AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2016WR019898

Key Points:
- Drainage causes lasting changes to simulated peat structure depending on proximity to a drainage ditch and up or downslope position
- Drainage affects long-term simulated peat accumulation before and after ditch damming altering the developmental trajectory of a peatland
- Ecosystem models can complement field observations with insights into how peatlands respond to drainage and restoration over centuries

Supporting Information:
- Supporting Information S1

Correspondence to:
D. M. Young,
D.M.Young@leeds.ac.uk

Citation:
Young, D. M., A. J. Baird, P. J. Morris, and J. Holden (2017), Simulating the long-term impacts of drainage and restoration on the ecohydrology of peatlands, *Water Resour. Res.*, *53*, 6510–6522, doi:10.1002/2016WR019898.

Received 5 OCT 2016
Accepted 4 JUL 2017
Accepted article online 13 JUL 2017
Published online 4 AUG 2017

Simulating the long-term impacts of drainage and restoration on the ecohydrology of peatlands

Dylan M. Young[1], **Andy J. Baird**[1], **Paul J. Morris**[1], **and Joseph Holden**[1]

[1]water@leeds, School of Geography, University of Leeds, Leeds, UK

Abstract Drainage alters the carbon storage and accumulation functions of peatlands, but the long-term effects of drainage ditches, and their restoration, on peatland development are poorly understood. Timescales of monitoring studies in ditch-drained and restored peatlands are typically limited to a few years, and occasionally decades. In addition, experimental studies seldom monitor spatial changes in peat structure caused by ditches, despite such changes affecting water flow and water retention in peat. Ecosystem models offer an alternative to experimental studies and can help explain how complex systems such as peatlands may respond to external disturbances. Here we report on a 2-D application of a peatland development model (DigiBog) to explore how contour-parallel ditches, and their damming, affect the ecohydrology of peatlands over decades to centuries, using blanket peatlands as a case study. Drainage resulted in the rapid loss of peat due to increased oxic decay. The majority of these losses occurred in the first 100 years after the ditch was created, but water table dynamics were altered even centuries later. Restoration halted the loss of peat and encouraged net peat accumulation, although the amount lost in 100 years of drainage had not been replaced 200 years after the ditch was dammed. Restoration of ditches in sloping peatlands brought about more peat regrowth downslope of the restored ditch than further upslope. Our study demonstrates the potential for spatially distributed ecosystem-scale models as tools to explore complex spatiotemporal responses to disturbance, and to support land managers in making decisions about peatland drainage and restoration.

Plain Language Summary Peatlands are globally important stores of carbon, but many have been drained either artificially or because of gully systems. Drainage can destabilize the carbon stored in peatlands and as a result damming of drainage features has become widespread in peatland restoration. However, studies that monitor peatland drains and their restoration are often limited to a few years, or occasionally decades, and the longer-term effects on peatlands is poorly understood. We report on the use of a peatland model to explore how drains, and their damming, affect the ecohydrology of peatlands over timescales of decades to centuries. Drainage resulted in the rapid loss of peat due to increased decomposition. Most losses occurred in the first 100 years after the drain was created, and water table dynamics were altered even centuries later. Restoration halted the loss of peat and encouraged peat to accumulate, although the amount lost in 100 years of drainage had not been recovered 200 years after the drain was dammed. Peat regrowth downslope of the restored drain was more pronounced than further upslope. Our study demonstrates the potential for models to be used to explore complex responses to disturbance, and to support land managers in making decisions about peatland drainage and restoration.

1. Introduction

Peatlands around the world have been subjected to land-use change, with many drained by ditches to improve conditions for forestry, agriculture, peat extraction, and road construction [e.g., *Maljanen et al.*, 2010; *Parry et al.*, 2014; *Turetsky et al.*, 2015; *Page and Hooijer*, 2016]. Some peatlands have also developed gully systems as a result of natural and anthropogenic disturbances [e.g., *Tallis*, 1985] and these act in a similar way to networks of ditch drains [*Daniels et al.*, 2008].

Drainage ditches and gullies often alter peatland carbon (C) accumulation and storage functions because they impose deeper water tables and expose peat that may have been beneath the water table for centuries, or longer, to rapid oxic decomposition [*Tipping*, 1995]. This exposure results in the conversion of stored

C to carbon dioxide (CO_2), and dissolved compounds that are lost from the peatland in drainage outflow [*Hooijer et al*., 2010; *Moore et al*., 2013]. Deeper water tables are also likely to alter future peat accumulation through their effects on the composition and productivity of peatland plant communities. Although sometimes complicated, there is a relationship between water table depth (and regime) and the makeup of the peatland plant assemblage [*Talbot et al*., 2010], and changes in vegetation will cause changes in rates of litter production and litter quality, the latter affecting rates of decay of newly formed peat [e.g., *Belyea and Clymo*, 2001; *Robroek et al*., 2007; *Talbot et al*., 2010]. Drainage also increases the vulnerability of peatlands to wildfire, exacerbating the loss of C to the atmosphere [e.g., *Turetsky et al*., 2015]. Because of these negative effects, drainage ditches and gullies in many peatlands are being dammed as part of rewetting programs that seek to restore the ecohydrological functions that characterize intact peatlands [*Schimelpfenig et al*., 2013; *Dixon et al*., 2014; *Beadle et al*., 2015; *Page and Hooijer*, 2016]. Despite an appreciation of the ways in which drainage and subsequent rewetting might affect peatland ecohydrological functioning over decadal timescales, the longer-term effects of both activities remain poorly understood. A number of studies have compared water tables after several decades of drainage with those in restored sites using space-for-time substitutions, or before-after experiments, but postrestoration monitoring is usually limited to a few years' duration (less than 10 years) [e.g., *Holden et al*., 2011; *Bellamy et al*., 2012; *Schimelpfenig et al*., 2013; *Dixon et al*., 2014; *Menberu et al*., 2016]. Although some studies have reported water tables in peat adjacent to restored drainage features to be similar to those in pristine sites [e.g., *Schimelpfenig et al*., 2013; *Menberu et al*., 2016], others have found hydrological conditions to be intermediate between those of drained and intact sites [e.g., *Holden et al*., 2011; *Wallage and Holden*, 2011]. These differences may reflect long-lasting changes to peat hydraulic properties caused by dewatering, increased oxic decomposition, and compaction [e.g., *Williamson et al*., 2017] and inhibit full recovery to the hydrological and C-sequestration functions seen in intact peatlands.

Postrestoration monitoring studies commonly focus on water table depth as a measure of restoration success. Despite often recognizing the importance of peat hydraulic properties in determining water table dynamics, few studies incorporate such properties into sampling strategies [e.g., *Daniels et al*., 2008; *Wilson et al*., 2010; *Bellamy et al*., 2012; *Dixon et al*., 2014]. Those studies that have monitored changes in peat hydraulic properties of ditch dammed sites have found that while water tables were shallower than in drained sites, peat structure was not restored during the monitoring period [e.g., *Wallage and Holden*, 2011; *Schimelpfenig et al*., 2013].

There is good evidence that peatlands are complex adaptive systems in which there are complicated feedbacks between hydrological, ecological, and biogeochemical processes [*Belyea and Baird*, 2006]. As a result, it can be difficult to predict the long-term outcomes of management activities such as artificial drainage and restoration on the overall functioning of a peatland. Manipulative experiments which consider isolated columns of peat [e.g., *Bridgham et al*., 2008] are expensive to run over the long term and necessarily neglect potentially important spatial interactions. However, because changes in peat properties caused by drainage ditches in one part of a peatland may have effects on the peat around the ditch [*Holden et al*., 2006; *Talbot et al*., 2010], approaches that incorporate feedback mechanisms and spatial effects are needed.

An alternative to long-term experimental studies is the use of ecosystem models [*Evans*, 2012]. Models that describe important internal ecosystem processes allow the trajectory of a system to emerge from the interaction of these processes [*Evans*, 2012] over timescales that are relevant to the ecosystem being modeled, and can help elucidate the complex responses of an ecosystem to external disturbances such as climate change. Existing models that simulate peatland development over thousands of years include key ecohydrological processes such as plant litter production, peat decay, changes in peat hydraulic conductivity, subsurface water flow, and water table dynamics [e.g., *Frolking et al*., 2010; *Baird et al*., 2012; *Morris et al*., 2015a]. Although mostly used to simulate single columns of peat (as in manipulative experiments), versions of these models can also simulate spatial patterns in peatland development [e.g., *Morris et al*., 2012]. For example, the DigiBog peatland development model simulates the growth of a virtual peatland in 1-D [*Morris et al*., 2015a], 2-D [*Baird et al*., 2012; *Morris et al*., 2012], or 3-D. The 2-D and 3-D versions of the model represent a peatland as a series of spatially distributed hydrologically connected columns. The model also incorporates several mechanisms for autogenic feedbacks, including a negative feedback between peat decomposition, hydraulic conductivity, and water table depth [*Belyea and Clymo*, 2001; *Waddington et al*., 2015]. Under deepening water tables, this feedback reduces lateral seepage and may therefore play an important role in how a peatland responds to ditch drainage. DigiBog therefore provides a mechanistic framework for understanding the across-slope and along-slope effects of ditch drainage and restoration over long timescales.

Our aim is to explore the potential of using a modeling approach to provide new insights into how drainage ditches and gullies, and their restoration, affect the ecohydrology of peatlands over timescales of decades to centuries, which extends beyond the history of current monitoring and restoration programs. We use a new 2-D version of DigiBog [*Baird et al*., 2012; *Morris et al*., 2012, 2015a] to investigate how water table dynamics, peat structure, and peat accumulation change over space and time when a drainage ditch is created and restored.

2. Methods

2.1. Blanket Peatland Case Study

To illustrate how artificial drainage and subsequent rewetting affect the ecohydrology of peatlands, we used DigiBog to simulate blanket peatland development over both flat and sloping mineral substrates. Blanket peatlands are ombrotrophic bogs that form on slopes and plateaus covering large areas in hyperoceanic regions such as Norway, Iceland, Patagonia, eastern Canada, and the UK [*Gallego-Sala and Prentice*, 2012]. Although globally rare, blanket peatlands are the most extensive peatland type in the UK [*Ballard et al*., 2011; *Beadle et al*., 2015]. They are nationally and internationally important as habitats and as stores of C, and, while many UK blanket peatlands have been affected by fire, wind erosion, sheep grazing, and atmospheric pollution, artificial ditches and erosional gullies have had perhaps the greatest impact on their functioning [*Parry et al*., 2014]. As a result, damming of ditches and gullies has been widespread as part of restoration programs that aim to restore hydrological regimes to those of intact blanket peatlands [*Parry et al*., 2014].

2.2. Model Description

We configured our version of DigiBog to represent 2-D peatlands over flat and sloping mineral soil bases. Simulations begin with the addition of a single layer of plant litter to each column: a new layer of litter is then added at the rate p (kg m^{-2} yr^{-1}) to each column at the start of each subsequent year depending on the mean oxic zone thickness (Z) and mean annual air temperature (T_{ave}) [*Morris et al*., 2015a]

$$p=0.001\left(9.3+133Z-0.022(100Z)^2\right)^2(0.1575T_{ave}+0.0091)$$
$$\text{for } 0 \text{ m} \leq Z \leq 0.668 \text{ m}, \; p=0 \text{ where } Z > 0.668 \text{ m}. \tag{1}$$

This peat productivity function that predicts production across microhabitats (hummock, lawn, and hollow) depending on water table depth and air temperature was developed from a data set presented by *Belyea and Clymo* [2001] and was modified to include the effect of air temperature (refer to *Morris et al*. [2015a, supporting information]).

Layer thickness is calculated by dividing its mass by a constant value for dry bulk density (ρ) (Table 1). Depth-integrated oxic and anoxic decomposition of each layer takes place subannually according to the proportion of the layer above (ox) or below the water table (an), the value of the decay parameters (oxic (α_{ox}) and anoxic (α_{an})), and the temperature sensitivity (Q_{10}) (see supporting information and its discussion of parameter choice, Text S1),

$$M_t=M_{t-1}\left[\left(ox\cdot e^{-\Delta t\alpha_{ox,T_{BC}}Q_{10}^{(T_W-T_{BC})/10}}\right)+\left(an\cdot e^{-\Delta tm\alpha_{an,T_{BC}}Q_{10}^{(T_W-T_{BC})/10}}\right)\right], \tag{2}$$

where M_t is the mass of a peat cohort (kg m^{-2}) at time t, T_w is the mean weekly air temperature, and T_{BC} is the baseline temperature, 6.29°C, used by *Morris et al*. [2015a] to derive the productivity function described in equation (2). We incorporated a degree of recalcitrance into submerged peat by multiplying the anoxic decay parameter by the proportion of the original layer mass that remained after decomposition (m), where $m=(M_t/M_0)$, and M_0 is the original mass of the layer (see supporting information and its discussion of model assumptions, Text S2). In our model, the thickness of a layer can vary through the balance of litter addition and peat decomposition (but not compaction) and alter the surface profile of the modeled peatland. The hydraulic conductivity K_{coh} (m yr^{-1}) of each cohort declines with increasing decomposition according to m [*Morris et al*., 2012, 2015b],

10.1002/2016WR019898

Table 1. Default Model Parameters

Parameter	Symbol	Value	Units	Source
Oxic decomposition	α_{ox}	3.5×10^{-2}	year^{-1}	*Hogg* [1993] and *Morris et al.* [2012]
Anoxic decomposition	α_{an}	10^{-5}	year^{-1}	*Morris et al.* [2012]
Temperature sensitivity[a]	Q_{10}	3		*Helfter* [2015]
Dry bulk density	ρ	100	kg m^{-3}	*Wallage and Holden* [2011]
Hydraulic conductivity parameter[b]	a	15.8687	m yr^{-1}	*Lewis et al.* [2012] and
Hydraulic conductivity parameter[b]	b	8		*Cunliffe et al.* [2013]
Drainable porosity	s	0.3		*Holden et al.* [2001]
Peat column size		4	m^2	
Pond depth		2.5×10^{-3}	m	

[a]Applied to both oxic and anoxic decomposition parameters.
[b]Initial value of K before a new layer undergoes decomposition according to equation (3), which equates to 0.0015 m s^{-1} (0.15 cm s^{-1}).

$$K_{coh} = ae^{bm}, \tag{3}$$

where a and b are parameters, the values of which describe the relationship between decomposition and hydraulic conductivity (Table 1): a process that allows layers within and between columns to develop different values of hydraulic conductivity depending on local water table position. Water tables are dynamic, as opposed to the steady state solution used in *Morris et al*. [2012], and variable subannual time steps are used to produce a numerically stable solution to water flow between columns. As in *Morris et al*. [2012], water flow occurs horizontally between columns as a finite-difference solution of,

$$\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\kappa(d)}{s(d)} d \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\kappa(d)}{s(d)} d \frac{\partial h}{\partial y}\right) + \frac{P(t) - E(\mathrm{h}, \mathrm{t})}{s(d)}, \tag{4}$$

where h is water table height (m) above a datum, t is time (s), x and y are the horizontal distances (m), d is the thickness of flow (i.e., the local height of the water table above an underlying impermeable base) (m), κ is depth-averaged hydraulic conductivity below the water table (m s^{-1}), s is drainable porosity (dimensionless), P is the rate of rainfall addition to the water table (m s^{-1}), and E is the rate of evapotranspiration (m s^{-1}) [*Baird et al*., 2012]. Although DigiBog does not simulate the vertical movement of water within a column, changes in water table height occur when water moves horizontally between columns depending on the space available for storage in layer pores and above the peatland in a surface ponding layer. Groundwater recharge is based on net rainfall (*P-E*); although overland flow is not modeled explicitly, once surface water exceeds the ponding depth it is lost from the model domain—a process akin to rapid overland flow. The version of DigiBog described here simplifies or omits some peatland process, including the treatment of bulk density, drainable porosity and the recalcitrance of peat [*Baird et. al.,* 2012; *Ingram,* 1978; *Leifeld et al.,* 2012; *Morris et. al.,* 2012], the development of pipes [*Cunliffe et al.,* 2013; *Holden and Burt,* 2002; *Holden,* 2005a, 2005b], changes in column height due to mechanical compaction [*Baird et al.,* 2017; *Hooijer et al.,* 2012; *Williamson et al.,* 2017; *Wösten et al.,* 1997], and the development of bare peat [*Tallis,* 1985; *Parry et al.,* 2014] (all are discussed in supporting information, Text S2). While these processes could be developed in a future version of the model, our aim at this stage was to simulate the development of plausible peatlands and to explore the effects of artificial drainage in space as well as time; which is different from previous studies that use 1-D models [e.g., *Frolking et al*., 2014; *Kurnianto et al*., 2015]. Importantly, our 2-D model allows spatial heterogeneity to emerge in the rate at which litter is added to each column, and in the variation of hydraulic conductivity (groundwater flow) within and between columns across the modeled landscape. This heterogeneity is likely to play an important role in the model system's response to ditch drainage.

2.3. Model Setup and Initial Parameter Values

We simulated blanket peatland development along transects comprising twenty-five 2 m × 2 m columns on both sloping and flat bases (i.e., the mineral substrate below the peat): a conceptual model of the configuration used for the sloping base simulations is shown in Figure 1. Although blanket peatlands can form on steep slopes, they commonly form on gentle slopes [*Holden*, 2005a]: we therefore chose to set the angle in our sloping base simulations to 3°. Model boundary conditions were based on (1) climatic inputs in the form of a time series of net rainfall (*P-E*) and temperature, (2) a Neumann no-flow condition at the drainage divide (topslope in the case of sloping peatlands), (3) a Dirichlet constant water level condition to simulate

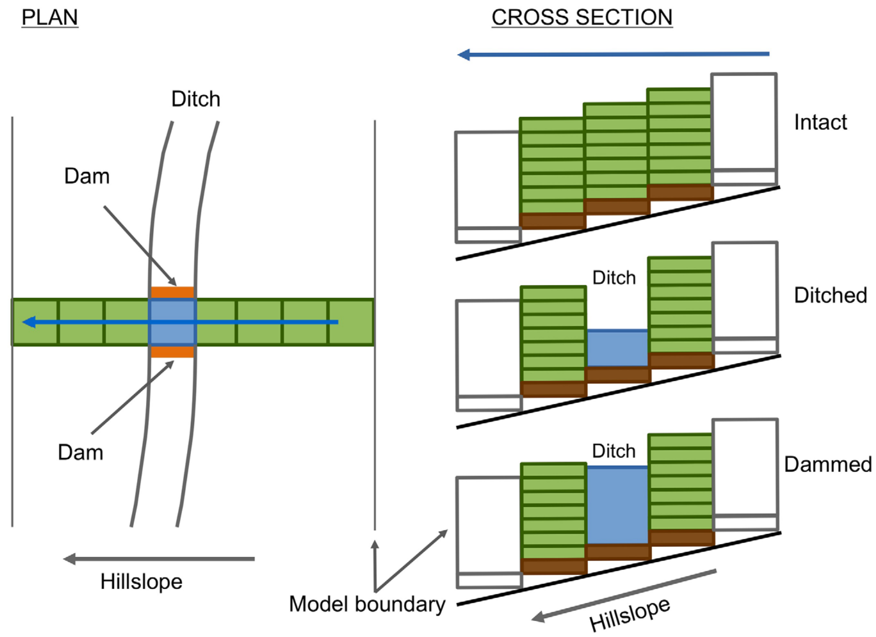

Figure 1. Conceptual model of a contour parallel drainage ditch and its restoration in a sloping peatland. Plan: green squares are the simulated peatland columns, the solid blue arrows represent downslope water flow, and the blue square represents the drainage ditch. Cross section: sequence of artificial drainage and restoration. Peat columns are made up of individual layers (green) with properties that can vary vertically within a column and horizontally between columns (brown layers represent the mineral soil base). The water in the drainage ditch is shown in blue.

drainage into a stream, and (4) an impermeable base below a 0.02 m layer of mineral soil. We used a weekly time series of net rainfall and temperature from Keighley Moor, a blanket bog in the north of England (53°51′N, −02°01′E) [*Blundell and Holden*, 2015]. Climate data from the University of Leeds weather station on Keighley Moor (mean of 2010–2013) gave annual rainfall and temperatures of 1152 mm and 7.6°C, respectively. The mean temperature of the warmest month was 14.1°C, seasonal temperature variation was 7.2°C, and there were 364 wet days in our average year. These values are within the climatic criteria defined by *Lindsay et al.* [1988] and therefore represent a suitable input record for our study. Using these data, mean weekly temperature and net rainfall values were calculated with each modeled year having the same weekly inputs so that the response of the simulated peatland to ditch drainage and restoration was isolated from the effect of interannual climate variation.

Prior to running our final simulations, we investigated the effects of Q_{10} and the oxic decay parameter (α_{ox}) on litter addition and peat decomposition (see supporting information Text S1). We also explored the

Figure 2. Infilling drainage feature after damming on Keighley Moor, Yorkshire, UK. Photograph courtesy of Antony Blundell, reproduced here with permission.

10.1002/2016WR019898

Table 2. Drainage Ditch and Restoration Model Configurations[a]

Peatland Base	Dammed/Not Dammed	Dam Type
Sloping	Dammed	Infilling
Sloping	Dammed	Fixed
Sloping	Not dammed	
Flat	Dammed	Infilling
Flat	Not dammed	
Sloping	Control (not ditched or dammed)	

[a]The drainage ditch was located 26–28 m from the peatland margin.

effects of three temporal resolutions of our climatic inputs on peat accumulation (supporting information Text S1). We found that the different resolutions were important drivers of the final size of the peatland, and plan in future to report the implications for peatland development models. Other model parameters were chosen within the range of previously reported values (Table 1). Using this model setup on a sloping base and the weekly climate inputs described above in a baseline simulation of 5000 years led to the development of a peatland with a mean peat depth of ~1.6 m and a mean annual water table depth of ~0.05 m. The baseline simulation produced a peatland of plausible shape that was slightly domed and with a steeper slope toward the downslope margin, suggesting greater decomposition in that portion of the peatland [e.g., *Lapen et al*., 2005].

We simulated a contour parallel drainage ditch, often found on blanket bogs [e.g., *Gatis et. al*., 2016], by removing peat layers from a column after 4000 years, and setting a Dirichlet constant water level at half column height, into which the remaining peat columns would drain. After 4100 years, the drainage ditch was dammed (Figure 1), and the simulation allowed to continue for another 200 years. Ditch damming and restoration were simulated by reestablishing a near-surface water table (constant water level) that was either fixed or increased with the height of the downslope ditchside column as time progressed. The latter approach was used to simulate sediment infilling and vegetation encroachment between ditch dams that has been observed in some locations (Figure 2) [e.g., *Beadle et al*., 2015]. We assumed that the water level in the ditch did not vary seasonally in the open ditch and ditch dammed simulations. A selection of ditched and dammed configurations was simulated for sloping and flat base models (Table 2). The drainage ditch in one sloping base and one flat base simulation was not dammed (i.e., after 4000 years of peatland development, a ditch was created that remained open for 300 years). We also ran a control simulation for the sloping base peatland (i.e., 4300 years without drainage), and compared the results to the dammed simulations (see supporting information Text S3).

3. Results

Our simulated ditch drainage resulted in the rapid loss of peat due to increased oxic decay in both sloping (Figures 3 and 4) and flat base models. Here we present the results of the simulations that used the sloping base model, while the results for the flat base model and control simulation are presented and discussed briefly in the accompanying supporting information (Text S3). The majority of peat loss occurred during the first 100 years of the open ditch simulation. In the two scenarios where the ditch was dammed (fixed dam and infilling ditch, Table 2), the

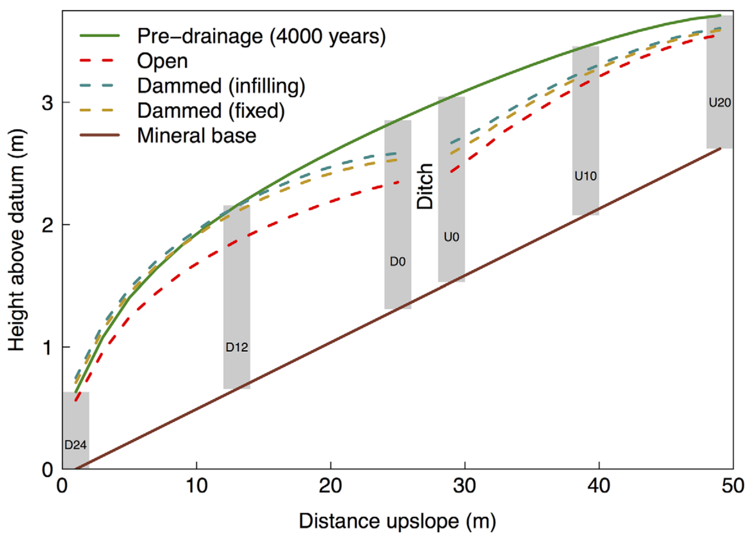

Figure 3. Modeled peatland surface before (4000 years) and after (4300 years) ditch drainage and damming. Annotated peat columns (e.g., D24, U10) are considered in more detail in the main text and in Figures 4–6. The columns are identified using their position upslope (U) or downslope (D) of the ditch, and the distance (m) of their edges that are nearest to the ditch (e.g., column U10 begins 10 m upslope of the ditch).

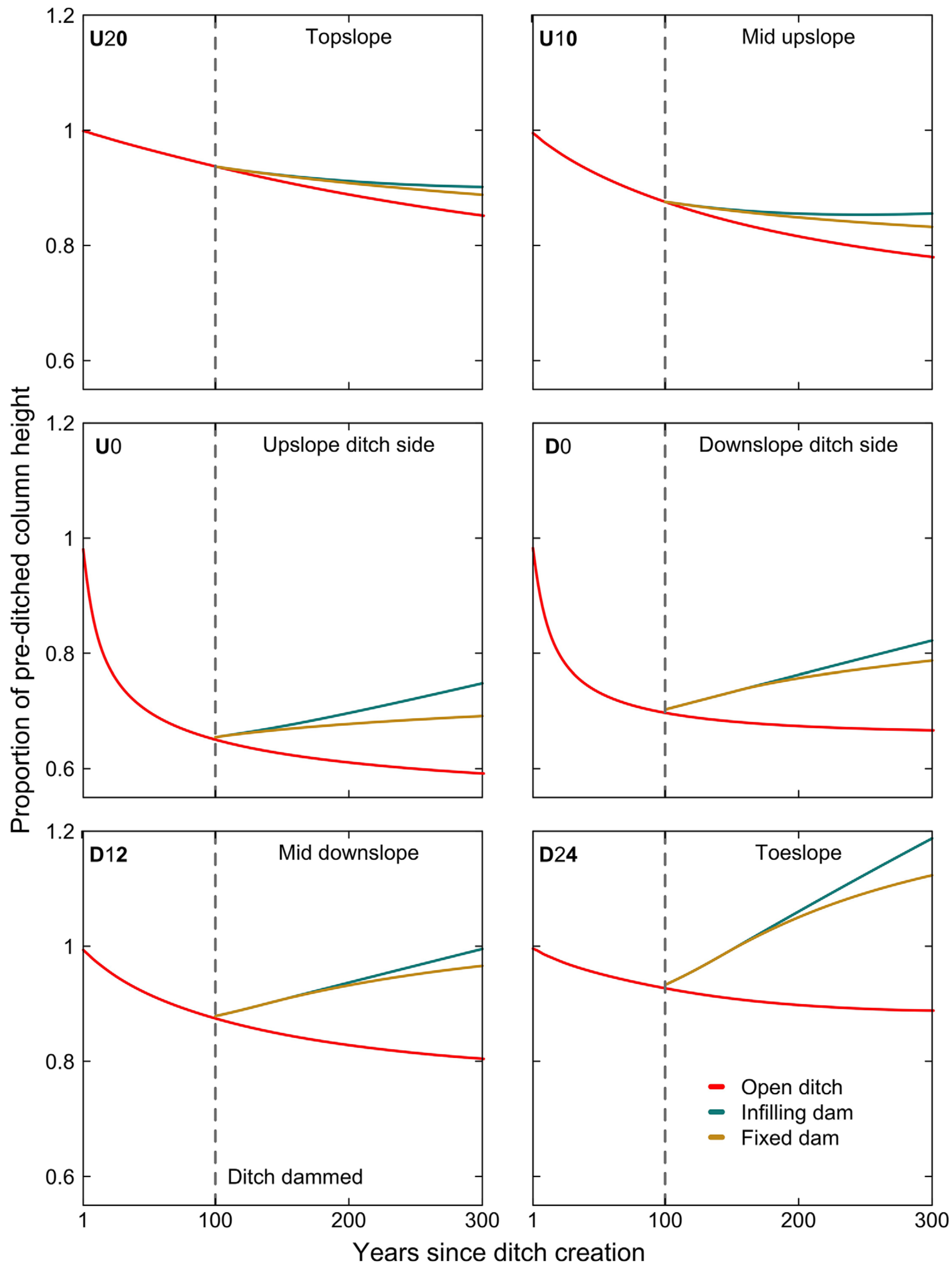

Figure 4. The simulated effect of drainage and ditch damming on peat accumulation across a sloping base model. Each figure represents the change in peat height since ditch drainage and restoration in six of the 25 hillslope columns. The ditch was created 26–28 m upslope from the peatland margin. Column identification is based on their upslope (U) or downslope (D) distance from the ditch (m) (refer to Figure 3 for a description).

balance between litter addition and decomposition was reversed in favor of net accumulation (green and yellow dashed lines, Figure 3). However, the peat mass lost in 100 years of drainage had still not been replaced 200 years after damming. Losses due to postdrainage decomposition (i.e., ignoring the peat removed directly from the column used to create the ditch) for the sloping base model were 16% of mean peat depth, rising to 23% when the ditch was allowed to remain open for a further 200 years (red dashed line, Figure 3). Following simulated ditch damming, peat accumulation in the sloping model varied according to the type of dam, whether the peat column was upslope or downslope of the ditch, and proximity to the ditch (Figure 4). Peat accumulation was greatest with the infilling ditch (which, during the simulation, increased in height by ~0.18 m): after

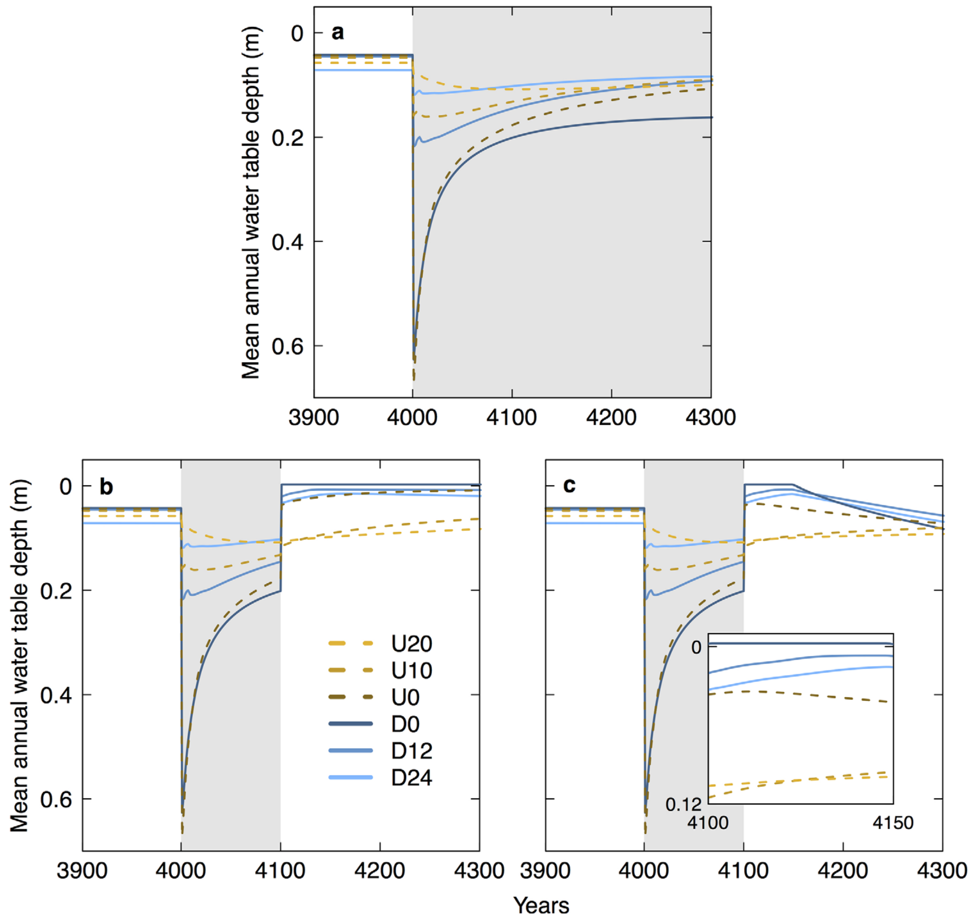

Figure 5. The effect of a ditch and ditch damming on water tables in a selection of columns across the hillslope. (a) Open ditch, (b) infilling ditch, and (c) fixed height ditch dam with inset of the first 50 years water tables postdamming. Dashed lines are columns upslope of the ditch, solid lines are downslope of the ditch, and lighter colors indicate increasing distance from the ditch. Column identification is based on slope position (upslope (U) and downslope (D)) and distance (m) from the ditch (refer to Figure 3 for a detailed description). Shading represents the time the ditch remained open.

200 years, losses were reduced to 9 and 12% of the preditched mean peat depth for the infilling ditch and fixed dam, respectively (Figure 4).

The model with the sloping base lost the greatest amount of peat via decay from the columns directly adjacent to the ditch (i.e., the ditchsides, Figure 4, D0 (downslope) and U0 (upslope)). These columns lost 30 and 35% of their preditch depth, respectively, before damming; and 33 and 41%, respectively, when the ditch remained open for 300 years. After damming, losses from these columns were reduced to 18% (infilling ditch) and 21% (fixed dam) for the downslope ditchside (Figure 4; D0), and 25 and 31%, respectively, for the upslope ditchside (Figure 4; U0). As the downslope distance from the ditch increased, peat accumulated to depths that equaled (column D12), or exceeded (column D24) preditched depths (Figure 4). However, after damming, peat columns upslope of the ditch either accumulated peat at a much slower rate or losses continued (Figure 4; U0, U10, and U20). For example, prior to damming, column U10 lost 12% of its peat depth which increased to 15 or 17% (infilling ditch or fixed dam respectively) by the end of the simulations: although by this time the rate of loss was less than 0.1% yr^{-1}.

Figure 5 shows the effect of the ditch and the two ditch damming methods on water tables in the sloping base peatland. Prior to drainage, mean annual water table depth for all columns was 0.04–0.07 m. Water tables across the hillslope rapidly became deeper when the ditch was created, falling to depths of more than 0.6 m for ditchside columns but when the ditch remained open, water table depths ended the simulation (i.e., at 4300 years) at 0.08–0. 16 m (Figure 5a). This response is due increased oxidation of peat which effectively lowers the peat surface toward the water table, as well as reducing the flow of water into the

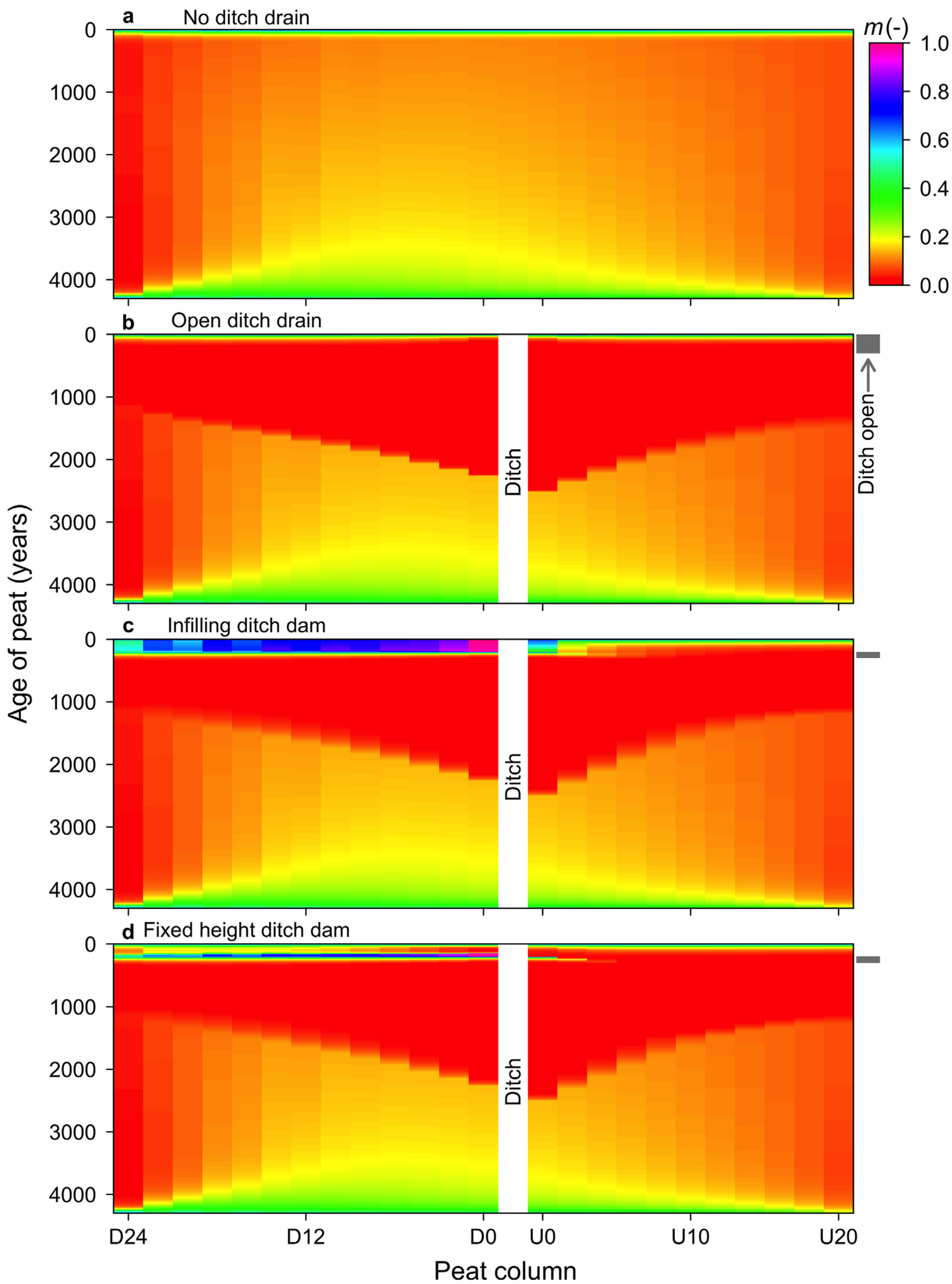

Figure 6. Comparison between simulations of the effect of ditch drainage on peat decomposition (proportion of mass remaining (m)) after 4300 years. (a) Control, (b) open ditch, (c) infilling ditch dam, and (d) fixed height ditch dam. Simulations a–d used the sloping base model. The annotated columns are identified using their upslope (U) or downslope (D) position, and distance (m) from the ditch. Gray bars on the upper right edge of figures 6b–6d represent the time the ditch remained open. Figures 6a–6d do not show the variable thickness of peat layers and the modification of surface topography caused by ditch construction. The effect of the ditch on peatland height can be seen in Figures 3 and 4.

ditch because of changes in peat structure. When the infilling ditch was simulated, the downslope area and both ditchside columns maintained near or at surface water tables whereas upslope water tables were slightly deeper at 0.06–0.08 m (Figure 5b). Peat accumulation in the downslope ditchside column (D0) exceeded the height of the fixed dam after ∼50 years, and water table depths were 0.06–0.09 m ∼200 years after damming; which were similar to those before drainage, but the spatial distribution of water table depths across the hillslope had changed (Figure 5c).

Secondary decomposition [*Tipping*, 1995] occurs when peat that has been relatively well preserved, under predominantly anoxic conditions, is exposed to high rates of oxic decay due to recently lowered water tables (Figure 5a). Our simulated ditch drainage has reproduced this effect in the modeled peatland (Figure 6). To highlight the effect of ditch drainage on peat accumulated many years before artificial drainage takes place, Figure 6 shows the age of peat layers and the proportion of the original peat mass that remains (i.e., the amount of decomposition) in each layer of a column at the end of all simulations (control, ditch drained only, and the two dammed configurations). Total decomposition increased when the ditch was simulated: ditch drainage caused varying degrees of secondary decomposition in peat layers that first formed many years before ditch drainage. It is notable how peat in columns adjacent to the ditch (D0 and U0) that accumulated between ~2000 and 2500 years ago has been exposed to secondary oxic decomposition resulting in a loss in peat height of ~30–40% (Figure 4). Without ditch drainage, this would not have occurred and older peat layers would have remained relatively well preserved as they have in the control simulation (Figure 6a). Saturated conditions that followed damming led to the formation of well-preserved peat, except in the topslope columns U10 and U20, and enabled net peat accumulation to restart.

4. Discussion

Our simulations show how an ecosystem model can be used to explore the spatiotemporal response of a peatland to ditch drainage and ditch damming over decades and centuries. Although we have simplified or omitted some peatland processes (see supporting information, Text S2), our simulated peatlands are plausible and show that the model can be used to explore the effect of ditch drains in 2-D. While we have highlighted the areas of the model that could be improved, any alterations need to be compared to the current model results and the benefits of adding complex, and possibly poorly understood, processes assessed before changes are made.

Previous modeling and fieldwork have shown the margins of blanket peatlands are commonly highly decomposed, and that peat in central areas is often comparatively well preserved [*Lapen et al*., 2005; *Lewis et al*., 2012]. Both of these characteristics were reproduced by our model (Figure 6a). Artificial drainage causes rapid deepening of ditchside water tables (0.63–0.67 m for downslope and upslope ditchside columns, respectively) leading to secondary decomposition of older previously saturated and well-preserved peat because of exposure to high levels of oxic decay [*Tipping*, 1995]. This process changes the structure of peat resulting in lower hydraulic conductivity across the hillslope (supporting the suggestion of *Holden et al.* [2006]). The columns of peat that later become the side walls of the ditch (D0 and U0) develop under shallow water tables and have higher depth-averaged hydraulic conductivity than the columns at the margin. As a result, when the ditch is created, columns upslope of the ditch initially lose water into the ditch more quickly than downslope columns drain from the margin, lowering upslope water tables and subjecting upslope columns to a greater degree of secondary decomposition (Figures 4 and 6b, U0, U10, and U20).

Although ditch drainage takes place 300 years before the end of the simulations, signals of increased decomposition can be seen in ditchside peat formed around 2000 years earlier, and not at the time of drainage (Figure 6b). Because our model links peat columns hydrologically across a peatland, these findings demonstrate how the signals of artificial drainage in blanket peatland humification records are also likely to vary in relation to the location of the drainage ditch and hillslope position (Figure 6). Furthermore, in our simulations, ditch drainage affects the accumulation of peat over tens of meters both before and after ditch damming. Although studies have discussed the role of topography and peat properties on the impact of drainage ditches in peatlands [e.g., *Price et al*., 2003; *Holden et al*., 2011; *Menberu et al*., 2016], our findings suggest that these characteristics produce a spatial effect that may alter the development trajectory of a site over centuries in both ditched and dammed situations.

Peat columns show a varying response to ditch damming, which is dependent on hillslope position and the type of dam simulated. In downslope ditchside columns peat accumulation is restarted by damming, but this effect is less pronounced above the ditch where losses from increased decomposition are only reduced or stopped in the top portion of the hillslope (U10–U20). Figures 6c and 6d show that downslope peat that accumulates after ditch damming is less decomposed because of the shallower water tables imposed by the dams, a result also observed in field studies of ditch damming in blanket peatlands [*Holden et al*., 2011], whereas newly accumulated peat upslope of the ditch shows no changes in the rate of decomposition. This effect highlights the need to consider the location of the ditch in relation to the restoration objectives for water tables across a hillslope [*Holden et al*., 2011].

The water table depths shown in Figures 5a–5c should be interpreted in relation to the loss of peat across the hillslope because the overall height of the peatland decreases during artificial drainage as a result of subsidence caused by increased oxic decay (Figure 3). Mean annual water table depth is a result of the combined effects of decreasing peat column height, through oxidation, and the negative feedback mechanism between increased decomposition and decreased hydraulic conductivity that reduces the flow of water into the ditch. However, when the ditch remains open, the simulated peatland shifts to a drier state with more spatially variable water tables (Figure 5a), which is consistent with field observations made by *Holden et al*. [2011]. The water table in the downslope ditchside column remains deeper than other columns after drainage (Figure 5a, D0), an effect that has also been reported in empirical studies into the effect of drainage ditches in blanket peatlands [e.g., *Holden et al*., 2006; *Wilson et al*., 2010]. Our simulations indicate that this effect may persist in some hillslope positions for hundreds of years after ditch drainage, despite lasting changes in peat structure due to secondary decomposition (Figure 6b).

Mean water table depths in simulated peat show greater variation along the hillslope after ditch drainage and ditch damming than before drainage, indicating that ditch damming did not re-establish preditched water table dynamics on decadal timescales. These results agree with the observations of *Holden et al*. [2011], who found greater spatial variation in blanket peatland water tables where there were open and dammed drainage ditches when compared to intact sites. However, after damming, downslope water tables depend on the simulated damming method. Whereas the infilling ditch method imposes near-surface downslope water tables throughout the simulation (Figure 5b), the fixed-height dam results in deeper and more variable water tables (Figure 5c): newly added peat increases the gradient to the ditch water causing water tables to deepen, and after 200 years they converge to depths comparable to preditched values. Ultimately, this difference between the height of the peat surface and the height of the ditch water becomes a limiting factor in the recovery of peatland C storage over the timescales we modeled (Figures 4 and 6d).

After 300 years the rate of modeled peat loss from the open ditch system slowed substantially and in some columns losses almost stopped (Figure 4). We suggest that where this occurs, net accumulation will restart without restoration even though mean water table depth is likely to be different from an intact peatland. In this respect, our findings are consistent with those of *Swindles et al*. [2016] who showed that after repeated human disturbance, net peat accumulation can resume spontaneously in the long term, demonstrating resilience over timescales of hundreds of years, far beyond those considered by contemporary restoration monitoring programs. *Williamson et al*. [2017] proposed that around ditches, blanket peatlands "self-rewet" as a result of a loss of peat height following ditch drainage which could lead to little change in water table depth after ditch damming. Although the location and orientation of the ditches in the study of *Williamson et al*. [2017] were different from that which we modeled, our results are similar to the conceptual model they propose. In the first few decades after a ditch is installed, increased oxic decay rapidly lowers the peatland surface. This process also causes hydraulic conductivity to decrease which, in turn, reduces the rate of water lost from the peatland (especially in peat columns downslope of the ditch) leading to shallower water tables and may have eventually favored the net accumulation of peat.

There have been numerous studies into the effects of drainage ditches and ditch damming in different peatland types, but our work is the first to simulate their impacts in 2-D over centennial timescales by using an ecosystem model. Ditches have been previously simulated in 1-D peatland models [e.g., *Frolking et al*., 2014; *Kurnianto et al*., 2015]. Although *Kurnianto et al*. [2015] simulated a drainage ditch in a 1-D peatland development model by fixing the water table position within a column of peat, the effects of ditch drainage and restoration can vary spatially: unlike 1-D models, our 2-D approach allows water table dynamics and peat accumulation to vary across a virtual peatland in space as well as time. Our model also allows us to explore the effects of ditch drainage and ditch damming on peat structure, a factor few empirical studies include. The simulations have also reproduced some of the observations made during field experiments, but can complement these observations by suggesting how blanket peatlands may respond to restoration over hundreds of years.

5. Conclusions

Our simulations provide plausible insights into how peatlands that have developed on slopes, and over flat terrain (see supporting information Text S3) may respond to contour parallel ditch drains, and to their restoration over decadal to centennial timescales. The majority of simulated peat loss occurs during the first 50–100 years after drainage and is not replaced after 200 years of ditch damming. The model shows how the reduction of peatland height and changes to peat structure caused by the increased oxic decomposition of old, poorly decomposed, peat (Figures 4 and 6) can lead to shallower water tables even when the ditch remains open (Figure 5a). Therefore, the response of water tables to ditch damming is likely to depend on the time since ditch drainage occurred as well as hillslope position, and, as found empirically by *Williamson et al*. [2017], there may be little change in water table depth at some locations. The development of spatial heterogeneity within and between peat columns show how slope, and upslope or downslope proximity to a ditch, may affect the loss of peat during ditch drainage and its renewal following damming. The model also shows how sloping and flat peatlands are likely to respond differently to ditch drainage, albeit our sloping and flat bases have yet to be configured to represent real terrain.

The 2-D model used in this study demonstrates the potential for such an approach to be used as a decision support tool for peatland and restoration managers by incorporating spatial effects and by simulating timescales that extend beyond our current experience of restoration. For example, water table position is often used as a measure of restoration success, but the water table dynamics in the fixed dam restored peatland were not comparable to those of the intact peatland for centuries, suggesting that these comparisons may not always be helpful in the short term. Our next step is to use real underlying topographies from ditch drained sites, over longer transects, with current and predicted climate variables to explore the performance of the model in these situations. We used the example of blanket peatlands, but our model incorporates key processes that are relevant to all peatlands and, as such, it could be adapted to simulate other peatland types. For example, future numerical experiments could include other ditch drained peatland types [e.g., *Menberu et al*., 2016], including tropical peatlands where artificial drainage and subsequent fires have resulted in a significant loss of stored C [*Hooijer et al*., 2010], and an understanding of their long-term response to restoration could feed into land-use policy.

Acknowledgments
All data generated by this study (i.e., model outputs) and model code are available from the authors upon request by e-mail: d.m.young@leeds.ac.uk. This research was funded by the UK Natural Environment Research Council and the Economic and Social Research Council (grant ES/I903038/1) awarded to Holden and Chatterton.

References

Baird, A. J., P. J. Morris, and L. R. Belyea (2012), The DigiBog peatland development model 1: Rationale, conceptual model, and hydrological basis, *Ecohydrology*, *5*(3), 242–255, doi:10.1002/eco.230.

Baird, A. J., R. Low, D. Young, G. T. Swindles, O. R. Lopez, and S. Page (2017), High permeability explains the vulnerability of the carbon store in drained tropical peatlands, *Geophys. Res. Lett.*, *44*, 1333–1339, doi:10.1002/2016GL072245.

Ballard, C. E., N. McIntyre, H. S. Wheater, J. Holden, and Z. E. Wallage (2011), Hydrological modelling of drained blanket peatland, *J. Hydrol.*, *407*, 81–93, doi:10.1016/j.jhydrol.2011.07.005.

Beadle, J. M., L. E. Brown, and J. Holden (2015), Biodiversity and ecosystem functioning in natural bog pools and those created by rewetting schemes, *WIREs Water*, *2*(2), 65–84, doi:10.1002/wat2.1063.

Bellamy, P. E., L. Stephen, I. S. Maclean, and M. C. Grant (2012), Response of blanket bog vegetation to drain-blocking, *Appl. Veg. Sci.*, *15*(1), 129–135, doi:10.1111/j.1654-109X.2011.01151.x.

Belyea, L. R., and A. J. Baird (2006), Beyond the limits to peat bog growth: cross-scale feedback in peatland development, *Ecol. Monogr.*, *76*(3), 299–322.

Belyea, L. R., and R. S. Clymo (2001), Feedback control of the rate of peat formation, *Proc. Biol. Sci. R. Soc. B*, *268*, 1315–1321, doi:10.1098/rspb.2001.1665.

Blundell, A., and J. Holden (2015), Using palaeoecology to support blanket peatland management, *Ecol. Indic.*, *49*, 110–120, doi:10.1016/j.ecolind.2014.10.006.

Bridgham, S. D., J. Pastor, B. R. Dewey, J. F. Weltzin, and K. Updergraff (2008), Rapid carbon response of peatlands to climate change, *Ecology*, *89*(11), 3041–3048.

Cunliffe, A. M., A. J. Baird, and J. Holden (2013), Hydrological hotspots in blanket peatlands: Spatial variation in peat permeability around a natural soil pipe, *Water Resour. Res.*, *49*(9), 5342–5354, doi:10.1002/wrcr.20435.

Daniels, S. M., C. T. Agnew, T. E. H. Allott, and M. G. Evans (2008), Water table variability and runoff generation in an eroded peatland, South Pennines, UK, *J. Hydrol.*, *361*, 214–226, doi:10.1016/j.jhydrol.2008.07.042.

Dixon, S. D., S. M. Qassim, J. G. Rowson, F. Worrall, M. G. Evans, I. M. Boothroyd, and A. Bonn (2014), Restoration effects on water table depths and CO_2 fluxes from climatically marginal blanket bog, *Biogeochemistry*, *118*, 159–176, doi:10.1007/s10533-013-9915-4.

Evans, M. R. (2012), Modelling ecological systems in a changing world, *Philos. Trans. R. Soc. B Biol. Sci.*, *367*(1586), 181–190, doi:10.1098/rstb.2011.0172.

Frolking, S., N. T. Roulet, E. Tuittila, J. L. Bubier, A. Quillet, and J. Talbot (2010), A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation, *Earth Syst. Dyn.*, *1*, 1–21, doi:10.5194/esd-1-1-2010.

Frolking, S., J. Talbot, and Z.M. Subin (2014), Exploring the relationship between peatland net carbon balance and apparent carbon accumulation rate at century to millennial time scales, *Holocene*, *24*(9), 1167–1173, doi:10.1177/0959683614538078.

Gallego-Sala, A. V., and C. Prentice (2012), Blanket peat biome endangered by climate change, *Nat. Clim. Change*, *3*, 152–155, doi:10.1038/nclimate1672.

Gatis, N., D. J. Luscombe, E. Grand-Clement, I. P. Hartley, K. Anderson, D. Smith, and R. E. Brazier (2016), The effect of drainage ditches on vegetation diversity and CO_2 fluxes in a *Molinia caerulea*-dominated peatland, *Ecohydrology*, *9*, 407–420, doi:10.1002/eco.1643.

Helfter, C., C. Campbell, K. J. Dinsmore, J. Drewer, M. Coyle, M. Anderson, U. Skiba, E. Nemitz, M. F. Billett, and M. A. Sutton (2015), Supplement of drivers of long-term variability in CO_2 net ecosystem exchange in a temperate peatland, *Biogeosciences*, *12*, 1799–1811, doi:10.5194/bg-12-1799-2015-supplement.

Hogg, E. H. (1993), Decay potential of hummock and hollow *Sphagnum* peats at different depths in a Swedish raised bog, *Oikos*, *66*(2), 269–278.

Holden, J. (2005a), Controls of soil pipe frequency in upland blanket peat, *J. Geophys. Res.*, *110*, F01002, doi:10.1029/2004JF000143.

Holden, J. (2005b), Piping and woody plants in peatlands: Cause or effect?, *Water Resour. Res.*, *41*, W06009, doi:10.1029/2004WR003909.

Holden, J., and T. P. Burt (2002), Piping and pipeflow in a deep peat catchment, *Catena*, *48*(3), 163–199, doi:10.1016/S0341-8162(01)00189-8.

Holden, J., T. P. Burt, and N. J. Cox (2001), Macroporosity and infiltration in blanket peat: The implications of tension disc infiltrometer measurements, *Hydrol. Processes*, *15*(2), 289–303, doi:10.1002/hyp.93.

Holden, J., M. G. Evans, T. P. Burt, and M. Horton (2006), Impact of land drainage on peatland hydrology, *J. Environ. Qual.*, *35*(5), 1764–1778, doi:10.2134/jeq2005.0477.

Holden, J., Z. E. Wallage, S. N. Lane, and A. T. McDonald (2011), Water table dynamics in undisturbed, drained and restored blanket peat, *J. Hydrol.*, *402*, 103–114, doi:10.1016/j.jhydrol.2011.03.010.

Hooijer, A., S. Page, J. G. Canadell, M. Silvius, J. Kwadijk, H. Wosten, and J. Jauhiainen (2010), Current and future CO_2 emissions from drained peatlands in Southeast Asia, *Biogeosciences*, *7*(5), 1505–1514, doi:10.5194/bg-7-1505-2010.

Hooijer, A., S. Page, J. Jauhiainen, W. A. Lee, X. X. Lu, A. Idris, and G. Anshari (2012), Subsidence and carbon loss in drained tropical peatlands, *Biogeosciences*, *9*, 1053–1071, doi:10.5194/bg-9-1053-2012.

Ingram, H. A. P. (1978), Soil layers in mires: Function and terminology, *J. Soil Sci.*, *29*, 224–227, doi:10.1111/j.1365-2389.1978.tb02053.x

Kurnianto, S., M. Warren, J. Talbot, B. Kauffman, D. Murdiyarso, and S. Frolking (2015), Carbon accumulation of tropical peatlands over millennia: A modeling approach, *Global Change Biol.*, *21*(1), 431–444, doi:10.1111/gcb.12672.

Lapen, D. R., J. S. Price, and R. Gilbert (2005), Modelling two-dimensional steady-state groundwater flow and flow sensitivity to boundary conditions in blanket peat complexes, *Hydrol. Processes*, *19*(2), 371–386, doi:10.1002/hyp.1507.

Leifeld, J., M. Steffens, and A. Galego-Sala (2012), Sensitivity of peatland carbon loss to organic matter quality, *Geophys. Res. Lett.*, *39*, L14704, doi:10.1029/2012GL051856.

Lewis, C., J. Albertson, X. Xu, and G. Kiely (2012), Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope, *Hydrol. Processes*, *26*(10), 1527–1537, doi:10.1002/hyp.8252.

Lindsay, R. A., D. J. Charman, F. Everingham, R. M. O'Reilly, M. A. Palmer, T. A. Rowell, and D. A. Stroud (1988), *The Flow Country—The Peatlands of Caithness and Sutherland*, edited by D. A. Ratcliffe and P. H. Oswald, JNCC, Peterborough, U. K.

Maljanen, M., B. D. Sigurdsson, J. Guömundsson, H. Öskarsson, J. T. Huttunen, and P. J. Martikainen (2010), Greenhouse gas balances of managed peatlands in the Nordic countries present knowledge and gaps, *Biogeosciences*, *7*(9), 2711–2738, doi:10.5194/bg-7-2711-2010.

Menberu, M. W., T. Tahvanainen, H. Marttila, M. Irannezhad, A.-K. Ronkanen, J. Penttinen, and B. Kløve (2016), Water-table-dependent hydrological changes following peatland forestry drainage and restoration: Analysis of restoration success, *Water Resour. Res.*, *52*, 3742–3760, doi:10.1002/2015WR018578.

Moore, S., C. D. Evans, S. E. Page, M. H. Garnett, T. G. Jones, C. Freeman, A. Hooijer, A. J. Wiltshire, S. H. Limin, and V. Gauci (2013), Deep instability of deforested tropical peatlands revealed by fluvial organic carbon fluxes, *Nature*, *493*, 660–664, doi:10.1038/nature11818.

Morris, P. J., A. J. Baird, and L. R. Belyea (2012), The DigiBog peatland development model 2: Ecohydrological simulations in 2D, *Ecohydrology*, *5*(3), 256–268, doi:10.1002/eco.229.

Morris, P. J., A. J. Baird, D. M. Young, and G. T. Swindles (2015a), Untangling climate signals from autogenic changes in long-term peatland development, *Geophys. Res. Lett.*, *42*, 10,788–10,797, doi:10.1002/2015GL066824.

Morris, P. J., A. J. Baird, and L. R. Belyea (2015b), Bridging the gap between models and measurements of peat hydraulic conductivity, *Water Resour. Res.*, *51*, 5353–5364, doi:10.1002/2015WR017264.

Page, S. E., and A. Hooijer (2016), In the line of fire: The peatlands of Southeast Asia, *Philos. Trans. R. Soc. B*, *371*, 20150, doi:10.1098/rstb.2015.0176.

Parry, L. E., J. Holden, and P. J. Chapman (2014), Restoration of blanket peatlands, *J. Environ. Manage.*, *133*, 193–205, doi:10.1016/j.jenvman.2013.11.033.

Price, J. S., A. L. Heathwaite, and A. J. Baird (2003), Hydrological processes in abandoned and restored peatlands: An overview of management approaches, *Wetl. Ecol. Manag.*, *11*(1–2), 65–83, doi:10.1023/A:1022046409485.

Robroek, B. J. M., J. Limpens, A. Breeuwer, and M. G. C. Schouten (2007), Effects of water level and temperature on performance of four Sphagnum mosses, *Plant Ecol.*, *190*(1), 97–107, doi:10.1007/s11258-006-9193-5.

Schimelpfenig, D. W., D. J. Cooper, and R. A. Chimner (2013), Effectiveness of ditch blockage for restoring hydrologic and soil processes in mountain peatlands, *Restor. Ecol.*, *22*(2), 257–265, doi:10.1111/rec.12053.

Swindles, G. T., P. J. Morris, J. Wheeler, M. Smith, K. L. Bacon, T. E. Turner, A. Headley, and J. M. Galloway (2016), Resilience of peatland ecosystem services over millennial timescales: Evidence from a degraded British bog, *J. Ecol.*, *104*, 621–636, doi:10.1111/1365-2745.12565.

Talbot, J., P. J. H. Richard, N. T. Roulet, and R. K. Booth (2010), Assessing long-term hydrological and ecological responses to drainage in a raised bog using paleoecology and a hydrosequence, *J. Veg. Sci.*, *21*(1), 143–156, doi:10.1111/j.1654-1103.2009.01128.x.

Tallis, J. H. (1985), Mass movement and erosion of a southern Pennine blanket peat, *J. Ecol.*, *73*(1), 283–315, doi:10.2307/2259784.

Tipping, R. (1995), Holocene evolution of a lowland Scottish landscape: Kirkpatrick Fleming. Part I, peat and pollen-stratigraphic evidence for raised moss development and climatic change, *Holocene*, *5*(1), 69–81, doi:10.1177/095968369500500108.

Turetsky, M. R., B. Benscoter, S. Page, G. Rein, G. R. Van Der Werf, and A. Watts (2015), Global vulnerability of peatlands to fire and carbon loss, *Nat. Geosci.*, *8*, 11–14, doi:10.1038/ngeo2325.

Waddington, J. M., P. J. Morris, N. Kettridge, G. Granath, D. K. Thompson, and P. A. Moore (2015), Hydrological feedbacks in northern peatlands, *Ecohydrol.*, *8*(1), 113–127, doi:10.1002/eco.1493.

Wallage, Z. E., and J. Holden (2011), Near-surface macropore flow and saturated hydraulic conductivity in drained and restored blanket peatlands, *Soil Use Manage.*, *27*(2), 247–254, doi:10.1111/j.1475-2743.2011.00336.x.

Williamson, J., E. Rowe, D. Reed, L. Ruffino, P. Jones, R. Dolan, H Buckingham, D. Norris, S. Astbury, and C. D. Evans (2017), Historical peat loss explains limited short-term response of drained blanket bogs to rewetting, *J. Environ. Manage.*, *188*, 278–286, doi:10.1016/j.jenvman.2016.12.018.

Wilson, L., J. Wilson, J. Holden, I. Johnstone, A. Armstrong, and M. Morris (2010), Recovery of water tables in Welsh blanket bog after drain blocking: Discharge rates, time scales and the influence of local conditions, *J. Hydrol.*, *391*(3–4), 377–386, doi:10.1016/j.jhydrol.2010.07.042.

Wösten, J. H. M., A. B Ismail, and A. L. M. van Wijk (1997), Peat subsidence and its practical implications: A case study in Malaysia, *Geoderma*, *78*, 25–36, doi:10.1016/S0016-7061(97)00013-X.