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Historical peat loss explains limited short-term response of drained blanket bogs to rewetting

Williamson Jennifer [a*], Rowe Edwin [a], Reed David [b], Ruffino Lucia [b], Jones Peter [b], Dolan Rachel [c], Buckingham Helen [c], Norris David [a], Astbury Shaun [a] & Evans Chris D. [a]

a: Centre for Ecology & Hydrology, Environment Centre Wales, Deiniol Road, Bangor, UK. LL57 2UW

b: Natural Resources Wales, Maes y Ffynnon, Penrhosgarnedd, Bangor, UK. LL57 2DW

c: National Trust, Dinas, Betws-y-Coed, UK. LL24 0HF

* corresponding author: jwl@ceh.ac.uk

Abstract

This study assessed the short-term impacts of ditch blocking on water table depth and vegetation community structure in a historically drained blanket bog. A chronosequence approach was used to compare vegetation near ditches blocked 5 years, 4 years and 1 year prior to the study with vegetation near unblocked ditches. Plots adjacent to and 3 m away from 70 ditches within an area of blanket bog were assessed for floristic composition, aeration depth using steel bars, and topography using LiDAR data. No changes in aeration depth or vegetation parameters were detected as a function of ditch-blocking, time since blocking, or distance from the ditch, with the exception of non-*Sphagnum* bryophytes which had lower cover in quadrats adjacent to ditches that had been blocked for 5 years. Analysis of LiDAR data and the observed proximity of the water table to the peat surface led us to conclude that the subdued ecosystem responses to ditch-blocking were the result of historical peat subsidence within a 4-5 m zone either side of each ditch, which had effectively lowered the peat surface to the new, ditch-influenced water table. We estimate that this process led to the loss of around 500,000 m^3 peat within the 38 km^2 study area following drainage, due to a combination of oxidation and compaction. Assuming that 50% of the volume loss was due to oxidation, this amounts to a carbon loss of 11,000 Mg C over this area, i.e. 3 Mg C ha^{-1}. The apparent 'self-rewetting' of blanket bogs in the decades following drainage has implications for their restoration as it suggests that there may not be large quantities of dry peat left to rewet, and that there is a risk of inundation (potentially leading to high methane emissions) along subsided ditch lines. Many peatland processes are likely to be maintained in drained blanket bog, including support of typical peatland vegetation, but infilling of lost peat and recovery of original C stocks are likely to take longer than is generally anticipated.

Keywords

Drainage; Ditch blocking; Peatland vegetation; Restoration; Peat subsidence; Water table

1 Introduction

Blanket bogs are a distinctive peatland type characterised by landscape coverage of peat soil that is anoxic, acidic, low in nutrients and dominated by peat-forming species of *Sphagnum* mosses and a limited range of ericoids and graminoids. They are found in high-latitude, oceanic climates with high levels of rainfall, including the British Isles, coastal Canada, Chile and Tasmania (Gallego-Sala and Prentice, 2013). During the 20th century, many UK blanket bogs were subjected to drainage with the aim of increasing their productivity for livestock grazing or plantation forestry. Deep drainage ditches were dug across large areas of the UK uplands (i.e. higher-elevation areas). However, improvements in productivity often proved to be marginal or non-existent (Stewart and Lance, 1983) and the ditches were hazardous for stock (Wilson et al., 2011). Peatland ditches are thought to have increased peak flow streamflow rates, with potential detrimental consequences for flood generation, but made little difference to total runoff volumes (Robinson, 1985) and in blanket peat may only have reduced water table height in sites at the lower limit of their rainfall range (Coulson et al., 1990). More recently, there has been an increase in appreciation of the wider benefits provided by peatlands, including protection of distinctive biodiversity, regulation of water flows, and regulating the exchange of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). There has therefore been considerable interest in restoring the peatlands by appropriate management interventions, most notably ditch blocking.

Studies of the impacts of ditch blocking on blanket peat in the UK uplands have tended to focus on the effects on water table depth and on carbon efflux. Several studies demonstrated that blocking ditches increased the water table in the vicinity (e.g. Armstrong et al., 2010; Cooper et al., 2014; Peacock et al., 2015), although a comparison with an intact peatland in Northern England showed that water tables had not recovered to background levels even six years after blocking ditches (Holden et al., 2011). Water table recovery in blanket bogs is, however, usually small in magnitude, for example 2 cm (Wilson et al., 2010) or 9 cm (Worrall et al., 2007), whereas studies on boreal mires drained for forestry have found that blocking drainage ditches increased the water table in the vicinity by approximately 80 cm (Haapalehto et al., 2014). There are a number of potential reasons for this difference including topography, higher hydraulic conductivity in boreal mires and the presence of trees causing increased evapotranspiration on land drained for forestry.

Despite the importance of peatlands for biodiversity and the specialist plants and lichens they support, the impact of ditch blocking on the floristic diversity of blanket bogs has been less well studied. This is likely to be at least partially because changes in floristic composition may not be evident for a number of years following the initial ditch blocking activity. A study in northern Scotland showed that cover of species indicative of bog recovery increased where ditches had been blocked and was highest when the ditches had been blocked for the longest time, i.e. 11 years (Bellamy et al., 2012). However, a study in Exmoor found that the presence of drainage ditches had no effect on vegetation structure, as measured in transects away from the ditch (Gatis et al., 2016). A recent study in north Wales also showed that blocking drainage ditches had no consistent impact on vegetation in the 3 years following blocking (Green et al., 2015). The majority of work published on the effects of ditch blocking on peatland vegetation has been carried out in Scandinavia, where it has been found that ditch blocking increased the cover of specialist bog plants such as *Eriophorum vaginatum* and *E. angustifolium* (Komulainen et al., 1999) and rich-fen species including *Sphagnum* and wetland bryophytes (Hedberg et al., 2012). A study of rewetted forest swamp in Finland found that the water table recovered to the level seen in an intact site within four years of ditch blocking, but plant communities did not recover to the same extent, with vegetation composition being half way between sites with open ditches and intact sites (Maanavilja et al., 2014).

In summary, blanket bogs appear to be less responsive to drainage or re-wetting than other peatland types. Previously, this observation has been linked to the extremely low hydraulic conductivity of blanket peat, which severely restricts subsurface flow and thus the extent to which ditching is effective in lowering water tables (e.g. Hoag and Price, 1995; Holden and Burt, 2003), particularly in comparison to other peat types (Evans et al., 2014). In this study, however, we investigate another possible contributory factor for the apparent lack of impact of ditch blocking on peatland function not previously measured on blanket peat, namely subsidence, a process first noted by Holden et al. (2016) as being a potential reason for small changes in water table following ditch blocking on sloping blanket peatlands. One of the most consistent effects of peat drainage is accelerated decomposition of peat on exposure to oxygen, which leads to a loss of organic matter within the aerobic zone. Together with compaction of the peat, as the peat matrix is no longer supported by water within pores, this can lead to significant lowering of the peat surface over extended periods (Lindsay, 2010). The role of subsidence is well established in lowland settings, where historical drainage of raised bogs and fens for agriculture have led to subsidence rates in the region of 1-2 cm yr^{-1}, resulting in a cumulative elevation changes of several metres (e.g. Hutchinson, 1980). Subsidence has also been established in the Florida peat swamps following drainage, although at a slightly lower rate of 0.4-1.5 cm yr^{-1} (Aich et al., 2014; Hohner and Dreschel, 2015). In lowland raised bogs, the effects of ditching can extend over large areas, with lowering of the peat surface detected up to 100 m either side the ditch in some cases (Lindsay, 2010). On blanket bog, the undulating topography makes subsidence effects harder to detect, and higher bulk density and resistance to drainage may be expected to limit its extent (Lindsay, 2010). Some of the clearest evidence for subsidence on blanket bogs derives from a site in Scotland, where rates of around 1-2 cm yr^{-1} were recorded during the first 30 years following drainage for plantation forestry (Shotbolt et al., 1998). In the absence of the drying and compression effects of trees, subsidence of blanket bogs drained to increase grazing quality are likely to be smaller, but may (over an extended period) nevertheless be sufficient to influence surface topography in the vicinity of ditches, and could be sufficient to lower the peat surface to the new (post-drainage) level of the water table.

To assess the effects of ditch blocking on blanket bog hydrology and vegetation, a structured survey of a peatland area in Wales was carried out in the late summer of 2015. A chronosequence (i.e. space-for-time) approach was used to assess vegetation near ditches blocked at different times, at two distances from the line of the ditch. Steel bars were installed and later retrieved to assess aeration depth (*cf.* Bridgham et al., 1991; Carnell and Anderson, 1986; Owens et al., 2008). We tested the following hypotheses: (H1) blocking drainage ditches increases the height of the water table; (H2) blocking drainage ditches results in increases in cover and prevalence of specialist bog species; and (H3) these increases are greater close to the ditches. LiDAR surveying of the site was used to map the extent of the morphological changes seen in the landscape following ditching and to put the results in context of the wider area.

2 Methods

2.1 Ditch Survey

The survey was located on the Migneint plateau in North Wales (52° 58’ N 3° 48’ W), an extensive area of peatland at 350–500 m altitude over impermeable silicic siltstones and mudstones (Lynas, 1973) receiving *ca.* 2300 mm precipitation yr^{-1}. Areas of relatively intact peat have blanket bog vegetation (*cf*. M19 *Calluna vulgaris* – *Eriophorum vaginatum* blanket mire) (nomenclature follows Rodwell, 1991), with gradations to wet heath assemblages (*cf*. M16 *Erica tetralix* – *Sphagnum compactum* wet heath) where organic horizons are shallower, and to flush assemblages (*cf*. M6 *Carex echinata* – *Sphagnum auriculatum / recurvum* mire) where there are minerotrophic influences. The plateau was extensively drained during the 1930s and again in the 1970s, resulting in the installation of ditches across nearly all peatland areas. Early ditches were mainly installed perpendicular to the contours of the hillslope by hand. Later ditches were installed mechanically, and predominately diagonally across the hillslope. Based on a recently produced map of Welsh peat extent (Evans et al., 2015), a total area of 3842 ha of peat falls within the Ysbyty Ifan estate, owned by the National Trust, which has undertaken a programme of blocking drainage ditches between 2011 and 2015. Ditches in some areas have not been blocked. The dates of ditch blocking were not random across the site (Figure 1), but as they were largely selected on the basis of land tenancy rather than physical site characteristics, blocking dates were not strongly associated with other potential sources of variation.

The locations of drainage ditches were mapped by Evans et al (2015) using digital analysis of aerial photography. Locations and dates of blocking were also mapped independently during the ditch blocking process. These maps showed a good level of agreement, so ditches that had not been blocked were selected from the Evans et al. (2015) map. Ditches were blocked in winter or spring, and those blocked in the early winter (December or November) were assigned to the subsequent year. A set of 25 ditches was chosen at random from each ditch age-class and from the open ditches. Some of the sites thus selected were subsequently found to have <50 cm depth of peat and were excluded. The design remained reasonably balanced – of the ditches surveyed, 20 ditches were blocked in 2011, 18 in 2012, 15 in 2015 and 17 were open ditches.

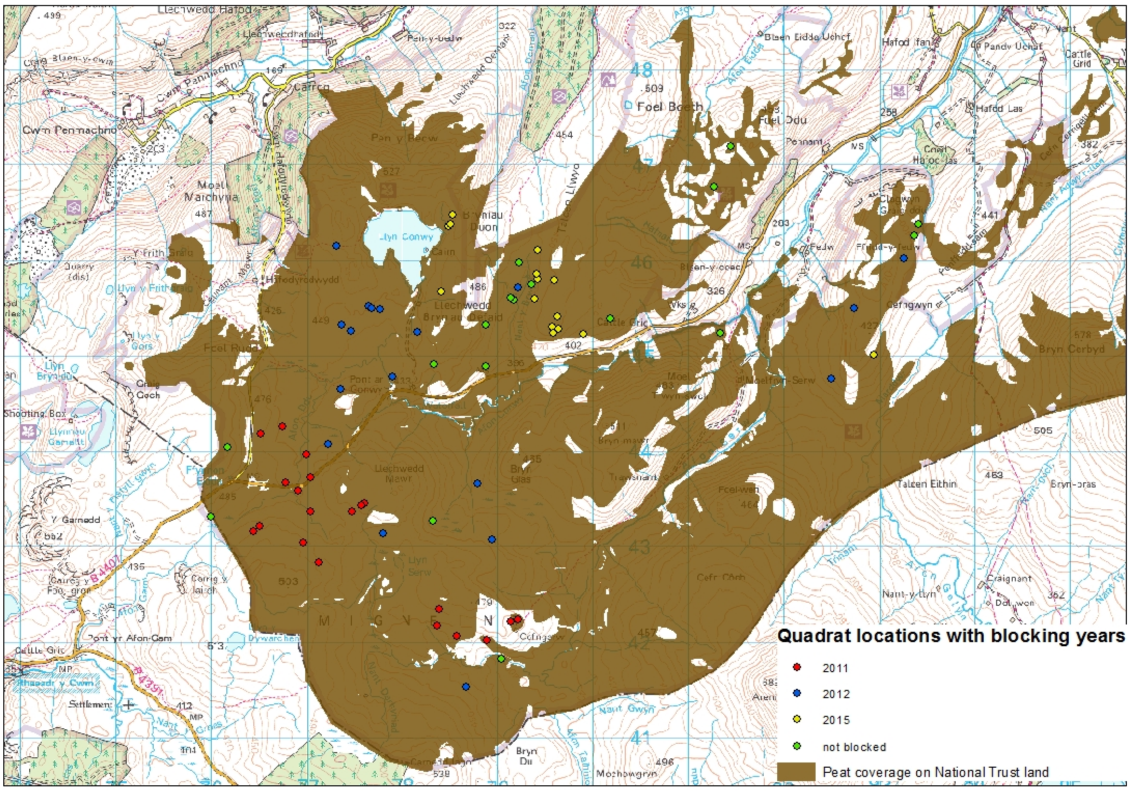


Figure 1. Locations of ditches blocked in different years (2011, 2012, 2015) or open (not blocked).

2.2 Plot design and recording

Ditch spacing was not regular across the whole site and the distance between ditches ranged from 10 m to approximately 30 m. The method used to block ditches at the site was to remove peat from borrow pits adjacent to the ditch to form a dam, taking care to ensure a complete seal using dense subsurface peat in accordance with best practice recommendations (Armstrong et al., 2009), and compacting the dam after formation. The dam nearest the midpoint of each length of ditch was chosen for survey, and marked out with two 4 × 1 m plots, one 0.5–1.5 m from the centre line of the ditch (‘Near’) and the other 2.5–3.5 m from the centre line of the ditch (‘Far’), both starting 1 m upstream of the dam (Figure 2). Both plots were situated on the same side of the ditch, on the downslope side where a gradient was discernible because previous studies have recorded greater water table draw-down downslope of the ditches (Cooper et al., 2014; Coulson et al., 1990). Where this location was clearly disturbed and appeared to have been the source of material for the dam, the plot was relocated to above an adjacent dam.

Vegetation composition was assessed during September and October 2015 by recording all plant and lichen species within a quadrat, together with visual estimates of cover using the Domin scale, following the methodology of Bosanquet et al. (2013). Nomenclature for vascular plants was based on Stace (2010) and for bryophytes on Atherton et al. (2010). The cover of some species groups was also recorded in the field: dwarf-shrubs, graminoids (*i.e.* plants in the Cyperaceae, Poaceae and Juncaceae families), forbs, *Sphagnum* mosses and non-*Sphagnum* bryophytes. Measurements were also taken of peat depth (maximum depth to which a probe could be pushed) between the two quadrats to minimise disturbance to the vegetation, and ditch depth (distance from the local surface level to the top of the peat or water in the ditch). Other potential factors that may differ between the plots such as slope of the site, the site aspect and site altitude were recorded in the field using a handheld GPS and a compass and checked using a 50m digital elevation model in ArcGIS.

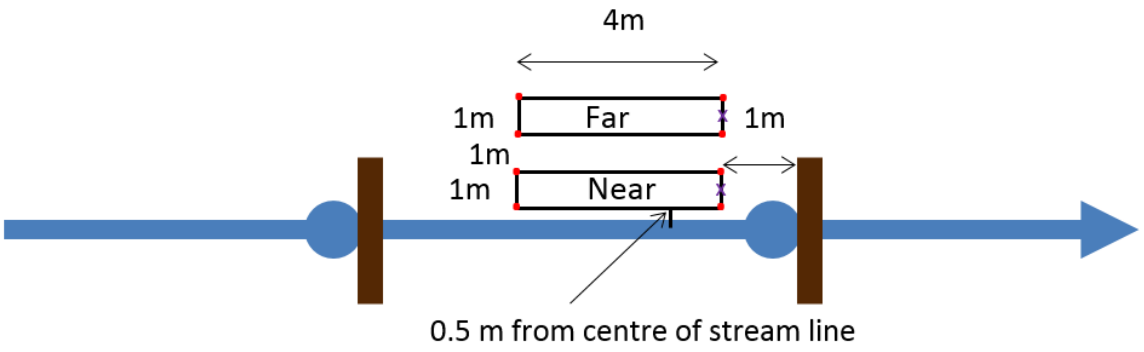


Figure 2. Layout of plots in relation to dams (brown bar) and the line of the ditch. Red dots show the locations of the orange plot marker canes. Purple crosses show the locations of the steel bars.

2.3 Mapping of surface topography

The topography of the Migneint had previously been surveyed using LiDAR (Light Detection And Ranging) data at 50 cm horizontal resolution and approximately 5 cm vertical resolution. This resolution was sufficient to pick out the changes in topography caused by the presence of drainage ditches. This survey was carried out in 2009 prior to any ditch blocking work on the Migneint. For each ditch used in the vegetation survey, transects of ground surface elevation were taken from the LiDAR mapping at 5 m intervals along the extent of the mapped ditch using ArcGIS (ESRI, 2015). Each transect was perpendicular to the ditch line and extended 100 m each side of the ditch. These transects were used to generate an average ditch transect, to eliminate potential variation caused by micro-topographic variation such as hummocks and hollows. Local regression smoothing was applied using the “loess” R package (Ripley, 2016) and used to plot the large scale topography across the 200 m transect; while small-scale variation not explained by the local regression was extracted as the difference between the modelled and measured peat surface. The high points of the small scale variation were taken as being the inter-ditch areas; these were extracted from the plot and a further local regression model was used to estimate the pre-drainage topography. The output of this model was added to the original modelled topography as an estimate of pre-ditch peat surface. The lateral extent of the impact of the drains on peatland topography, the cross-sectional area of peat lost through ditching and the volume of peat lost per ditch were calculated from the mapped extent of the ditches.

2.4 Estimation of aeration depth

The depth to which the peat was aerated was estimated by inserting steel rods (Figure 3), leaving these for six months, and then retrieving the rod to estimate the depth of rusting, as recommended in several previous studies (Bridgham et al., 1991; Carnell and Anderson, 1986; Owens et al., 2008). Steel rods (rebar 500 mm length, 10 mm diameter) were inserted into the soil in September 2015 and retrieved in late February 2016. One rod was inserted into each plot, at a point 1 m (near) or 3 m (far) from the centre of the streamline. The distance was measured from the soil surface to the bottom of the oxidised zone, which is characterised by mottling with bright orange-brown (7.5YR 5/8) and dark brown (10YR 2/2) iron oxides and oxyhydroxides. Below this zone, the steel rod retained its original bright grey (5Y 6/1) and dark grey (N4/0) colours, indicating that predominantly anoxic conditions were maintained (Owens et al., 2008). Any small flecks of orange further down the rod were ignored (Bridgham et al., 1991).

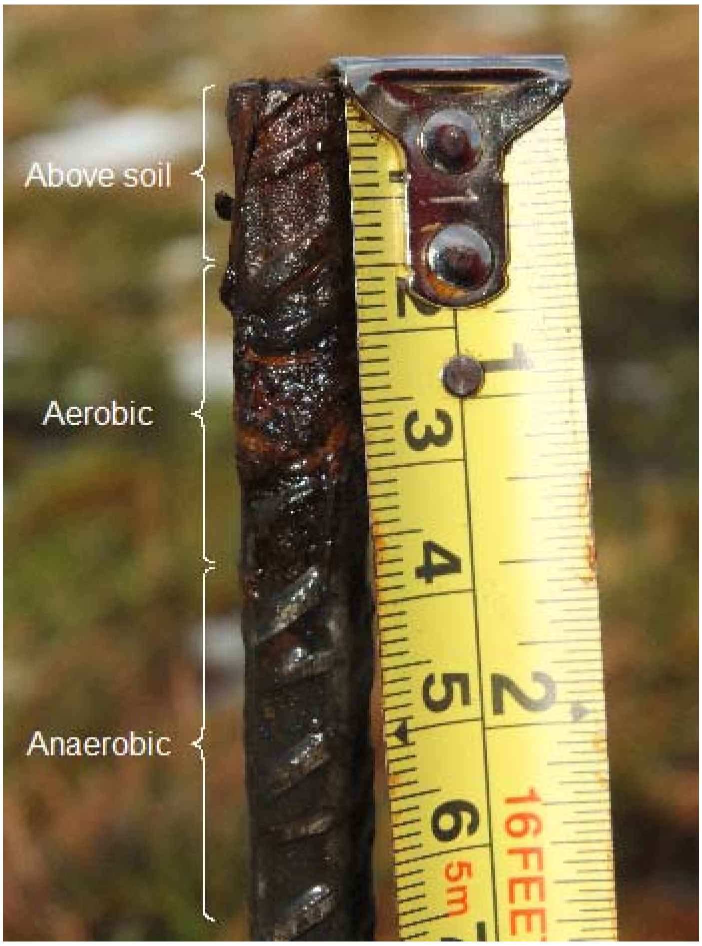


Figure 3. Steel rod extracted from peat with a high water table, showing uniform oxidation in the part that remained above the soil, mottled oxidation in the aerobic zone of the peat, and little oxidation in the lower zone.

2.5 Analysis of floristic data

Percentage cover values were estimated from cover classes as recorded in the field for species and functional groups, assuming that visual estimates were a reasonably accurate reflection of the true cover (Sykes et al., 1983) and that Domin scores of 1-10 corresponded to 1%, 2%, 3%, 7%, 18%, 29.5%, 42% , 63%, 83% and 95% cover, respectively. Percentage cover data were arcsine transformed prior to analysis and back transformed for presentation. The functional groups assessed were: dwarf shrubs; graminoids; *Sphagnum* species; and non-*Sphagnum* bryophytes. Forbs do not form a major component of the vegetation cover in blanket bogs, and forb cover was < 3% in all quadrats, so forb abundance was not analysed.

Summary statistics were derived from the floristic observations. Mean environmental trait scores were calculated on the Moisture ('F') axis (Ellenberg et al., 1992) as recalculated for British species by Hill et al. (2000). Cover-weighting was not applied since it can introduce extra error (Kafer and Witte, 2004). We also calculated the total number of species, and the total number of 'positive indicator' species for bog habitats (i.e. species that are characteristic for this habitat) as defined in the UK Common Standards Monitoring guidance (JNCC, 2004, 2006) (Table 1).

Table 1. Indicator species: characteristic species for bog (Common Standards Monitoring "positive indicator species"). Only species found during the survey are listed.

positive indicator species for bogs

Calluna vulgaris
Cladonia arbuscular
Cladonia furcate
Cladonia portentosa
Cladonia uncialis
Drosera rotundifolia
Empetrum nigrum nigrum
Erica tetralix
Eriophorum angustifolium
Eriophorum vaginatum
Narthecium ossifragum
Sphagnum capillifolium
Sphagnum cuspidatum
Sphagnum denticulatum
Sphagnum fallax
Sphagnum fimbriatum
Sphagnum magellanicum
Sphagnum palustre
Sphagnum papillosum
Sphagnum subnitens
Sphagnum tenellum
Tricophorum cespitosum
Vaccinium myrtillus
Vaccinium ocycoccus
Vaccinium vitis-idaea

2.6 Statistical analysis

All variables were were checked for conformance with a normal distribution and constancy of variance before analysis. Percentage cover data were arc-sine transformed prior to analysis and back-transformed for presentation. Data were analysed using a mixed model, with plot as a random effect and blocking year and distance as fixed effects, using the nlme procedure (Pinheiro et al., 2016) within R (R Core Team, 2015).

3 Results

3.1 Biophysical characteristics of study plots

The sites blocked at different dates were comparable in terms of peat depth and aspect (Table 2). There was some confounding with altitude: the ditches blocked in different years had similar mean altitudes (between 435–460 m), but the mean altitude of the open ditches was a little lower at 425 m. All received similarly large precipitation rates, 2162–2664 mm yr^{-1} (UKCIP mean annual precipitation 1961-1990) and there was no difference in mean annual precipitation between the sites.

Ditch depth was found to be shallower in the ditches blocked in 2012 ($p < 0.05$) and 2015 ($p < 0.01$) compared to the open ditches, although there was no difference in ditch depth between ditches blocked in 2011 and the open ditches (Table 2).

Table 2: Characteristics of plots adjacent to ditches blocked in 2011, 2012 or 2015, or not blocked. Results are shown as the mean of all sites ± standard errors.

Blocking Year	Peat Depth (m)	Ditch Depth (m)	Rainfall (m yr^{-1})	Altitude (m)
2011	1.36 ± 0.13	0.35 ± 0.04	2.285 ± 0.01	460 ± 4
2012	1.68 ± 0.18	0.26 ± 0.03	2.363 ± 0.02	435 ± 6
2015	1.36 ± 0.14	0.22 ± 0.04	2.327 ± 0.01	444 ± 5
open	1.57 ± 0.16	0.42 ± 0.06	2.308 ± 0.02	425 ± 8

3.2 Effects of ditches on aeration depth

There was no indication that the aeration depth differed between the blocked and open ditches. Contrary to expectations, the aeration depth was deeper (relative to the ground surface) with greater distance from the ditch (*p* < 0.01) (Figure 4).

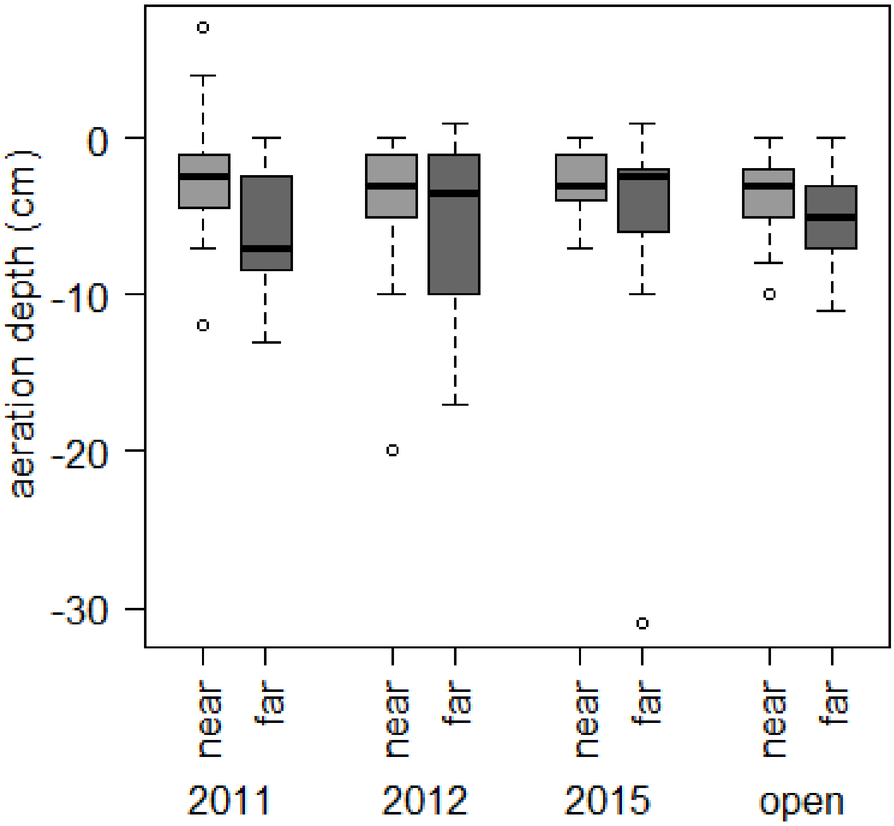


Figure 4: Aeration depth, as measured by the extent of rusting on steel bars inserted to a depth of 50 cm into the peat. Depths are expressed relative to the ground surface.

3.3 Effects of ditches on vegetation

Average Ellenberg moisture scores for each quadrat are shown in Figure 5. Quadrats adjacent to ditches blocked in 2015 had lower average Ellenberg moisture scores than the quadrats blocked in 2011 ($p < 0.05$) but there were no further differences between the different years or between the quadrats 1 m and 3 m away from the drainage ditches in any year.

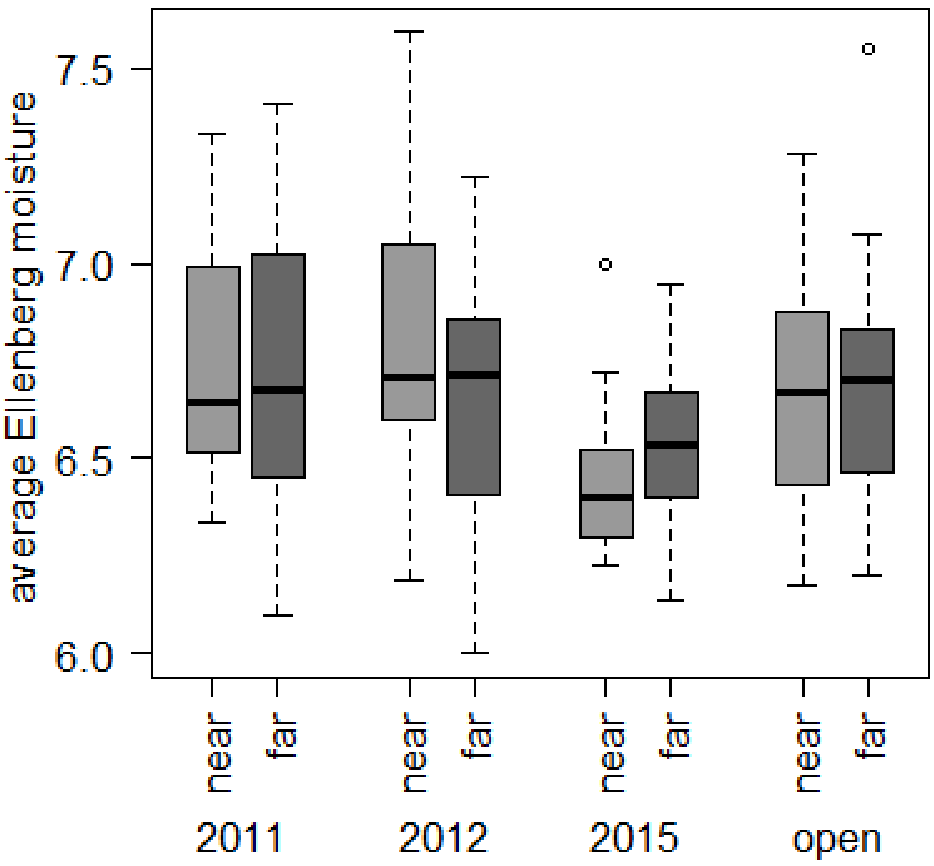


Figure 5. Effect of blocking year and distance from ditch line on Ellenberg Moisture score.

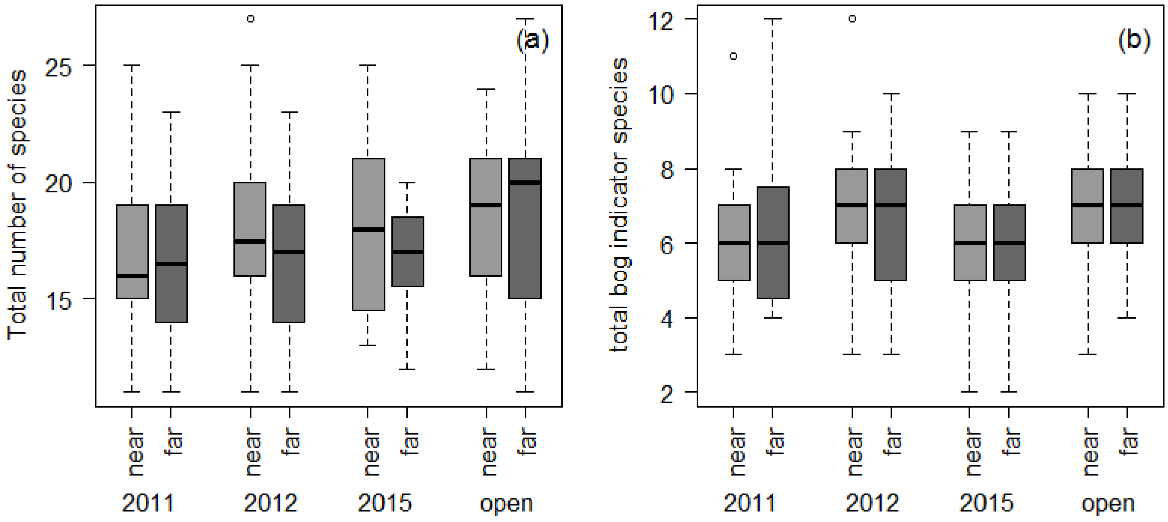


Figure 6. Effect of blocking year and distance from ditch on: a) Species richness; b) number of positive indicator species for bog.

There were no effects of time since blocking or distance from ditch on species richness or on number of bog positive indicator species ($p > 0.05$ in all cases) (Figure 6).

The percentage cover of dwarf shrub species was higher in the plots further from the drainage ditches ($p < 0.05$), although for plots by ditches blocked during 2015 there was no difference in the median cover of shrubs between the near and far plots. There were no differences in the total cover of graminoids and *Sphagnum* mosses attributable to the time since ditch blocking or the distance from the drainage ditches. Percentage cover of non-*Sphagnum* bryophytes was lower ($p < 0.05$) in quadrats adjacent to ditches blocked in 2011 compared to the non-blocked ditches and the ditches blocked in 2015 (Figure 7).

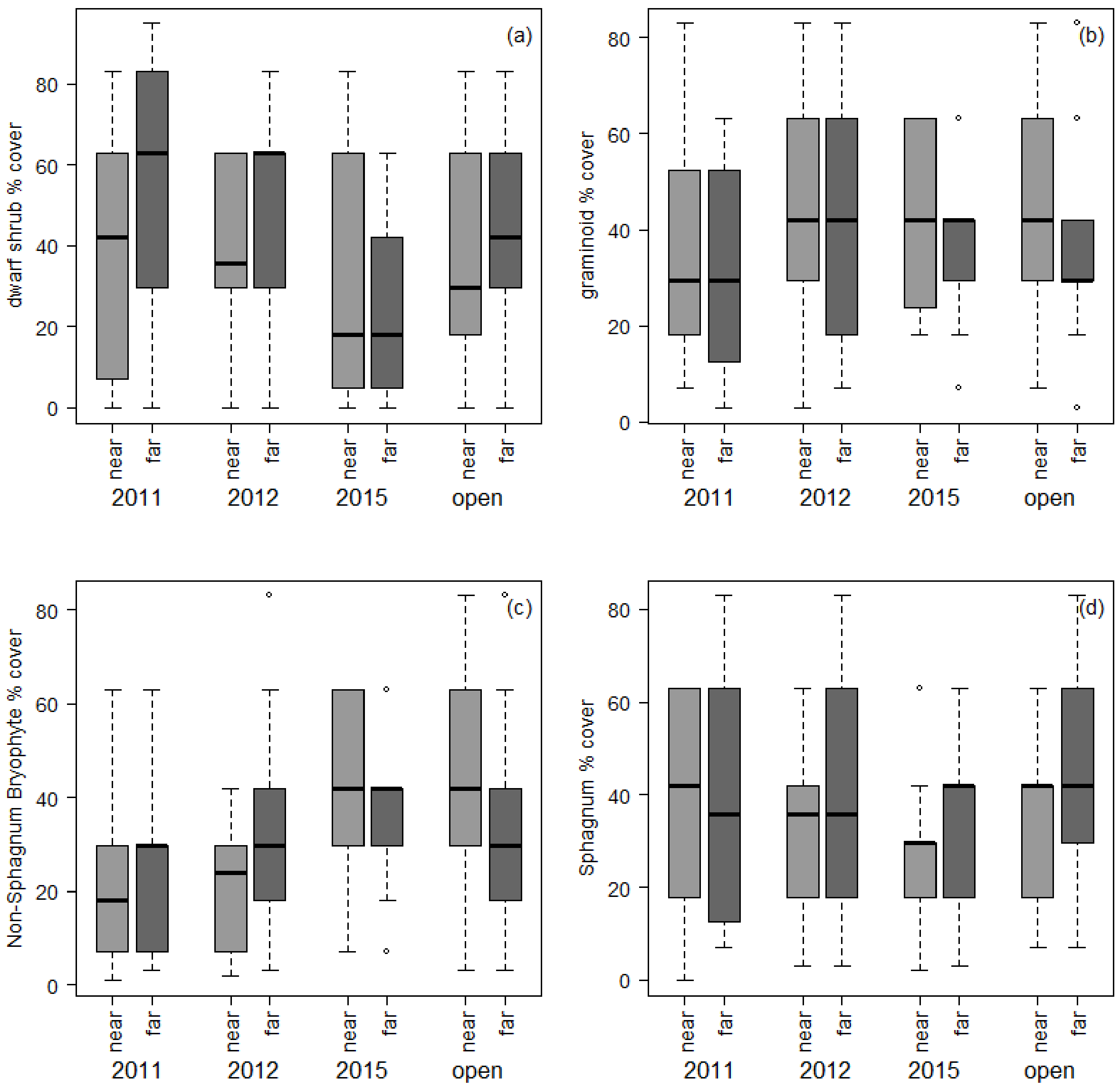
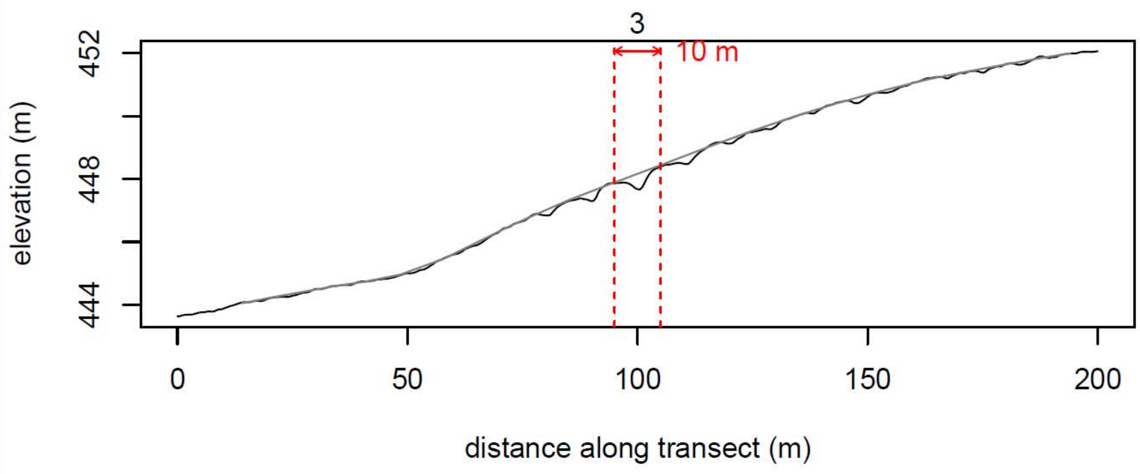
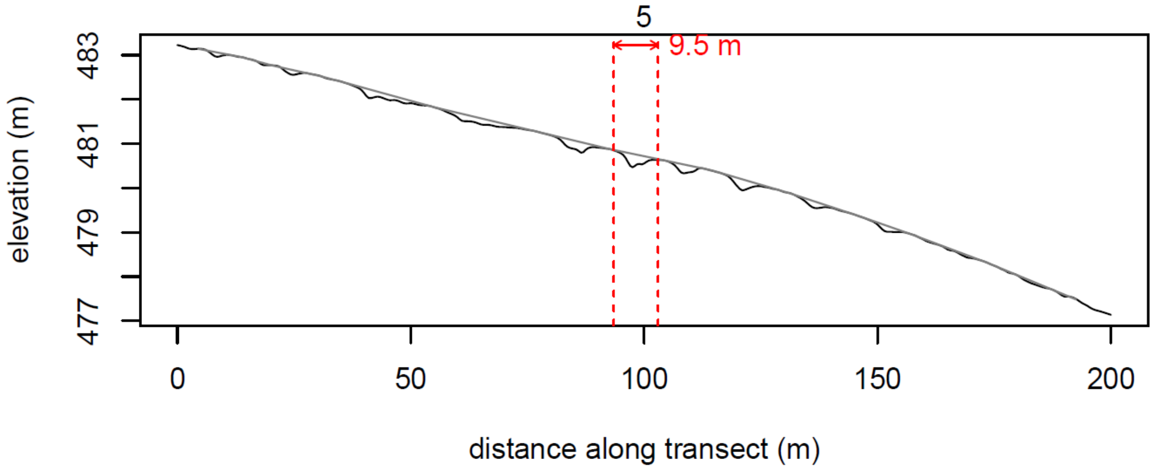


Figure 7. Percentage cover of a) dwarf shrubs; b) graminoids; c) non-*Sphagnum* bryophytes; d) *Sphagnum*.

3.4 Effects of drainage on subsidence in the vicinity of the drainage ditches

Measurements of the changes in peat height perpendicular to the drainage ditches suggests that the extent of the impact of drainage extends well beyond the original ditch, with clear evidence of subsidence extending approximately 4-5 m either side of each ditch on average, particularly for ditches on sloping ground (Figure 8). The average cross-sectional area and total estimated volume of peat lost through a combination of ditch excavation, erosion, oxidation and compaction are shown in Table 3. Ditches running perpendicular to the contour line appeared to have greater affected cross-sectional area. If these estimates of peat loss are scaled up to the full length of mapped ditches on National Trust land on the Migneint, and the proportion of ditches running across and down the slope is assumed to be similar to our survey subset, then the total volume of peat that has been lost from the Migneint is in the region of 500,000 m^3 (Table 4). Assuming a pre-drainage bulk density of 0.091 g cm^{-3} (Lark et al., 2014), a 50% carbon content, and that subsidence resulted equally from oxidation and compaction, based on estimates generated from temperate lowland peat (Erkens et al., 2016), the total carbon loss from the area due to 20th century drainage can be estimated at 11,375 Mg C, *i.e.* 3.0 Mg C ha^{-1}.





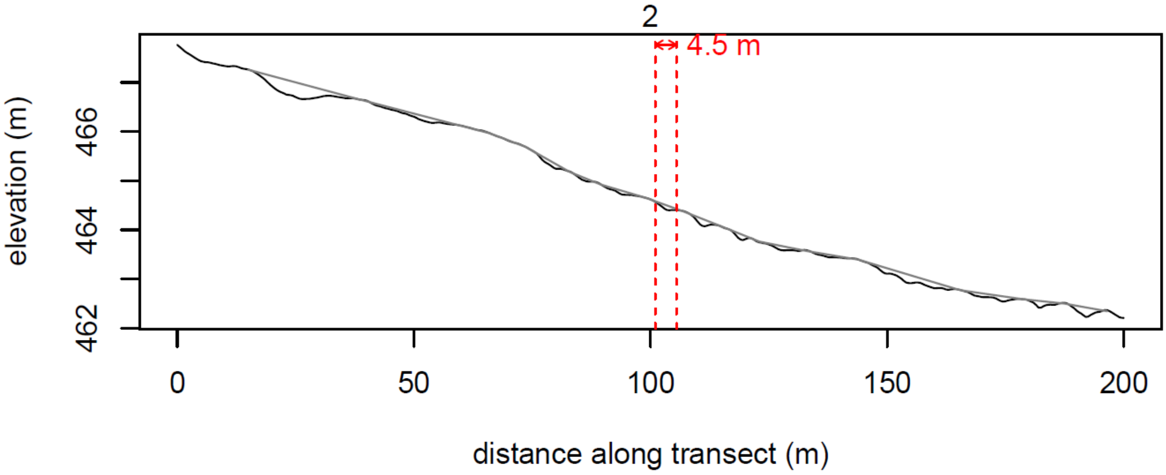


Figure 8: Mapped peat surface (in black) and modelled original peat surface (in grey) showing the extent of peat loss from the sides of three example drainage ditches. The dashed red lines show the mean lateral extent of peat loss from both sides of the ditches. These are 3 representative examples of the change in peat surface perpendicular to the drainage ditches.

Table 3: Properties of the ground surface affected by the presence of ditches.

Ditch orientation	Proportion of total ditches	Mean cross-sectional area (m^2)	Mean lateral distance ground surface affected by ditch (min – max) (m)	Total lost volume through compaction and erosion (m^3)
Across slope	0.34	0.92	8.7 (1.0 – 21)	2,205
Down slope	0.66	1.23	9.2 (0.5 – 24.5)	3,263

Table 4: Estimated total peat loss from the Migneint, assuming a similar proportion of ditches running across and down the slope to that observed in the study.

Ditch orientation	Length of ditches (m)	Total lost volume through compaction and erosion (m^3)
Across slope	148,000	182,000
Down slope	282,000	353,000

4 Discussion

The hypotheses we formulated were based on the assumption that drainage had drawn down the water table and changed the vegetation adjacent to ditches. Surprisingly, the results show that these assumptions were not justified. There was no difference in aeration depth between plots near to and further from open ditches (Figure. 4). There was also little discernible difference in vegetation composition in plots near to and further from open ditches (Figure. 5). It is therefore unsurprising that aeration depth and vegetation structure were not affected by drainage ditch blocking, although this is in contrast to other studies (Armstrong et al., 2010; Cooper et al., 2014; Peacock et al., 2015) that found water table recovery (albeit limited) following ditch blocking. The lack of vegetation change following ditch blocking on the Migneint reflects the conclusions of Green et al. (2015) that there was little change in vegetation composition in the three years following ditch blocking. Our results are also comparable with the findings of Coulson et al. (1990) who found that upland blanket bogs with high rainfall showed very little response in vegetation structure or water table following ditching, with the water table downslope of the ditches being lowered by only approximately 3 cm. Holden et al. (2016) also showed that water table depths in one area of the Migneint were shallow and spatially variable prior to ditch blocking and, although blocking the drainage ditches did result in a shallower water table, this was not seen in all locations.

The lack of change in aeration depth and vegetation cover following ditch blocking on the Migneint led us to rethink our conceptual model of how drainage ditches affect the blanket peat landscape (Figure 9). We now think that the initial impact of the drainage ditches was to lower the water table in the vicinity of the ditches (Figure 9a) and that the newly aerated peat would have been subjected to a mix of oxidation and compaction. Over time the peat would have effectively “self-rewetted” and returned to a new stable state with the peat surface again close to the water table (Figure 9b). This process has been seen in temperate lowland peat sites (e.g. Hutchinson, 1980; Lindsay, 2010; Schothorst, 1977) and tropical peat sites (e.g. Hooijer et al., 2012; Kool et al., 2006; Wosten et al., 1997), with the impacts of oxidation and compaction following drainage being relatively well understood in these systems. This process was briefly discussed as a potential mechanism for the limited effect of ditch blocking on water table depths in blanket peat soils in Holden et al. (2016) but to our knowledge this is the first measurement of this effect in blanket peat systems. This conceptual model of how blanket peats have responded to changes in water table depth following drainage explains why our study, and several similar studies, have shown either no change or small changes in water table depth following ditch blocking on blanket peat; the water table is still near to the peat surface and blocking the ditch has relatively little effect as there is little dry peat to rewet.

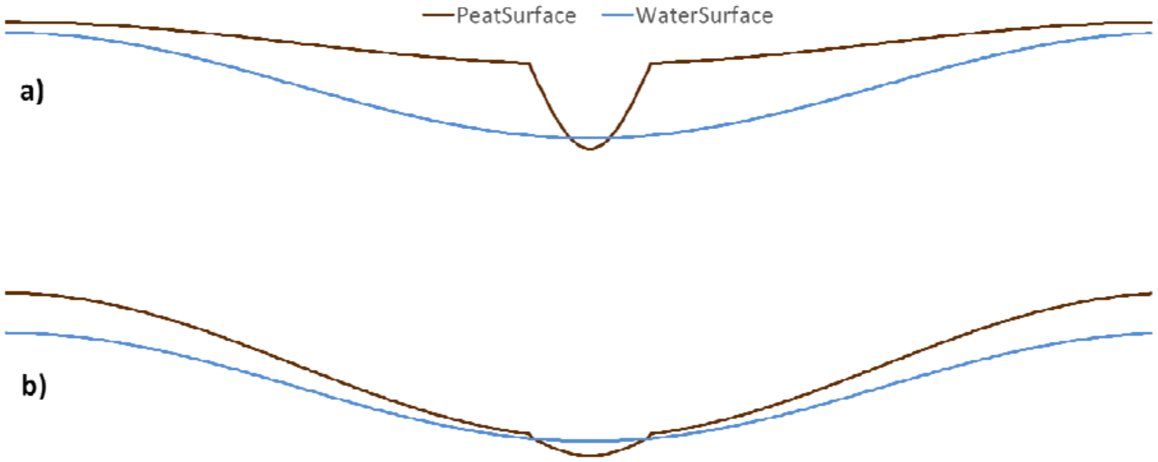


Figure 9: Effects of ditching on peat and water-table profiles in cross-section: a) initial view, showing lowering of water-table due to the ditch; b) final view, also showing the lowering of the peat profile.

The LiDAR survey of the Migneint allowed us to examine the current topography of the site at very high resolution, meaning that small changes in elevation could be detected over a large scale. These changes in elevation adjacent to the drainage ditches suggest that, rather than the drainage ditches being ineffective at lowering the water table when they were first installed, there was a relatively rapid change in the peat surface (certainly within the 40 years following drainage ditch installation, and probably early within this period) as the water table dropped adjacent to the ditches, on a smaller scale but due to a similar process to the peat surface lowering seen at drained lowland peat sites (Erkens et al., 2016; Lindsay, 2010) and in drained tropical peats (e.g. Hooijer et al., 2012; Kool et al., 2006; Wosten et al., 1997). This led to the compaction and decomposition of the newly drained peat such that the peat surface returned to the lower water table. Our calculations show that the effects of the ditches on the peat surface extend laterally, on average 4.5 m from the centre line of the ditch and that an estimated 500,000 m^3 of peat have been "lost" from the landscape, with a resulting carbon emission to the atmosphere of 3 Mg C ha^{-1}. Measurements from tropical peats suggest that the ratio of oxidation to compaction ranges from 60:40 (Wosten et al., 1997) to 92:18 (Hooijer et al., 2012), which would suggest that our estimate of carbon loss is likely to be conservative if such data are comparable between tropical and blanket peat. Bulk density measurements from peat cores on the Migneint (R. Collier pers. com.) suggest that decomposition may account for a higher proportion of volume loss in temperate blanket peats, but further study of changes in bulk density adjacent to the drainage ditches would be required to increase the accuracy of the loss estimate. Although the loss of carbon when these blanket bogs were drained was large, the rate of loss seems likely to have declined as the peat surface lowered to within a few cm of the water table. This has implications for greenhouse gas (GHG) emission calculations as it is plausible that historically drained blanket bogs now have GHG fluxes similar to those at to intact sites. This is in agreement with Green et al. (2015) who found that sites on the Migneint showed no change in CO_2 or CH_4 fluxes following the blocking of drainage ditches. If the peat has decomposed as a result of drainage then it is likely that blocking drainage ditches on blanket bogs will not result in as much of a reduction in net GHG emission as has been hoped. For example, the IPCC Tier 1 emission factors for rewetted nutrient poor peats is -0.23 t CO_2-C ha^{-1} yr^{-1} (IPCC, 2014).

The change in peat surface also gives a potential explanation of why studies on peatland rewetting in Scandinavia found that water tables recovered rapidly and by an order of magnitude more than the differences seen in UK blanket bog studies (Haapalehto et al., 2014; Haapalehto et al., 2011; Hedberg et al., 2012; Maanavilja et al., 2014; Maanavilja et al., 2015). Vegetation changes in these studies indicate recovery to intact peatland vegetation (Haapalehto et al., 2014; Haapalehto et al., 2011; Hedberg et al., 2012; Kareksela et al., 2015; Komulainen et al., 1999; Maanavilja et al., 2014; Maanavilja et al., 2015). These sites are however lowland sites that had been drained for forestry production, and the effects of drainage on vegetation composition were presumably more profound than at our study site. Planting trees on peat systems is likely to greatly increase evapotranspiration and water table draw-down, and it is also probable that ditches in an active forestry site are maintained more actively than the drainage ditches we investigated. It is likely that Scandinavian forest sites have not reached a stable state with the water table close to the peat surface.

5 Conclusions

This work raises a number of interesting questions regarding the efficacy of ditch blocking as a strategy for peatland rewetting. It is important to note that the Migneint is a relatively intact blanket bog, and the drainage ditches have largely not eroded through the peat to the mineral layers underneath, so the outcomes of this may not be directly relevant to sites with extensive erosion gullies and vegetation loss. For such relatively intact sites however, it seems that blocking the drainage ditches has had little impact on short-term vegetation structure and water table depth. Other benefits may however result from blocking drainage ditches meaning that the technique may still be a useful restoration intervention, albeit for a different reason than previously considered to be the main benefit. Blocking ditches may reduce erosion and therefore improve downstream water quality. Hydrological effects of blocking ditches may include a reduction in peak flow rates in the streams draining the peatland. Ditches are clearly hazardous for grazing animals, and blocking them may reduce stock losses. From previous results (Cooper et al., 2014; Peacock et al., 2013) it is plausible that the linear wet features resulting from blocked ditches will infill with vegetation, and over time new peat will form in these. The apparent 'self-rewetting' of blanket bogs in the decades following their drainage has implications for their restoration as it suggests that there may not be large quantities of dry peat left to rewet, and that there is a risk of inundation (leading to short-term high CH_4 emissions) along subsided ditch lines, particularly if they are colonised by *Eriophorum vaginatum* (Cooper et al., 2014). Without more significant restoration intervention, it may take much longer to infill lost peat and restore carbon stocks than was initially anticipated.

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