Published paper
Holden, J. (2006) *Sediment and particulate carbon removal by pipe erosion increase over time in blanket peatlands as a consequence of land drainage.* Journal of Geophysical Research (Earth Surface), 111 (F2). F02010.

SEDIMENT AND PARTICULATE CARBON REMOVAL BY PIPE EROSION INCREASE OVER TIME IN BLANKET PEATLANDS AS A CONSEQUENCE OF LAND DRAINAGE

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Abstract

Land drainage is common in peatlands. Artificially drained blanket peat catchments have been shown to have a significantly greater soil pipe density than intact catchments. This paper investigates the role of surface land drains in the enhancement of soil piping in blanket peats. The density of piping was found to significantly increase in a linear fashion with the age of the drainage. Thirty five years after drains were cut, slopes would be expected to have twice the density of soil piping than an undrained blanket peat catchment. The rate of pipe erosion increases exponentially over time so that particulate carbon loss from subsurface pipes is greatest where drains are oldest.

Introduction

Soil pipes have been reported on every continent, except Antarctica, and in a broad range of environments (Roberge and Plamondon 1987, Nieber and Warner 1991, Tsuboyama et al. 1994, Elsenbeer and Lack 1996, Gutierrez et al. 1997, Carey and Woo 2000, Uchida 2004). Pipes are common in peatlands. For example they have been reported in the peatlands of Scandanavia, New Zealand, Tasmania, Indonesia, Canada, Siberia, Ireland and the UK (Jones 1981, Mark et al. 1995, Norrstrom and Jacks 1996, Jones et al. 1997, Holden et al. 2004, Holden 2005). Soil pipes consist of connected natural conduits often many centimeters in diameter, which transport water, sediment and solute through soil systems. These pipes can often be several hundred meters in length and typically form branching subsurface networks which undulate throughout the peat profile (Jones 1981, Holden et al. 2002, Holden and Burt 2003b, Holden 2004). They have been found to transport over 10 % of stream flow in blanket peats (Holden and Burt 2002) and 49 % in peaty podzols (Jones and Crane 1984).

Peat pipes tend to form by removal of material, and not by compaction of the peat (Gilman and Newson 1980; Jones, 1981; Holden and Burt, 2002; Jones, 2004). Jones (2004) showed that for a catchment in Wales, the areas of piping yielded more sediment to the stream than the areas without piping. The production of sediment by pipes in peatlands may not only be important as a geomorphological process but also as a component of peatland carbon cycles. Peatlands are a huge pool of particulate organic carbon (Turetsky et al. 2002) storing between one third and one half of global soil carbon. Most research on particulate carbon loss from peatlands focuses on streambank or surface erosion (Tallis 1995, Warburton 2003, Evans and Warburton 2005) and there is very little research on subsurface particulate erosion (Holden and

Burt 2002, Jones 2004). Pipes appear to be components of peatlands around the world and yet there are no data on how important pipes might be for peatland sediment or carbon budgets. It is therefore not possible to predict how disturbance of peatlands through environmental change may affect pipe development and the role of pipes in peatland carbon production.

Soil pipe formation has been attributed to a number of factors including climate (periods of desiccation and periods of intense rainfall; Jones 1981), faunal activity (burrowing animals) decaying root channels, and can preferentially occur in soils that have particular combinations of soil chemical and pedological properties (see Jones 1981). For example, pipes are often found in soils where there are sharp contrasts in hydraulic conductivity between soil layers. Peats tend to have large vertical and lateral differences in hydrological properties (hydraulic conductivity, bulk density) over very short distances (Holden and Burt 2003a) and this can encourage preferential flow paths to develop. Faunal activity is not an important factor in pipe formation in upland peats as the acidic environment deters such activity. In the Maesnant catchment of mid-Wales, Jones (2004) reported that desiccation cracking was the main initiator of the ephemerally flowing pipe networks in peaty podzols. However, it is not known whether desiccation is an important factor in deep peat soils. Peat soils do shrink and crack when they are dried and this could open up new routes for bypassing flow. Many peats can become hydrophobic if they become too dry and do not regain their initial moisture holding capacity (Eggelsmann et al. 1993). It might therefore be expected that any environmental change that encourages desiccation of peat, may also encourage soil pipe development provided that enough water is still supplied to the peatland to flow through the preferential flow paths and enlarge them.

Land drainage has been a common practice in peatlands throughout the world (Bowler 1980, DeMars et al. 1996, Holden et al. 2004). It is still occurring in most of the 130 countries that have peat soils so that the amount of intact peat is decreasing each year. In the UK, for example, peat drainage was at its peak between the 1940s and 1970s but it still actively continues, albeit on a much smaller scale. Holden et al. (2004) provided a detailed review of the history and practice of peatland drainage and can be consulted for further detail. Some peat drainage is associated with afforestation practice, but this present paper focuses on non-afforestation drainage. Severe erosion of peatland drain channels themselves has been reported (Mayfield and Pearson 1972, Holden et al. 2004) but not the erosion of subsurface pipes that are connected to drain systems. There has only been one study that has examined the role of peatland drainage in subsurface pipe development. Holden (2005) found during a ground penetrating radar (GPR) survey of blanket peat catchments that i) piping existed in all surveyed catchments and ii) piping was significantly greater where surface cut land drains were present. On the 57 slopes with drainage the mean density of piping was 127.4 pipes per km of GPR transect (standard error = 6.2) compared to 56.6 pipes per km (standard error = 2.0) on the 263 undrained slopes. However, it is not known how quickly pipe networks develop on drained slopes. Given that pipe network expansion is also associated with the removal of particulate carbon from the peat mass it is important to understand the role of piping in peatland carbon loss. Therefore the aims of this paper are to determine i) the rate at which pipe networks develop in drained peats and ii) the contribution of piping to particulate carbon loss from drained peats.

Methods

Holden et al. (2002) and Holden (2004) reported on the successful utility of 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 was used to survey 57 blanket peat slopes across the UK with surface land drains and 263 slopes without drains (Figure 1). On each slope three plots were surveyed consisting of 6 x 20 m transverse GPR transects spaced at 10 m intervals downslope. Thus each plot was 50 m x 20 m and a total of 115.2 km of GPR survey took place using 100 and 200 MHz antennae depending on peat depth. Signals were emitted at 10 cm intervals along GPR transects. GPR works by transmitting short pulses of high frequency electromagnetic energy by antennae through the ground surface. These pulses are reflected from boundaries between layers or from internal irregularities which have differences in electrical properties. The reflection is detected on the surface. Moving the transmitter and receiver antennae across the test area builds up a complete cross section of the site. GPR transmits energy through the ground in wide beam and so the antennae are therefore not detecting reflections from directly below but also to the front, back and sides. The GPR should therefore have detected features that were between the 10 cm sampling interval. Pipes were identified on radargrams and the number of pipes crossed per km of survey transect was calculated. Pipes smaller than 6 cm in diameter could not be detected using the GPR.

A range of sources was used to determine the year in which land drainage took place on each slope, including landowner survey, air photos, published materials and parish records. It was possible in all but two cases to get data on the year of drainage. In the two remaining cases the year was available +/- 2 years. It should be noted that drain spacing could influence the relationships. However, there were not enough samples to be able to examine this factor satisfactorily. Nevertheless, there were no significant relationships between drain spacing and age of drainage and so this could not be considered to bias the results.

The density of pipes on each slope was estimated from the plot surveys by transforming pipes per km of GPR transect into an areal unit (km km^{-2}). This was done by multiplying the mean number of pipes crossed per km of GPR transect by the plot length. This is a reasonable assumption because there were six GPR transects per plot and each transect ran across the slope. Pipes tend to run downslope. Hence while not all pipes will be connected down the whole of the plot slope, on average the pipe length within the plot will be equivalent to this value. To estimate the volume of pipes on each slope, the mean length of piping per plot was multiplied by the mean cross sectional area of pipes within each slope. Unfortunately GPR cannot provide information on pipe diameters. It was possible to measure pipe diameters at stream banks or ditch sides on each slope where pipe outlets could be located. However, pipe diameters can change dramatically over just a few cm of the length of the pipe (Terajima et al. 2000). Nevertheless there were no other available data on pipe diameters across the slopes and it was assumed that stream or ditch bank diameters were representative of pipe diameters on the slope.

An estimate of cumulative carbon loss caused by pipe volume erosion was provided by multiplying the volume of pipes by the amount of carbon present within a unit volume of intact peat. While the carbon content usually increases slightly with depth, pipes are known to undulate throughout blanket peat soil profiles (Holden and Burt 2002, Holden 2004). Therefore the carbon content of the peat was sampled for the entire peat depth at each site. One 50 mm diameter core was taken from each GPR plot using a stainless steel corer. Bulk density and organic content were calculated through oven drying and loss on ignition and were determined for the core as a whole (without sub-sampling). The bulk carbon content of the peat at each site was then determined using a regression of the form $C = 0.562 L - 0.167$ where C is the carbon content (%) and L is the loss on ignition (%). This relationship was determined for UK upland peats by Bol et al. (1999). The carbon loss for each plot was then determined using the individual core carbon content for each GPR plot. The mean carbon loss value for each slope was then determined based on the three individual plot values. This site specific approach minimised errors as the alternative methods would have involved either i) using one value as a estimate of carbon content for peats (often simply expressed as 50 % of organic content; Worrall et al. 2003) or ii) using the mean carbon content of all cores and applying this mean value to the whole dataset. The peat depths at each site were determined by both the GPR and coring and so values for the proportion of peat mass lost to subsurface erosion could be established. Data were tested for normality and could be used in their raw form. Slopes were the unit of replication for statistical analysis. Unpaired t-tests were used to test for difference in pipe diameter, loss on ignition and bulk density between drained and undrained slopes.

Results

Figure 2 demonstrates a clear relationship between soil pipe density and age of drainage. The relationship is significant at $p < 0.001$ with an R^2 of 74.9 %. The equation is pipe density (pipes km^{-1}) = 41.6 + 2.10*age (years). The credibility of this equation can be given extra weighting given the closeness of the intercept (41.6 km^{-1}) to the value for pipe density in undrained peats determined by Holden (2005) of 56.6 km^{-1} (standard error = 2.0). Thirty five years after drains were cut, slopes would be expected to have approximately twice the density of soil piping than an intact undrained slope.

Mean pipe diameter on undrained slopes (11.6 cm; standard error 0.6 cm) was significantly lower than that on drained slopes (15.9 cm; standard error 0.8 cm) at $p = 0.003$. Figure 3 demonstrates that there is a linear increase in pipe diameter with age of drainage. While only 10.3 % of the variance in pipe diameter is explained by age of drainage, the relationship is significant at $p = 0.009$. Neither Figure 2 nor Figure 3 indicate any sort of threshold beyond which pipe network development does not further develop. It may be that such a threshold exists but that the age of the drainage investigated is not sufficient for that threshold to have been reached.

For undrained slopes the mean proportion of the peat mass volume occupied by pipes was 0.27 % (standard error = 0.03 %). This compares to 1.28 % (standard error = 0.35) on drained slopes. Given the time dependency demonstrated by Figures 2 and 3, the volume of peatland occupied by soil pipes on a drained slope is likely to increase over time. This means that as time progresses since drainage, more subsurface sediment is removed from blanket peats.

There were no significant differences in loss on ignition (mean = 91.7 %, standard error = 0.3 %, maximum = 99.0 % and minimum = 73.5 %), bulk density (mean = 0.118 g cm^{-3}, standard error = 0.002 g cm^{-3}, maximum = 0.260 g cm^{-3} and minimum = 0.020 g cm^{-3}), or estimated carbon content (mean = 51.3 %, standard error = 0.2 %, maximum = 55.5 % and minimum = 41.1 %) from the peat core samples between drained and undrained slopes. The carbon loss values were used independently for each drained slope to produce Figure 4, which demonstrates a significant positive log-linear relationship with the age of peatland drainage ($p < 0.001$, $R^2 = 41.7$ %) described by log C loss (log (kg C km^{-2})) = 5.02 (log (kg C km^{-2})) + 0.01*age (years). These data therefore indicate that the rate of particulate carbon loss from subsurface piping increases exponentially over time in drained catchments. Use of the carbon relationship developed above suggests that, on average, for slopes where drainage is 40 years old there would be an extra 5.8 x 10^3 kg C km^{-2} yr^{-1} exported from subsurface pipe erosion alone over that 40 year period, compared to that from an undrained slope. This value would be in addition to any surface erosion related to ditch channel incision or other surface processes.

Discussion

The growth rate of peat pipes following ditch installation has been investigated. The density of piping and the size of pipes both significantly increase over time, with pipe density increasing at a rate of 2.1 pipes km^{-1} yr^{-1} and mean pipe diameter at a rate of 0.09 cm yr^{-1}. The combined effect of this pipe network and pipe size expansion on sediment and carbon loss from the peat mass is shown in Figure 4. The relationship in Figure 4 is log-linear and so the rate of pipe erosion increases over time following open-cut drainage. Those slopes where drainage is oldest will have the fastest rate of subsurface peat erosion. Therefore if peatland restoration aims to reduce carbon loss, then resources should be targeted towards slopes where drainage is oldest as long as there is still a chance of some peatland recovery.

It is important to place the magnitude of sediment or carbon loss found above into perspective. Turunen et al. (2002) estimated that during the Holocene carbon sequestration in peatlands was between 12 to 23 x 10^3 kg C km^{-2} yr^{-1}. Hence pipe erosion exacerbated by drainage may be important. For example, the particulate carbon loss from pipes calculated for slopes where drainage is 40 years old was 5.8 x 10^3 kg C km^{-2} yr^{-1}. This compares with total particulate carbon loss from UK peatland rivers as determined from results in the literature shown in Table 1. Worrall et al (2003) examined particulate, dissolved and gaseous carbon components for a blanket peat catchment in northern England. The catchment was considered to be one of the healthier blanket peat catchments in the UK in terms of carbon sink potential. This intact catchment was estimated to export 3.7 x 10^4 kg C km^{-2} yr^{-1} riverine carbon (particulate and dissolved) but when gaseous exchanges were taken into account the catchment was a net carbon sink of 1.3 x 10^4 kg C km^{-2} yr^{-1}. Thus the effects of land drainage on piping would be enough to approximately halve the carbon sink of the catchment. The additional pipe erosion alone would amount to one sixth of the riverine carbon export and one quarter of particulate export. In many catchments this may be enough to transform the catchment from a sink to a source of carbon. It should be noted that the particulate losses of carbon from piping alone would be in addition to those losses from drain erosion or expected increases in dissolved and gaseous carbon loss resulting from hydrological and biogeochemical change associated with a reduction in saturation (Holden et al. 2004). These results assume that pipe erosion results in sediment and carbon losses from the system as a whole. However, it may be that sediment removed the pipe networks is deposited and stored on the peat surface, the stream bank or stream bed, at least in the short-term. Nevertheless, once peat is removed from the *in situ* peat mass, degradation of that eroded peat can be very rapid relative to the largely anaerobic peat mass, through biogeochemical weathering processes and through decomposition releases of solutional and gaseous carbon forms (Holden et al. 2004). However, the rate of recalcitrant humic molecules will depend on many factors including the environment in which they are deposited. Particulates deposited for any length of time on the anaerobic streambed may be much slower to decompose.

The results of this research have shown that drainage induced desiccation is followed by rapid pipe network expansion through erosion of material along flowpaths. Desiccation processes therefore appear to be important drivers of pipe formation in peat catchments. Desaturation causes peat to shrink and crack. The exposed faces of open drains also allow summer surface peat desiccation and winter freeze-thaw activity to alter peat structure and to potentially encourage macropore flow. Water flow through newly created preferential flowpaths is then likely to enlarge the pipes and allow pipe networks to expand. This expansion continues at an exponential rate and data presented showed no evidence that pipe network development reaches a threshold beyond which its growth slows (although data were only available for artificial drainage systems up to 80 years old). Hence some form of intervention would be required to slow the rate of subsurface pipe erosion in disturbed peats.

Pipeflow in peats impacts streamflow and water quality (Jones 1981, (Holden and Burt 2002). The results therefore suggest that streamflow response to peat drainage may continue to change over long time periods as pipe networks expand. Studies which have investigated streamflow response to drainage in the immediate aftermath of drainage may not, therefore, be representative of the more lagged long-term response. This may partly explain the wide range of reported effects of peat drainage on streamflow (Holden et al. 2004).

The British Isles has approximately 30 % of the world’s blanket peats (Tallis et al. 1998), which typically form in wet oceanic regions. The blanket peats of the British Isles are typical of blanket peats found elsewhere in north-west Europe and parts of eastern Canada. However, further work is required to establish whether similar pipe and drainage relationships exist in other types of peat. While this paper has focussed on artificial drainage as a desiccation mechanism, other environmental changes that result in increased desiccation may exacerbate pipe development and subsurface peat erosion. Such erosion may become a very important component of peatland carbon budgets under climate change in marginal peat forming areas or where human intervention results in enhanced desiccation. The important results presented in this paper should act as a trigger for further research.

Summary

Soil pipe density significantly and linearly increases with age of drainage in blanket peat. This is the first time such data has been reported and the research demonstrates that effects of drainage on peat properties and bypassing flow may alter over several decades. The cumulative volume of particulate carbon loss from the peat mass through subsurface piping increases exponentially over time on drained slopes. Many peatland drains are now being blocked as part of wetland restoration schemes and if carbon loss is considered an important management issue then resources could be targeted towards slopes where drainage is oldest as long as there is still a chance of some recovery. However, it should be remembered that piping is also a natural process (Jones 2004) and is present in intact peatlands. Thus piping should be considered when preserving and restoring peatlands, as well as when analysing impacts of management on peat carbon and sediment budgets, landform development, and runoff mechanisms.

Acknowledgements

This research was carried out while the author was in receipt of a UK Natural Environment Research Council Fellowship NER/I/S/2001/00712. The comments of three anonymous reviewers are acknowledged as they helped improve the quality of the manuscript.

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Table 1. Fluvial export of particulate carbon calculated for UK catchments

Reference	Fluvial export of particulate C, kg km^{-2} yr^{-1} x 10^3	Location	Other comments
Francis (1987)	34.0	Mid-Wales	Catchment with gully erosion
Labadz et al. (1991)	38.9	S. Pennines	Catchment with gully erosion
Hutchinson (1995)	31.3	S. Pennines	
Dawson et al. (1995)	0.12	N. Scotland	Partially peat-covered (64%)
Dawson et al. (2002)	2.7	Mid-Wales	
Dawson et al. (2002)	1.9	NE Scotland	
Worrall et al. (2003)	19.9	N. Pennines	

Figure captions

Figure 1. Location of the field sampling sites

Figure 2. Scatterplot of number of pipes crossed per length of GPR survey against age of drainage

Figure 3. Scatterplot of mean stream bank pipe diameter against age of drainage

Figure 4. Scatterplot of estimated cumulative particulate carbon loss from the peat caused by piping against the age of drainage