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PIPING AND WOODY PLANTS IN PEATLANDS; CAUSE OR EFFECT?

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Abstract

This paper presents for the first time, evidence to show that *Calluna* species are one causative factor of piping in blanket peat catchments. Ground penetrating radar survey on 960 plots illustrated that piping was prevalent throughout blanket peats. However, soil pipe occurrence was significantly higher where bare peat (149 pipes per km) or *Calluna* (87 pipes per km) were present compared to other species (67 pipes per km). A case study catchment where there was an altitudinal limit to *Calluna* provided some control over potential factors that may lead to an association between piping and *Calluna.* Under the controlled conditions of topographic index, peat depth and water table, piping was greater under the *Calluna*-covered peat than under other vegetation covers. Laboratory experiments demonstrated that 10 years worth of rainfall was enough to almost double the proportion of macropore flow occurring in recently colonised *Calluna* peatlands. This suggests that given enough water and time, the woody *Calluna* plants result in water being preferentially channelled through the upper peat. Improvements are therefore required in our understanding of the relationships between peatland plant nutrient and water supply, and the feedbacks between ecosystem functioning and landform development. These results are also important given the propensity to encourage *Calluna* growth for game bird enhancement in many northern peatlands.

1. Introduction

Natural soil pipes are common in many parts of the world and particularly in blanket peats (Holden and Burt, 2002a; Holden, 2004; Jones *et al.*, 1997; Gilman and Newson, 1980). However, there are problems in finding and defining soil pipe networks which are often located deep within the peat (Bryan and Jones, 1997). These pipes result in preferential bypassing vertical and lateral flow. They have been associated with changes in streamwater pH related to buffering where pipes interact with mineral soil layers, and increased acidity where pipes interact with an organic soil with abundant dissolved organic carbon. The pipes in upland humid catchments can transmit a large proportion of river flow with 49 % reported at Maesnant, mid-Wales (Jones and Crane, 1984) and 10 % at Moor House, northern England (Holden and Burt, 2002a). The pipes often lead to gully development (Higgins, 1990; Jones, 1994; 1997c). Some pipes can be over 1 m in diameter and may be found across blanket peat hillslopes and in stream banks. They may be important agents of peatland carbon removal and for understanding long-term ecosystem and landform development (e.g. Jones, 1997b).

Holden and Burt (2003a) noted that pipes may transcend the traditional acrotelm-catotelm model of ombrotrophic peatlands. This model suggests that all of the water and nutrient transfers take place in the upper few cm of the peatland whereas the lower part of the peat is saturated, stagnant, and anoxic (Ingram, 1983). However, pipes allow direct coupling of water, sediment and solutes from deep, shallow and surface layers of the peat profile. In fact during high flow, many pipes emit sediment onto the peat surface containing both peat and minerals from depth when pipes scour the underlying substrate (e.g. a glacial till clay). This may result in nutrient sources for local vegetation that have hitherto been ignored in blanket peat ecology.

Soil pipes have been associated with marked vegetation patterns. Jones *et al.* (1991) hypothesised that piping was responsible for vegetation distributions on peaty-podzol covered slopes in upland

Wales. Here the podzolic and peat soils were thin (50 - 100 cm thick) and pipes were generally found within 50 cm of the surface in the podzols, with larger pipes at the mineral interface in the peats. It was suggested that the pipes improved drainage and aeration by lowering the phreatic surface and that they channelled nutrients along depressions created by the piping. The result of this is that piping is associated with local vegetation that differs from that of the surrounds. The suggestion here is that piping causes changes in vegetation. At Moor House, a large blanket peatland in northern England, Holden and Burt (2002a) noted that similar surface vegetation 'tracks' could be observed coincident with the underlying network of soil pipes. Here, as on Maesnant, grasses such as *Eriophorum vaginatum*, *Juncus* and *Nardus stricta* overlie some pipes. However, at Moor House this was only the case for shallow pipes where peats were thin and the limestone geology was prominent.

While small-scale, shallow, pipe – plant ecology associations have been noted, there has been no work examining larger-scale patterns of piping and vegetation in peatland environments, including piping that exists several metres below the surface. Where deeper piping occurs in the peats at Moor House, for example, (and this is common; Holden *et al.*, 2002) there are no local changes in vegetation directly surrounding individual pipes. There may, however, be some general overall differences on a larger-scale. In other words, whole peatlands or whole hillsides with certain ecological characterictics may be associated with different amounts of subsurface piping. This has never been investigated.

Many blanket peats around the world have suffered from surface vegetation removal either due to overgrazing, industrial pollution or extraction. Such bare peats are susceptible to summer shrinkage cracking. These cracks may then initiate pipe development once the peatland wets up again (Gilman and Newson, 1980; Jones, 1981). Holden and Burt (2002b) found that dry summers caused an increase in macroporosity and infiltration on bare peat surfaces and Holden and Burt (2002c) suggested that severe droughts permanently increased peatland macroporosity. Again bare surfaces appeared to be more susceptible. Thus, it may be that bare peats are more susceptible to pipe network development and the loss of organic carbon through subsurface erosion, supplementing surface losses.

Calluna is a favoured species of upland peat management in many northern peatlands due to its association with improved game bird survival (e.g. grouse) and its growth is often encouraged (Shaw *et al*., 1998; Mowforth and Sydes, 1989). This paper aims to show that there is a difference in pipe frequency on slopes with *Calluna* and slopes without *Calluna*. In addition it will show that there are similar differences on slopes with bare peat and on slopes with a surface vegetation cover. Secondly, and more importantly, it aims to explain why these differences occur. It is assumed that increased piping would be a result of desiccation processes. However, this paper also seeks to determine whether the difference in piping associated with *Calluna* is a cause or effect of *Calluna* presence. *Calluna* may, for example, through its woody stem structure open up preferential flowpaths for water which allow pipe network development. Typically a third of a season's photosynthate is used to create woody stems and branches, many of which are just below the peat surface (Grace and Marks, 1978). This is important because if *Calluna* causes increased piping it may result in exacerbated carbon loss via pipe erosion. Alternatively it is reported that *Calluna* tends to favour better drained peats (Smith and Forrest, 1978; Ingram, 1983) and so it may be the case that the piping provides this improved drainage encouraging *Calluna* establishment and growth. Hence in order to understand whether *Calluna* impacts piping (and hence the associated hydrological and geomorphological processes) research is required.

This paper presents research that consists of a large-scale geophysical field survey in British blanket peats which aims to examine whether there are any general associations between surface vegetation species and piping. The research also uses a case study catchment in which factors can be controlled in order to examine differences in piping associated with vegetation. Finally, the paper reports on a laboratory experiment which used samples from the case study site and examined differences in macropore initiation associated with species cover. These three studies do not measure the same process at three different scales; rather they provide different lines of enquiry to investigate the hypothesis that *Calluna* is an important factor leading to enhanced piping.

2. Methods

2.1 Pipe survey

Until recently it has been difficult to determine the frequency of piping due to the lack of appropriate survey techniques. Holden *et al.* (2002) and Holden (2004) reported on the successful utility of ground penetrating radar (GPR) for surveying soil piping. This technique allows pipes to be remotely mapped in a non-destructive manner and enables measurements of the frequency of piping in peatlands to be made. A GPR survey of piping was carried out in 160 upland blanket peat catchments between 0.8 km^2 and 4.2 km^2 across the UK (Figure 1). 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.

In each catchment six plots were surveyed. Each plot consisted of six 20 m GPR 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. Holden *et al*., (2002) provide full details of the technique and so 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 and thus the GPR should 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 GPR cannot provide information on pipe diameters and so no information about the relative size of pipes on different parts of the hillslope could be obtained.

For each plot the presence or absence of key blanket peat species was noted (e.g. *Calluna, Sphagnum, Eriophorum,* bare surface). 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; Jones 1997a)) as an indicator of the topographic concentration of drainage. Two points with the same topographic index should therefore be equivalent in terms of the ratio between drainage area and slope. In addition it was possible to check whether *a* (topographic water flow path length) was a control on propensity for piping. The topographic index was calculated from ground survey using acquired real-time kinematic GPS with a precision of 3 cm. The calculation of this index allows determination of whether piping and vegetation cover are both controlled by the same topographic drainage control (e.g. same likely saturation extent). This is important because we might find that any associations between piping and vegetation could be explained by topography.

2.2 Moor House case study

A further 32 GPR plots were studied on the Moor House Reserve, in the northern Pennine hills, England (54°41’N, 2°23’W). This UNESCO Biosphere Reserve occupies 35 km^2 with an altitudinal range of 290 to 848 m. Blanket peat covers around 70 % of the reserve with vegetation dominated by *Calluneto-Eriophorum-Sphagnum* blanket bog. *Eriophorum vaginatum, Calluna vulgaris* and *Sphagnum* species (mainly *Sphagnum rubellum, Sphagnum papillosum* and

Sphagnum magellanicum) dominate the site. The area is fully described in Heal and Smith (1978), Rawes and Welch (1969), Eddy *et al.*, (1969) and Johnson and Dunham (1963). Most of the reserve can be classified as NVC M19 *Calluna vulgaris-Eriophorum vaginatum* blanket mire (Rodwell, 1991). *Calluna* requires moist oceanic conditions with mean summer temperatures above 7°C, but above 650 m altitude at Moor House, NVC M20 *Eriophorum-vaginatum* blanket mire dominates as low summer temperatures restrict *Calluna* growth (Rawes and Welch, 1969; Grace and Marks, 1978; Holden and Adamson, 2001; 2002, Holden 2001). *Calluna* is almost completely absent from these higher parts of the Reserve. This therefore allows a field-scale comparison of piping and large-scale vegetation associations. The site is appropriate because it is a location where *Calluna* is only absent or present due to temperature conditions and not due to the differences in drainage characteristics. Hence it is possible at Moor House to get a control, within one field site, on *Calluna*-piping associations without there being differences in local hydrology. Sixteen of the GPR plots were in the lower part of the reserve where *Calluna* was dominant and sixteen in the upper part of the reserve where *Calluna* was absent. The underlying geology and peat depths were comparable between non-*Calluna* and *Calluna* plots. Each plot was on a different hillslope and was chosen so that it had the same mid-point topographic index and approximately the same drainage and slope characteristics. It was also necessary to take aspect into account in this controlled investigation because Jones *et al.* (1997) suggested that southern and western facing slopes in the northern hemisphere might be more susceptible to pipe development due to summer desiccation of the peat. Therefore slopes were chosen systematically so that for both *Calluna* and non-*Calluna* slopes, four plots faced each of north, south, east and west. Slope was not investigated as a separate factor as this has been dealt with elsewhere (Holden, 2005) and was varied in order to ensure a fair comparison between *Calluna* and non-*Calluna* sites. The water table was monitored at the mid-point of each plot on a bi-weekly basis for 12 months using a perforated 10 mm PVC tube of 1 m in length.

2.3 Experiment

Forty-eight peat blocks of 1 m x 0.5 m and 0.5 m deep were extracted from the Moor House Reserve. They were carefully removed in order to ensure they were kept intact and were taken to the laboratory in rigid PVC containers, the faces of which were smeared with petroleum gelatine prior to use in order to create a good seal between the peat and the container. Four vegetation covers where chosen as treatments (*Eriophorum, Sphagnum, Calluna* and bare peat) with twelve blocks for each cover type. Each block had a least 90 % of the specified vegetation cover and 10 % or less, of any other cover. In order to test whether pipes could be initiated on a bare peat surface *without* shrinkage desiccation, the bare peat blocks were taken from an actively eroding slope and the upper 30 cm of the peat was discarded. Hence the newly emerged peat surface should be free from the effects of summer desiccation and only the influence of rainfall was examined in this experiment.

The 12 *Calluna*-dominated peat blocks were taken from a part of Moor House where *Calluna* had only colonised within the last eight to ten years. This colonisation is associated with *Calluna* moving to higher altitudes in response to local recent warming over the past few decades (Holden and Adamson, 2002). Thus the *Calluna* blocks were recently colonised peat blocks and could be used to examine whether *Calluna* colonisation was associated with pipe initiation.

Each peat block was split into two so that each original block now consisted of two 0.5 x 0.5 x 0.5 m peat blocks. One block from each pair was then investigated for preferential flow. This was done by using a tension infiltrometer to determine the proportion of macropore flow at the surface and at 10 cm and 30 cm depth. This instrument works by allowing water to infiltrate into the peat matrix (small pores) whilst preventing water from infiltrating into larger voids by creating a small negative pore water pressure at the surface. If the surface pressure is varied it is possible to evaluate how much water movement occurs through large and small pore spaces by comparing results from each test. Full details of the principles of tension-infiltrometry and the procedure are provided in Holden *et al.*, (2001). The tension infiltrometer measurements are provided in three forms. Firstly results are available for the proportion of flow from the instrument through the peat that is through pores between 0.05 to 2 mm in diameter. Secondly, there are results for the proportion of flow moving through pores larger than 2 mm in diameter. Finally adding together values for the first two pore classes provides a measure of the overall proportion of flow taking place in pores larger than 0.05 mm in diameter.

For the remaining block from each pair, a rainfall simulator was used to provide water to the vegetation and peat surface. A drip type simulator was used below which hung a swinging wire mesh (3 mm squares; Bowyer-Bower and Burt, 1989) in order to randomly break up and scatter raindrops over the peat blocks. This was so that raindrops do not repeatedly land in the same spot altering surface microtopography and potentially influencing macropore development. The simulator produced drop diameter distributions close to that of natural rainfall in northern England. The wire mesh was positioned 2 m above the peat block surface and a steady rainfall intensity was controlled at 12 mm hr^{-1}. Rainfall intensity in the UK rarely exceeds 12 mm hr^{-1} and so it was not justifiable to use larger intensities. Further details on the rainfall simulator design (although slightly smaller than that used in the present study) and methods applied, can be found in Holden and Burt (2002b) and Holden and Burt (2002c). The simulator used in this study was 2.5 m x 2.5 m allowing up to twenty-five 0.5 m^2 blocks to be simultaneously placed beneath the simulator.

The rainfall simulation sequence consisted of six hours of rainfall followed by six hours without rainfall, followed by six hours of rainfall and so on. This was repeated for 140 days. Thus, the total amount of rainfall delivered to each block was 20160 mm. Mean annual precipitation at Moor House is around 2000 mm per year (Holden and Adamson, 2001) and hence the rainfall simulation provided 10 years worth of rainfall but at realistic intensities. After 140 days the tension infiltrometer tests were performed on the rain treatment blocks in order to establish whether macropore flow had increased in any of the blocks (assuming that the untreated half of the block was representative of the rainfall treated half). Thus there were two sets of tension infiltrometer results. One set for 48 untreated blocks (with four surface cover types and three depths) and one set of 48 blocks subject to 10 years rainfall (with four surface cover types and three depths).

In summary the laboratory experiments allow exploration of pipe initiation on peat surfaces in two ways. Firstly by subjecting bare peat (that has not been previously desiccated) to rainfall equivalent to that occurring in 10 years but using realistic intensities it is possible to examine whether desiccation cracking drives pipe formation (no desiccation cracking could occur over the 140 days of rainfall simulation) or whether it is only an adequate water supply that is needed. Secondly the experiments allow us to examine whether, given enough water supply, pipes will preferentially form under a vegetation cover of *Calluna* compared with *Sphagnum*, *Eriophorum* and bare peat.

3. Results

3.1. Field survey

Soil pipes were detected by the GPR survey 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 an ANOVA where species presence or absences are factors. Tests for equal variance related to the presence or absence of a particular vegetation type revealed no significant difference for *Calluna*, *Eriophorum* or *Sphagnum.* There was a difference in variance for the bare peat at $p<0.05$, but this was not significant at $p<0.01$. Therefore the ANOVA was assessed as normal. Table 1 shows that the presence or absence of *Sphagnum* is not a significant factor in pipe density but the presence of *Calluna* and bare peat appear to be overwhelming controls. *Calluna*-covered peats or peats with a bare surface tend to have a significantly higher frequency of soil piping ($p<0.001$) than peats without these cover types (Table 2). Thus there is a clear association between surface vegetation and subsurface pipe frequency in blanket peatlands. There were no significant relationships between topographic index, or a, and pipe frequency. An ANOVA was performed for the measured topographic indices with vegetation cover as a factor. No significant differences were found. Thus pipe frequency or vegetation distribution was a not a simple function of topographic index and the associations found in Tables 1 and 2 can now be considered independently in terms of direct cause and effect. In fact this would tend to suggest that increased piping is an effect of *Calluna* presence rather than a cause of *Calluna* presence, because *Calluna* sites should originally be no better drained than the 504 plots without *Calluna* cover examined in this survey.

3.2 Moor House case study

Further evidence comes from the Moor House case study where sixteen plots from sites without *Calluna* (from above its altitudinal limit) were compared to those with *Calluna*. Each plot had the same topographic index and yet a Mann-Whitney U-test indicated there was significantly more piping on the hillslopes below 650 m altitude where *Calluna* was present (median = 108 km^{-1}) than those at higher altitudes where *Calluna* was not present (median = 25 km^{-1}; $p = 0.0008$). Given that each plot was chosen to control factors such as slope and drainage area this again strongly suggests that there is a direct relationship between *Calluna* and pipe frequency. The mean annual water table at each of the 16 plots ranged from -3.6 cm to -4.4 cm. The maximum difference in water table depth between the 16 sites for any given time over the entire year was only 2.7 cm. This was between two sites on the *Calluna* covered part of the catchment. Hence the Moor House case study provides adequate control on local hydrology to demonstrate that the link between *Calluna* and larger-scale pipe frequency is not simply a function of surrounding hydrological processes resulting in both *Calluna* and piping prevalence at the same sites. The association appears to be somewhat independent (nothwithstanding the need for a water surplus and peat). Indeed these results suggest that it is *Calluna* which causes increased piping in peat catchments. However, it could be argued that because altitude is a factor here, warmer summer temperatures lower down the catchment would make it more susceptible to desiccation and hence cracking and pipe network initiation. Therefore it is necessary to control such conditions in a laboratory experiment. In addition a laboratory experiment can provide further insight into cause and effect.

3.3 Laboratory experiments

Macropore flow was a significant proportion of flow for control plots with 8.6 % of flow occurring through pores between 0.05 and 2 mm in diameter and 19.4 % through pores greater than 0.2 mm. Thus almost one third of flow (28 %) occurred in pores greater than 0.05 mm in diameter. The distribution of values was approximately symmetrically distributed around the mean. The proportion of flow in pores greater than 0.05 mm in diameter on control and rainfall treatment plots ranged from 5.8 % to 93.5 % and had standard deviation of 15.6 %. It is therefore suitable in raw form for an analysis of variance in relation to depth, vegetation cover and rainfall treatment. In these tests, depth is treated as a categorical variable.

For each of the three sets of results (for different pore size categories) Table 3 presents results of an ANOVA. Surface vegetation and the rainfall treatment are significant factors at all macropore sizes analysed. Depth is a significant factor at the 95 % level for pores 0.05 - 2 mm and significant at the 99 % level for pores greater than 2 mm in diameter. The interaction between vegetation and rainfall treatment is significant and the vegetation x depth interaction is only significant for pores greater than 2 mm in diameter. The other interactions are not significant.

The detailed cross-tabulation of the means (Table 4) show that for the control plots, *Sphagnum* peats tend to have a higher mean flow proportion through macropores of between 0.05 and 2 mm in diameter than under other vegetation covers. However, for macropores greater than 2 mm in diameter it is *Calluna* which provides more bypassing flow. For all vegetation covers there is a greater mean proportion of flow occurring through pores larger than 2 mm than for the pores 0.05-2 mm in diameter. Table 4 also shows that for the three macropore size categories the proportion of macropore flow is much greater on the plots subject to rainfall treatment only in the case of *Calluna* covered peat. Paired t-tests showed that no post-rainfall differences were significant other than those for *Calluna* ($p < 0.001$). Hence the only peat to have developed macropores and small pipes (> 2 mm) during the experiment, was that under a young *Calluna* cover. Figure 2 shows the mean proportion of macropore flow at the peat surface under each vegetation cover for blocks subject to rainfall as well as treatment blocks. Before rainfall treatment *Calluna* peats have approximately the same proportion of macropore flow in pores over 0.05 mm in diameter as *Sphagnum* peats. Results are in line with Holden *et al.*, (2001) who also showed that bare peat and *Eriophorum* peat tended to have lower macroporosities than *Calluna* and *Sphagnum* covered peat. However, while no change is observed in the *Sphagnum* peat, or other peats, there is a 59 % increase in macropore flow in the *Calluna* peat after rainfall treatment. In fact, following rainfall treatment, more than 50 % of flow bypasses the peat matrix under *Calluna* cover compared to a mean of 26 % for other plots.

Macropore flow tends to be slightly greater at the surface than at lower levels (Table 4) but increased macropore flow is evident for *Calluna* throughout the measured depth of the peat blocks (i.e. up to 30 cm depth). This is important because most flow in intact blanket peats takes place in the upper few centimetres of the peat. At Moor House, Evans *et al.* (1999) and Holden and Burt (2003a; 2003b) reported that most of this was within the upper 5 cm of the peat.

The results from paired peat blocks (one half was the control and the other subject to rainfall treatment) are shown in Figure 3. The points are plotted for all depths and hence there are 72 points per vegetation cover per macropore category. The lines on these plots indicate a value for no change between control and treatment and this is adhered to in the case of bare peat, *Sphagnum* and *Eriophorum*. The *Calluna* plots tend to lie well above this line and there are only three to five cases for each macropore class for *Calluna* where the proportion of macropore flow is below that line (where macropore flow is less than before rainfall treatment).

4. Discussion

The evidence for an association between surface vegetation species on blanket peats and subsurface pipe frequency is overwhelming. This is on a larger scale than simple associations previously reported by Jones (1981) and Jones *et al.* (1991) between species located above individual pipes. In fact it was rare during the survey to encounter cases where pipes coincided with surface vegetation ‘tracks’. This is because the majority of the survey was carried out on deep peats where the peat was between 0.5 m and 8 m deep. The pipes were found throughout the peat profile. In this large GPR survey of 960 plots across Britain, consisting of over 115 km of survey transect, significantly more pipes were found below plots where bare peat and *Calluna* were present compared to those where they were absent.

The results appear to be in contrast to reports from the Maesnant site in Wales (Jones *et al*., 1991; Jones, 1997c) where the pipes were only found in *Calluna*-free areas. In the podzols soils at Maesnant, they were found under broad patches of grass adjacent to heath-covered areas, and pipes were shallow. Under the Maesnant peat (only 0.5-1.0 m deep), the pipes were perennially-flowing under grass strips in shallow hollows with the *Calluna* heath on the interfluvial ridges between the hollows. However, the present study only examined deep blanket peat sites, but this was over 160 different catchments. It may be that in other soil or peat types, different processes dominate.

Even within one case study site (Moor House) there were significantly greater pipe frequencies from *Calluna*-dominated areas to slopes where *Calluna* was absent. The fact that each of the 32 plots at Moor House had the same topographic index and similar local water tables suggests that *Calluna* causes increased piping. This is in contrast to the inference from Jones *et al.* (1991) that better drainage as a result of piping may encourage *Calluna* growth. This is not to say that that could not be the case. It may well be an important feedback in many places. Indeed it is likely that there is a both a cause and effect relationship between piping and *Calluna*. However, the evidence from the GPR survey across Britain for *Calluna* and bare peat being a causal factor in increased pipe frequency is strong. There were no relationships between topographic index and piping. This was also found by Jones (1986, 1994, 1997b) for the Masnant basin. In addition the Moor House case study site consisted of an altitudinal limit to *Calluna* growth so that other factors could be held constant at the site. However, it could be argued that lower altitudes at Moor House may be associated with warmer temperatures and enhanced desiccation. In order to control this effect laboratory experiments were performed.

In the laboratory experiments it was possible to investigate and speed up pipe initiation and development. Bare peat blocks did not suffer increased piping under the experimental conditions. In this experimental design these bare peat blocks were ones that started from a position of no initial desiccation (as they had their top layers removed before rainfall treatment). This suggests that a pre-requisite for pipe development in bare peat could be surface desiccation cracking during dry summer periods (Gilman and Newson, 1980). Thus since bare peats are associated with intense subsurface piping in addition to surface sediment loss, they should be avoided or revegetated (with *Sphagnum* or *Eriophorum* for example) where possible in order to reduce subsurface erosion, carbon loss and the chances of gully development.

For recently colonised *Calluna* plots, however, the proportion of water flowing through macropores almost doubled following the ten years worth of rainfall delivered during the experiment. This indicates that *Calluna* development involving its woody stem and root structure allows preferential flow development. While the experiment is not equivalent to a ten year time period (during which *Calluna* and peat growth would occur) it does give some strong indications that over a period of time during which *Calluna* colonises an area it can also result in the initiation of soil pipes. The laboratory experiments therefore confirm results from the field and indicate that *Calluna* is a causative factor in piping of peatlands.

Of course *Calluna* root development is only one causative factor and piping occurs under all blanket peat covers due to other pipe initiation processes (e.g. see Holden *et al.,* 2004; Holden and Burt 2003a; Holden and Burt, 2002a; Jones, 1990; Jones 1981). Holden *et al*. (2001) found that *Sphagnum*-covered peat had a greater proportion of macropore flow than peat under other species, for example. Thus at first glance the results presented above appear to contradict this finding. However, Holden *et al*. (2001) only presented data for one pore size. Indeed results in this paper are entirely consistent with their study in that for the control plots, *Sphagnum* peats had a greater mean proportion of flow (15 %) through macropores of between 0.05 and 2 mm in diameter than under other vegetation covers (6.5%). However, for larger macropores (greater than 2 mm in diameter) for which Holden *et al*. (2001) did not have data, then the results above indicate that *Calluna*-covered peats cause more macropore flow.

The *Sphagnum*-related macroporosity is likely to be related to the *Sphagnum* cushion which comprises a dense and finely porous ‘roof’ of side branches, supported on a much less dense layer of vertical columns interspersed by much larger spaces and obtaining some lateral bracing from the occasional divergent side branches (Ingram, 1983). At the same time *Sphagnum* does not produce significant root systems thereby reducing the mechanisms for creating larger and deeper macropores. Thus *Calluna* associated macropore development may be more important for turbulent macropore flow in pores larger than 2 mm and also for allowing deeper pipe development to occur more quickly via root channels.

5. Limitations

There are a number of limitations to the research presented above. Firstly, GPR cannot detect pipes smaller than 10 cm in diameter. The laboratory tests only examined pores at the scale of < 0.05 mm (ie matrix flow), 0.05- 2 mm in diameter and > 2 mm in diameter. There is thus a gap in measurable macropores and pipes which may be important. The laboratory tests showed that around one third of flow moved through macropores greater than 0.05 mm while in newly colonised *Calluna* peats 10 years worth of rainfall was enough to allow over half of water flow to move through macropores. Clearly then macropores are an important component of the ecohydrology of blanket peatlands. Pipes larger than 10 cm in diameter are also prevalent. However, we know very little about the role of the intermediate pore sizes. In addition it may be that the increase in water conduction through macropores under the colonising *Calluna* is predominantly in the vertical direction, whereas soil pipes drain the hillslope in a predominantly lateral direction. Further work is required to examine this.

Secondly, the laboratory experiments are only indicative of possible field processes and while every effort was made to provide realistically light rainfall, providing 10 years rainfall in 140 days must still be seen as a controlled laboratory simulation. Natural field ecological and hydrological processes may occur over any real ten year period that could alter the propensity to macropore development and piping (Clymo, 1983). Nevertheless, the field survey clearly demonstrated the strong association of *Calluna* and piping in peats which has hitherto never been demonstrated.

Thirdly, there is a gap between the depth of peat investigated in the laboratory, where macropore initiation processes were investigated, and the deeper peat where pipes were found in the field. There is therefore an important question relating to how what happens in the upper 30 cm of the peat affects pipe development several metres below the surface. This paper has identified relationships between surface vegetation, macropore development, and deeper piping even though the exact process-links between surface processes and deep peat processes need further study.

Finally, in the field, peat is not isolated but exists within a topographic context (hence the use of the topographic index during the field survey). Therefore pipes may develop locally due to changes in hydraulic gradient associated with breaks in slope or peat structure and due to local variations in lateral or vertical hydraulic conductivity (Holden and Burt, 2003c). Hence field conditions may exist to promote pipe network development that cannot be fully examined in a laboratory setting.

6. Conclusions and future work

This paper has presented for the first time, clear evidence to show that *Calluna* is one cause of piping in blanket peat catchments. Field survey showed that *Calluna* was associated with higher frequencies of soil piping. Bare peat also had large frequencies of piping. By examining topographic controls and performing laboratory experiments this paper has demonstrated that *Calluna* results in increased piping and pseudo-piping. Given enough water and time, the woody *Calluna* plants cause water to be preferentially channelled through the upper 30 cm of peat. This preferential flow network expands allowing development of subsurface pipe networks. Further work is required to examine the nature of such processes. Indeed, any woody plant (not just *Calluna*) may have a similar effect of enhanced piping. Testing in a wider range of peatlands may reveal whether this is the case, but in a UK context there are very few other woody plants that colonise the blanket peat. Further research is also required to examine feedbacks between root structure, preferential flow, nutrient delivery, local drainage and continued root and stem development. Given the clear importance of macropores and pipes in blanket peatlands more attention should be given to the hydroecological implications of the dominance of such processes. There is therefore a need for improved understanding of the relationships between peatland plant nutrient and water supply, and the feedbacks between ecosystem functioning and landform development. These results are also important given the propensity to encourage *Calluna* growth for game bird enhancement in many northern peatlands. As peatlands are important as global carbon stores any process that may encourage subsurface erosion and carbon loss should be carefully investigated.

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8. References

Bowyer-Bower, T.A.S. and T.P. Burt. Rainfall simulators for investigating soil response to rainfall. *Soil Technology*, **2**: 1-16. 1989.

Byran, R.B. and J.A.A, Jones. The significance of soil piping processes: inventory and prospect. *Geomorphology,* **20**: 209-218. 1997.

Carson, M.A. and M.J. Kirkby. *Hillslope form and process.* Cambridge University Press, Cambridge, 1972.

Clymo, R.S. Peat growth. In E.J. Cushing and L.C. Shane (editors) *Quaternary landscapes.* University of Minnesota Press, Minneapolis. 1991.

Eddy, A., D. Welch, and M. Rawes. The vegetation of Moor House National Nature Reserve in the North Pennines, England. *Vegetatio*, **16:** 239-284. 1969.

Evans, M.G., T.P. Burt, J. Holden and J.K. Adamson. Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995, *Journal of Hydrology, **221*****:** 141-160. 1999.

Gilman, K. and M.D. Newson. *Soil pipes and pipeflow; a hydrological study in upland Wales*. British Geomorphological Research Group Research Monograph No. 1, Geo Books, Norwich. 1980.

Grace, J. and T.C. Marks. Physiological aspects of bog production at Moor House. In Heal, O.W. and Perkins, D.F. (eds) *Production Ecology of British Moors and Montane Grasslands,* Springer, Berlin, 38-51. 1978.

Higgins, C.G. Gully development. In C.G. Higgins and D.R. Coates (editors) Groundwater Geomorphology; the role of subsurface water in Earth-Surface Processes and Landforms. *Geology Society of America Special Paper*, **252:** 139-155. 1990.

Holden, J. Controls of soil pipe frequency in upland blanket peat. *Journal of Geophysical Research*, **110**: doi: 10.1029/2004JF000143. 2005.

Holden, J. Hydrological connectivity of soil pipes determined by ground penetrating radar tracer detection, *Earth Surface Processes and Landforms*, **29**: 437-442. 2004.

Holden, J. Recent reduction in frost in the North Pennines. *Journal of Meteorology, UK,* **26***: 369-374.* 2001.

Holden, J. and J.K. Adamson. The Moor House long-term upland temperature record – new evidence of recent warming. *Weather,* **57**: 119-126. 2002.

Holden, J. and J.K. Adamson. Gordon Manley and the north Pennines. *Journal of Meteorology,* **26:** *329-333.* 2001.

Holden, J. and T.P. Burt. Hydrological studies on blanket peat: The significance of the acrotelm-catotelm model, *Journal of Ecology,* ***91*****:** 86-102. 2003a.

Holden, J. and T.P. Burt. Runoff production in blanket peat covered catchments. *Water Resources Research,* 39, 1191, DOI: 10.1029/2003WR002067. 2003b.

Holden, J. and T.P. Burt, Hydraulic conductivity in upland blanket peat; measurement and variability, *Hydrological Processes,* **17:** 1227-1237. 2003c.

Holden, J, and T.P. Burt. Piping and pipeflow in a deep peat catchment, *Catena* **48:** 163-199. 2002a.

Holden, J. and T.P. Burt. Infiltration, runoff and sediment production in blanket peat catchments: implications of field rainfall simulation experiments, *Hydrological Processes,* **16:** 2537-2557. 2002b.

Holden, J. and T.P. Burt. Laboratory experiments on drought and runoff in blanket peat, *European Journal of Soil Science,* **53:** 675-689. 2002c.

Holden, J., T.P. Burt, and N.J. Cox. Macroporosity and infiltration in blanket peat: the implications of tension disc infiltrometer measurements, *Hydrological Processes,* **15:** 289-303. 2001.

Holden, J., T.P. Burt, and M. Vilas. Application of ground-penetrating radar to the identification of subsurface piping in blanket peat, *Earth Surface Processes and Landforms, 27*, 235-249, 2002.

Holden, J., P.J. Chapman, and J.C. Labadz. Artificial drainage of peatlands: Hydrological process and wetland restoration, *Progress in Physical Geography,* 28, 95-123. 2004.

Ingram, H.A.P. Hydrology. In A.J.P. Gore (editor) *Ecosystems of the World 4A, Mires: swamp, bog, fen and moor,* Elsevier, Oxford, 67-158, 1983.

Johnson, G.A.L. and Dunham, K.C. *The geology of Moor House*. Monographs of nature conservancy, 2, H.M.S.O., London. 1963.

Jones, J.A.A. Pipeflow contribution areas and runoff response. *Hydrological Processes*, 11, 35-41. 1997a.

Jones, J.A.A. The role of natural pipeflow in hillslope drainage and erosion: extrapolating from the Maesnant data. *Physics and Chemistry of the Earth,* 22, 303-308, 1997b.

Jones, J.A.A. Subsurface flow and subsurface erosion. In D.R. Stoddart, (editor) *Process and form in geomorphology*, Routledge, London, 74-120, 1997c.

Jones, J.A.A. Soil piping and its hydrogeomorphic function. *Cuaternario y Geomorfologia*, 8, 77-102, 1994.

Jones, J.A.A. Piping effects in humid lands. In C.G. Higgins and D.R. Coates (editors) Groundwater Geomorphology; the role of subsurface water in Earth-Surface Processes and Landforms. *Geology Society of America Special Paper*, 252**,** 111-137. 1990.

Jones, J.A.A. Some limitations to the a/s index for predicting basin-wide patterns of soil water drainage. *Zeitschrift fur Geomorphologie, Supplementband* 60, 7-20. 1986.

Jones J.A.A. *The nature of soil piping: a review of research*, British Geomorphological Research Group Monograph Series 3, Geo Books, Norwich. 1981.

Jones J.A.A, J.M., Richardson, and H.J. Jacob. Factors controlling the distribution of piping in Britain: a reconnaissance, *Geomorphology, 20*, 289-306. 1997.

Jones, J.A.A., Wathern, P., Connolly, L.J. and Richardson, J.M. Modelling flow in natural soil pipes and its impact on plant ecology in mountain wetlands. *Hydrological basis of ecologically sound management of soil and groundwater*, Proceedings of the Vienna Symposium, August 1991. IAHS Publication 202. 1991.

Jones, J.A.A. and F.G Crane, Pipeflow and pipe erosion in the Maesnant experimental catchment. In T.P. Burt, and D.E. Walling, (editors) *Catchment Experiments in Fluvial Geomorphology*, Geobooks, Norwich, 55-72, 1984.

Mowforth, M.A. and C. Sydes. *Moorland management: a literature review.* Research and survey in nature conservation series, 25. Nature Conservancy Council, Peterborough. 1989.

Rawes, M. and D. Welch. Further studies on sheep grazing in the northern Pennines. *Journal of the British Grassland Society,* 19, 56-61, 1969.

Rodwell, J.S. British plant communities volume 2: mires and heaths. University of Cambridge, Cambridge. 1991.

Shaw, S., B. Wheeler, and J. Backshall. Review of effects of burning and grazing of blanket bogs: conservation issues and conflicts. In J.H. Tallis, R. Meade, and P.D. Hulme (eds) *Blanket mire degradation; causes consequences and challenges,* Proceedings , University of Manchester 9-11 April 1997, Macaulay Land Use Research Institute, Aberdeen, 174-182, 1998.

Smith, R.A.H. and G.I. Forrest. Field estimates of primary production. In Heal, O.W. and Perkins, D.F. (eds) *Production Ecology of British Moors and Montane Grasslands,* Springer, Berlin, 17-37, 1978.

Table 1. Analysis of Variance of the number of pipes per km of survey transect by species presence.

Species presence	Degrees of freedom	Mean square	F ratio	probability
Calluna	1	328780	90.7	<0.001
Bare surface	1	302638	83.5	<0.001
Eriophorum	1	13511	3.7	0.054
Sphagnum	1	637	0.2	0.675
Residual	955	3624		
Total	959			

Table 2. Number of plots where species present or not present, mean pipe frequency per km of transect and standard error.

Species presence	yes			no		
	n	Mean, km^{-1}	standard error	n	Mean, km^{-1}	standard error
Calluna	456	87.4	3.0	504	49.7	2.8
Bare surface	40	148.7	17.0	920	64.1	2.0
Eriophorum	890	65.0	2.1	70	101.1	11.8
Sphagnum	594	73.6	2.5	366	57.8	3.7

Table 3. Results from three separate ANOVAs for macropore contribution to flow for laboratory peat block experiments.

		% contribution for macropores 0.05 to 2 mm			% contribution for macropores > 2 mm			total % contribution for macropores > 0.05 mm		
Factor	d.f.	mean square	F	p	mean square	F	p	mean square	F	p
surface cover	3	1662	92.1	<0.001	4566	67.3	<0.001	10413	111.1	<0.001
depth	2	57	3.1	0.045	414	6.1	0.003	777	8.3	<0.001
rain	1	570	31.6	<0.001	632	9.3	0.003	2401	25.6	<0.001
cover x depth	6	26	1.4	0.199	231	3.4	0.003	244	2.6	0.018
cover x rain	3	474	26.3	<0.001	805	11.9	<0.000	2508	26.8	<0.001
depth x rain	2	0.1	0.01	0.995	26	0.4	0.638	23	0.2	0.783
depth x cover x rain	6	2	10.1	0.347	30	0.4	0.850	80	0.9	0.533
Residual	264	18			68			94		
Total	287									

Table 4. Cross-tabulation of means for proportion of flow occurring via macropores for three pores size classes by surface cover and depth during laboratory peat block experiments; P1 = % contribution for macropores 0.05 to 2 mm, P2 = % contribution for macropores > 2 mm, P3 = total % contribution for macropores > 0.05 mm

Cover	Depth	P1		P2		P3	
		no rain	rain	no rain	rain	no rain	rain
Calluna	0	9.1	19.7	30.0	46.6	39.2	66.4
	10	5.9	18.6	21.5	34.3	27.4	52.9
	30	8.6	16.8	22.9	32.3	31.6	49.2
marginal mean		7.9	18.4	24.8	37.7	32.7	56.1
Bare	0	7.2	7.4	13.7	12.0	20.9	19.4
	10	4.6	4.7	12.4	11.4	17.0	16.1
	30	4.6	4.2	13.0	12.1	17.6	16.2
marginal mean		5.5	5.4	13.0	11.8	18.5	17.2
Eriophorum	0	7.1	7.9	16.8	16.9	23.9	24.8
	10	6.4	6.3	18.7	19.0	25.1	25.3
	30	5.0	6.0	18.5	16.9	23.5	22.9
marginal mean		6.2	6.7	18.0	17.6	24.2	24.3
Sphagnum	0	14.6	14.0	24.0	25.6	38.6	39.7
	10	16.5	15.2	22.5	20.4	39.1	35.6
	30	13.8	16.4	18.3	20.4	32.1	36.8
marginal mean		15.0	15.2	21.6	22.1	36.6	37.4
all covers	0	9.5	12.3	21.1	25.3	30.7	37.5
	10	8.3	11.2	18.8	21.3	27.1	32.5
	30	8.0	10.9	18.2	20.4	26.2	31.3
marginal mean		8.6	11.4	19.4	22.3	28.0	33.8

Figure captions

Figure 1. Map showing a) areas of blanket peat in Britain and b) the location of the GPR survey catchments (circles) and the case study catchment, Moor House (triangle).

Figure 2. The mean proportion of macropore flow at the peat surface for control blocks and blocks subject to rainfall treatment, with standard error bars.

Figure 3. Scatterplots for paired peat blocks showing the proportion of flow through macropores with and without rainfall treatment, by species cover for measurements at all depths; a) proportion of flow through pores sized 0.05 to 2 mm in diameter, b) proportion of flow through pores greater than 2 mm in diameter; c) proportion of flow through pores greater than 0.05 mm in diameter.

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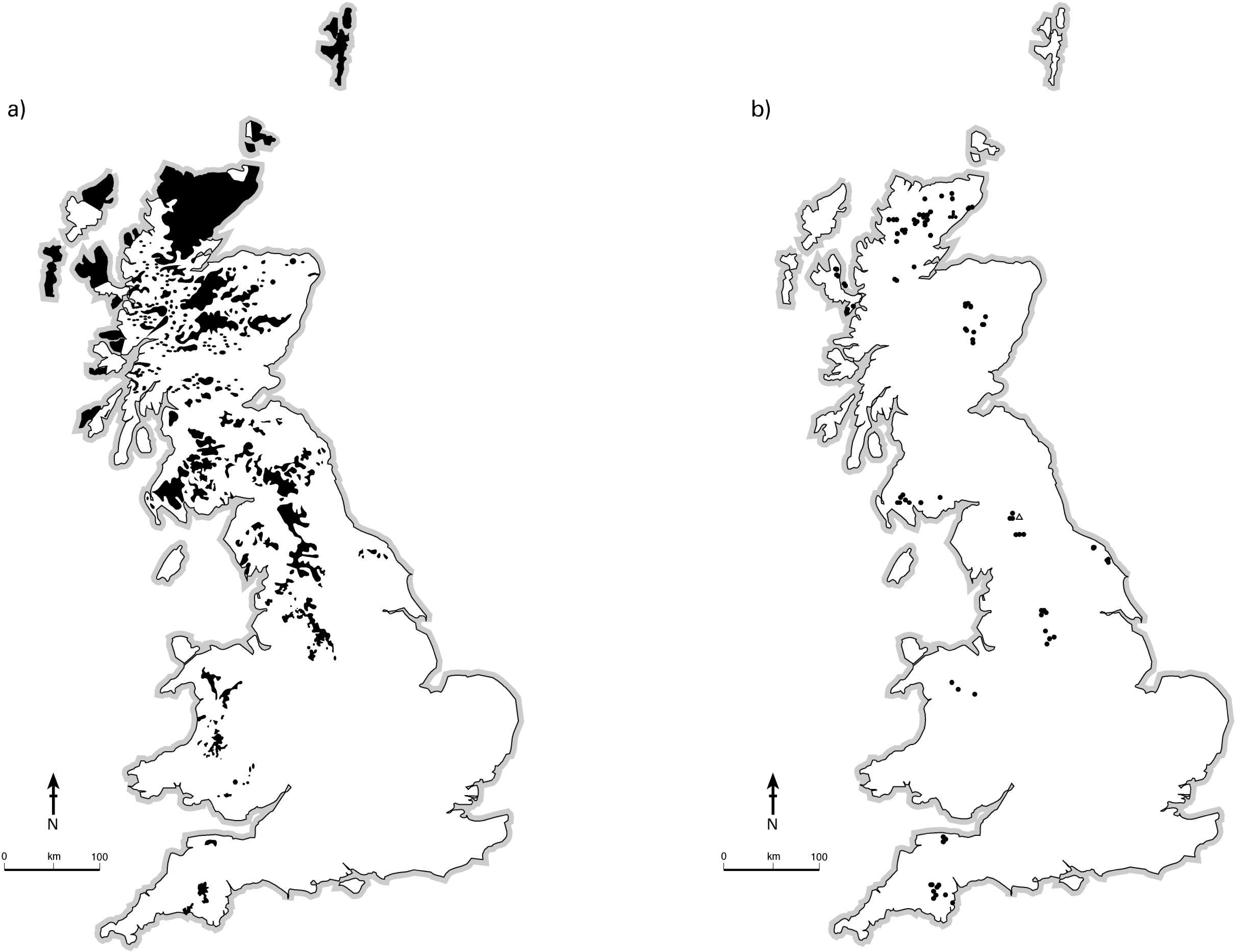

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