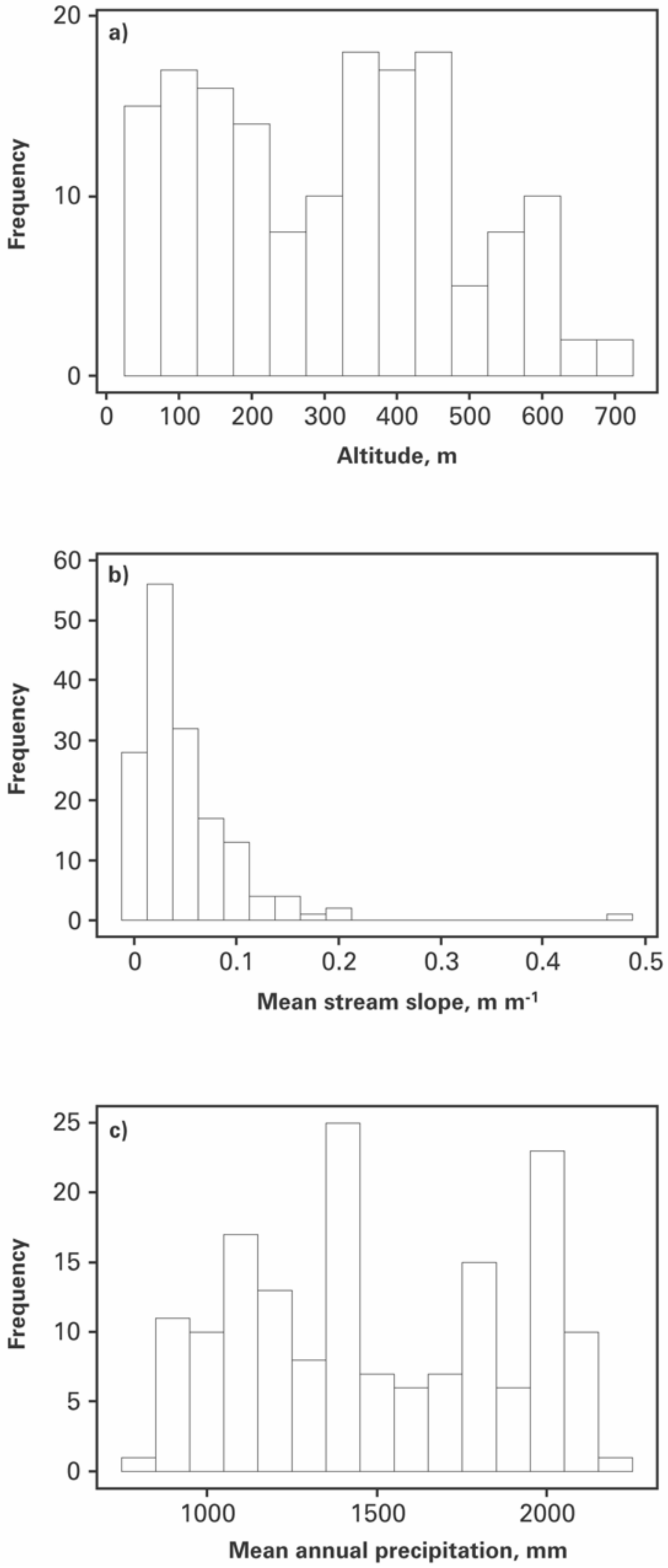

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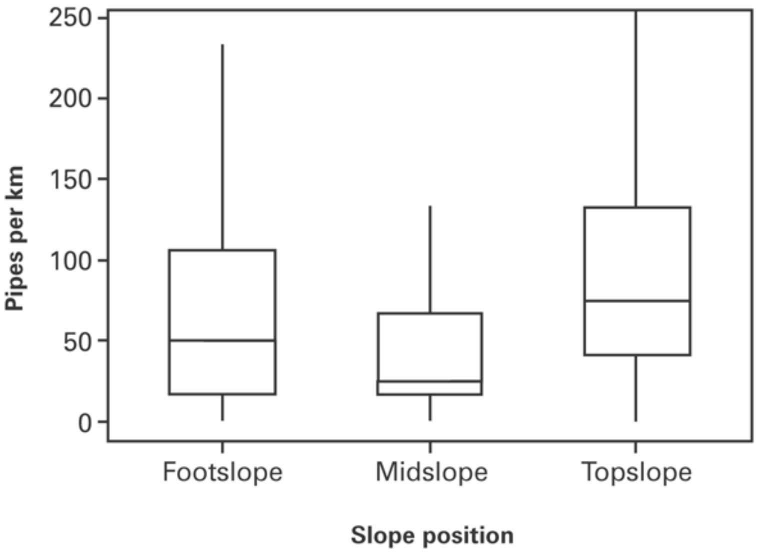
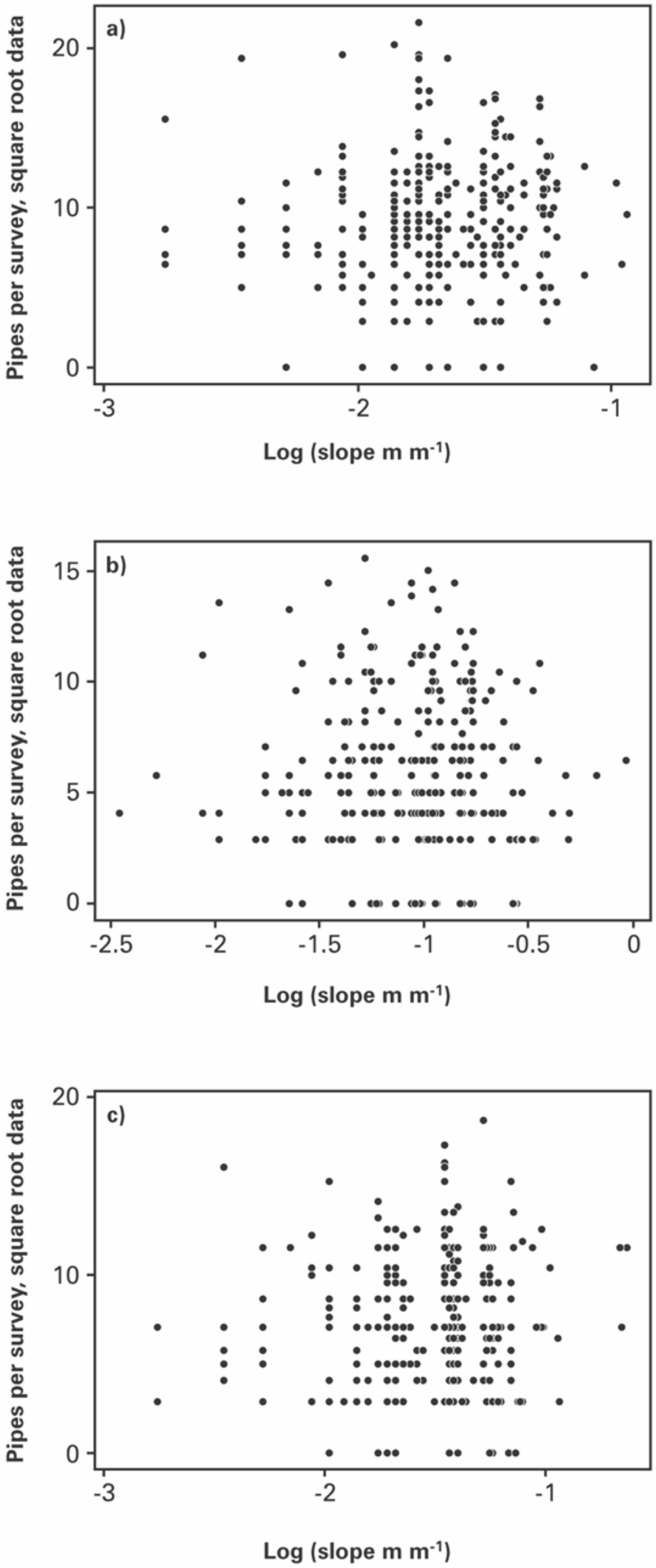


Figure 4: Scatter graphs plotting slope (log data) and pipe density (square root data) by topographic position; a) topslope sites; b) midslope sites; c) footslope sites There are no significant relationships



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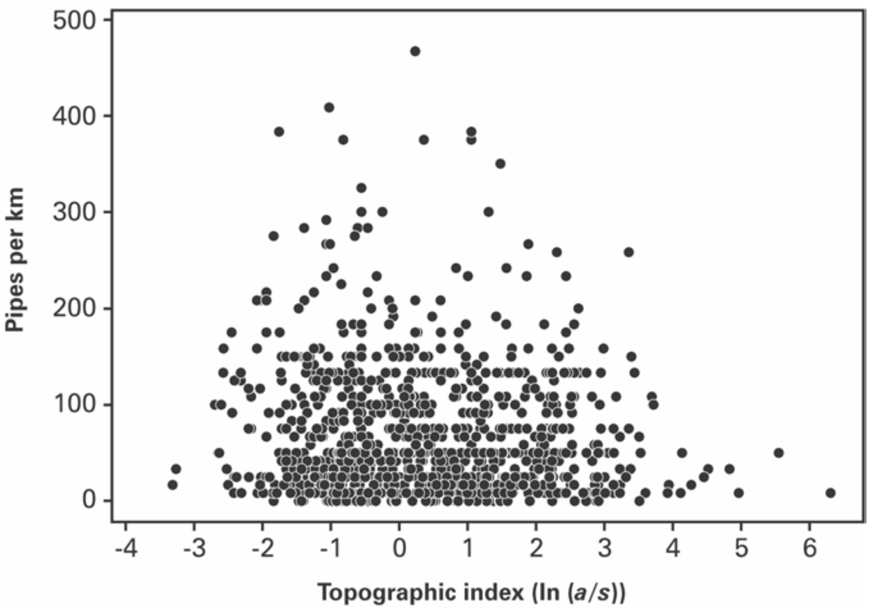

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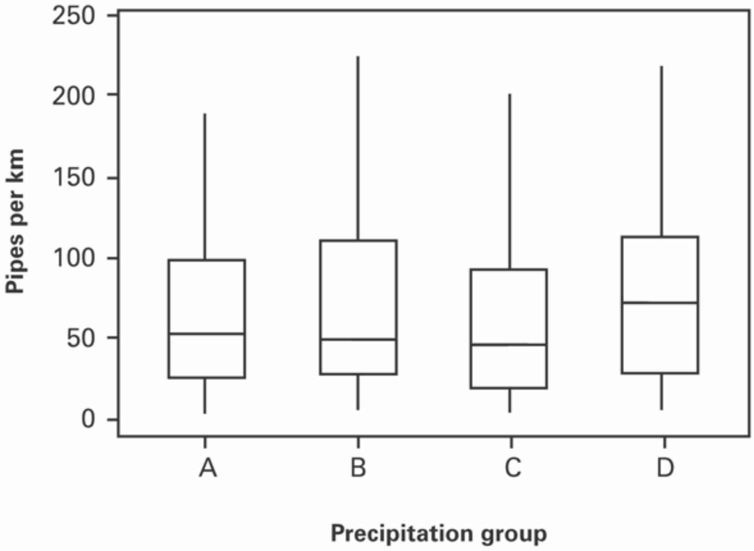

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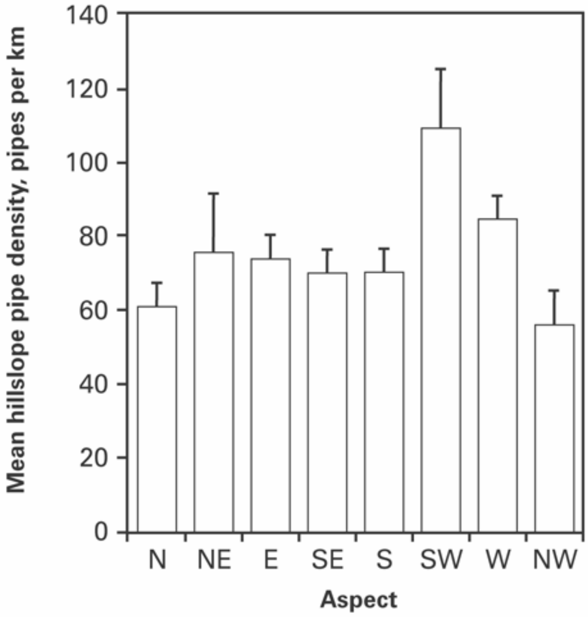

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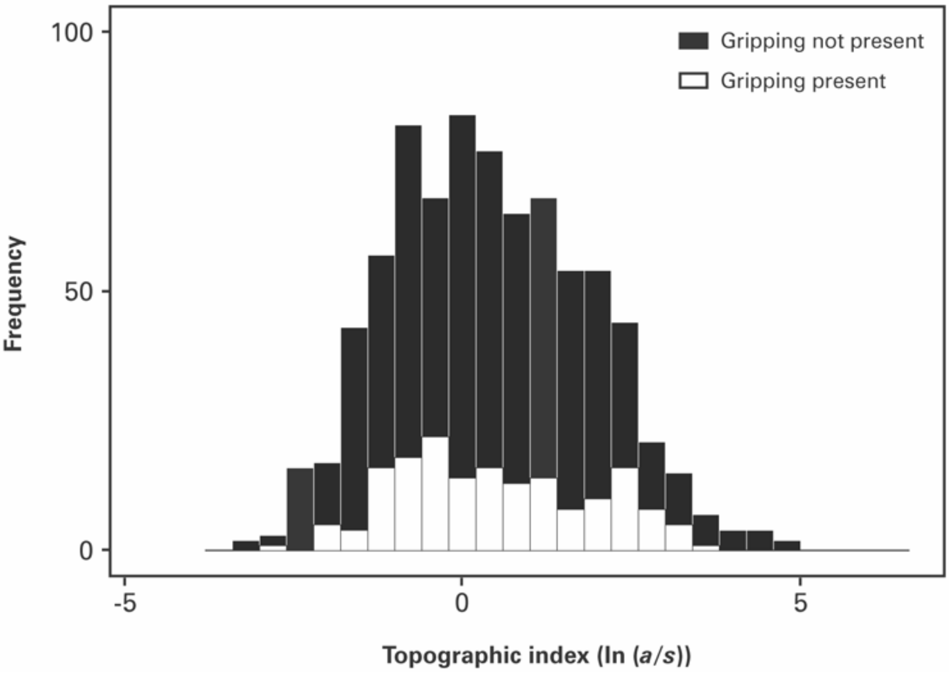

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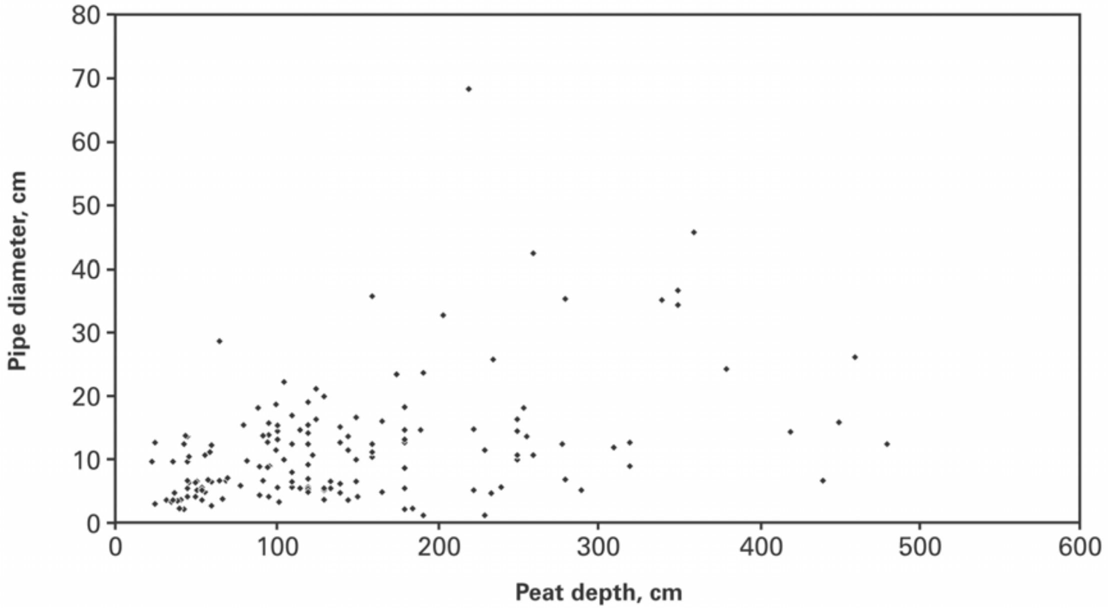

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