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Key Points:

- Simulations of a blanket peatland continue accumulating carbon until 2100 under all climate scenarios
- Topographic wetness correlates with peat thickness but does not fully explain accumulation patterns in blanket peatland landscapes
- Process-based ecohydrological models can better assess peatland carbon fate than simpler approaches by accounting for accumulation rates and spatial patterns

Supporting Information:

Supporting Information may be found in the online version of this article.

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Assessing the Response of Blanket Peatlands to Climate Change Using the DigiBog Model and Winter's Concept of the "Hydrologic Landscape"

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Abstract Peatlands are important global carbon stores, but it is unclear whether they will continue as carbon sinks under future climates, or degrade, leaking carbon to the atmosphere. We used the DigiBog peatland development model to explore this question for a blanket peatland in Glen Affric, Scotland, investigating how topography and climate have affected net peat accumulation across this complex landscape. DigiBog accurately captured spatial variation in measured modern peat thickness (Lin's Concordance Correlation Coefficient = 0.86). As expected, peat accumulated to greater depths in topographic basins compared to slopes and drainage divides over the Holocene. Simulations of the future suggest the study site will continue accumulating peat until 2100 CE under all Representative Concentration Pathways. However, DigiBog predicts greatest future peat accumulation away from basins, continuing a trend observed over the last c. 2000 years. We also tested Winter's (2000), https://doi.org/10.1111/j.1752-1688.2000.tb04269.x conceptual model, which proposes that wetland vulnerability to climate change depends on position in the hydrologic landscape, by comparing peat thickness with the Topographic Wetness Index. While correlations were moderate to strong, our finding of greater recent accumulation away from basins contradicts Winter's model's predictions. Additionally, DigiBog shows that thin (<40 cm) hillslope peats persisted throughout the Holocene despite drier climatic phases, rather than experiencing complete loss and re-establishment cycles. We conclude that process-based ecohydrological models like DigiBog can complement simpler modeling approaches and should be used when assessing rates and spatial patterns of peat accumulation and loss in response to 21st Century climate change.

1. Introduction

Peatlands are globally-important ecosystems and carbon (C) stores. Through the Holocene, they have accumulated more than 600 Gt C (Dargie et al., 2017; Page et al., 2011; Yu et al., 2010) and have had a net cooling effect on climate (Frolking et al., 2006). The build up of peat in these wetlands is due to waterlogging, which prevents the rapid decay of organic matter (Page & Baird, 2016). Net C accumulation in, or sometimes loss from, these systems depends on climate and a network of feedbacks between vegetation, water-table dynamics, peat decay, and peat physical properties. In isolation, these feedbacks cannot reveal whole-peatland behavior, which is why, to varying degrees, the processes behind them have been brought together in computer models of peatland development such as the Holocene Peat Model (HPM), MILLENNIA, MPeat/MPeat2D, and DigiBog (e.g., Frolking et al., 2010; Heinemeyer et al., 2010; Mahdiyasa et al., 2023; Morris et al., 2015; Ramirez et al., 2023; Treat et al., 2021; Young et al., 2021, 2023).

How a peatland functions will also depend on its topographical and geological setting. Winter (2000) used the concept of a "hydrologic landscape" to consider how supplies of ground, surface and atmospheric water combine to affect a wetland's "vulnerability" during dry periods ranging from months to decades and centuries. Winter (2000) did not define vulnerability in his paper; it can, however, be considered in terms of a wetland's ecohydrological functioning and ecosystem services, including carbon storage and uptake. A vulnerable peatland may switch from a carbon sink during wetter conditions to a source during drier periods. As such, it may be expected to have thinner peat than non-vulnerable peatlands. Winter (2000) argued that highly-vulnerable wetlands are located near slope divides and are dependent primarily on precipitation for their water supply, whereas

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those at the base of slopes that also receive discharges from regional groundwater flow systems will be less affected by droughts or sustained climatic drying.

We explored the importance of the hydrologic landscape to the past and future development of a blanket peatland in Glen Affric in the Highlands of Scotland using a modeling approach. Blanket peatlands are found in high-latitude oceanic and hyper-oceanic regions where precipitation (mostly rainfall) is usually abundant throughout the year (Gallego-Sala & Prentice, 2013; Lindsay, 2010; Supporting Information S1). They often occur on poorly-permeable rocks or sediments, so receive little water from regional groundwater systems, and are primarily dependent on precipitation for their water supply. They might, therefore, be classified as vulnerable to drought and changes in climate in Winter's scheme. However, because they cover entire landscapes, some parts of a blanket peatland will receive or retain substantially more water than other parts. In the simplest case, blanket peat toward the base of a hillslope will receive direct precipitation and any surplus precipitation (precipitation minus evapotranspiration) from upslope parts of the peatland, via both surface and subsurface (within-peat) flow. Following Winter's model, as explained in the previous paragraph, we would expect downslope parts of these peatlands to be less vulnerable and, therefore, thicker than higher up the slope.

Our study had two aims. First, we wished to test how well the DigiBog peatland development model was able to simulate the effects of past climate change and topography on net gains and losses of peat across a complex blanket peatland landscape in Glen Affric. This testing also allowed us to consider how the peatland might respond to future changes in climate. Second, by using field data, and outputs from DigiBog, we tested how well Winter's simple model could explain variations in peat thickness; we did so by comparing peat thickness with the Topographic Wetness Index (TWI), which we used as an indicator of vulnerability.

2. Model and Data

2.1. DigiBog and the Modeled Landscape

DigiBog is an ecohydrological model that simulates peatland development over time. It has been applied in a range of environments, from boreal (Ramirez et al., 2023), to temperate (Young et al., 2021), to tropical (Young et al., 2023), and is able to successfully replicate peat core data (e.g., Young et al., 2023). It was chosen here because it explicitly represents water movement through peat, which means it can simulate variations in soil wetness and water-table dynamics across a landscape. This capability is not available in models such as HPM and MILLENNIA. In the model, peat may accumulate during periods when conditions are favorable. A net loss of peat is also possible when the rate of new plant litter addition to the peatland is less than the rate of decay through the peat profile. In DigiBog, peatlands are represented as multiple abutting columns of peat, with each column made up of layers of peat. The version of DigiBog used here is the same as described by Young et al. (2017) but with an important update: in the more decomposed parts of the peat profile, adjacent layers of peat are lumped together, so that down-profile variations in peat properties are represented by up to a few hundred layers instead of several thousand, speeding up model run times (see Young et al., 2019). The masses and thicknesses of adjacent layers are combined if the layers are less than a user-specified thickness. The age of the new layer is calculated as a weighted average of the ages of the combined layers.

In the model, newly-produced plant litter is added annually to the top of each column, thereby becoming part of the peat profile. The rate of new litter production is a function of annual average air temperature and annual average water-table depth. The peat comprising each column decays according to its position relative to the water table (oxic decay above, anoxic below). Decay is also affected by temperature (a Q_{10} function is used). The oxic zone is assumed to track weekly temperature variations, whereas the anoxic zone is assumed to be represented by annual average temperatures. Water-table dynamics are simulated using a version of the Boussinesq equation for groundwater flow (Baird et al., 2012). Hydraulic conductivity in DigiBog depends on the degree of peat decomposition and can vary vertically through the peat profile and laterally between neighboring columns.

We applied DigiBog to a 360-m transect of blanket bog centered at 57.2415°N, 5.1010°W and running approximately northwest to southeast between the hills Cnoc Fada and Torran Beithe, near Loch Coulavie in west Glen Affric, Scotland (Figure 1). The transect comprises peat overlying poorly-permeable rocks (Tisdall, 2003); it varies between 259 and 278 m above sea level (UK Ordnance Datum), and its lowest point is an infilled basin, from which water flows south west and north east, approximately perpendicular to our transect. Our model is 2-dimensional and does not simulate flow across the transect, only along it. The stream running northeast is known

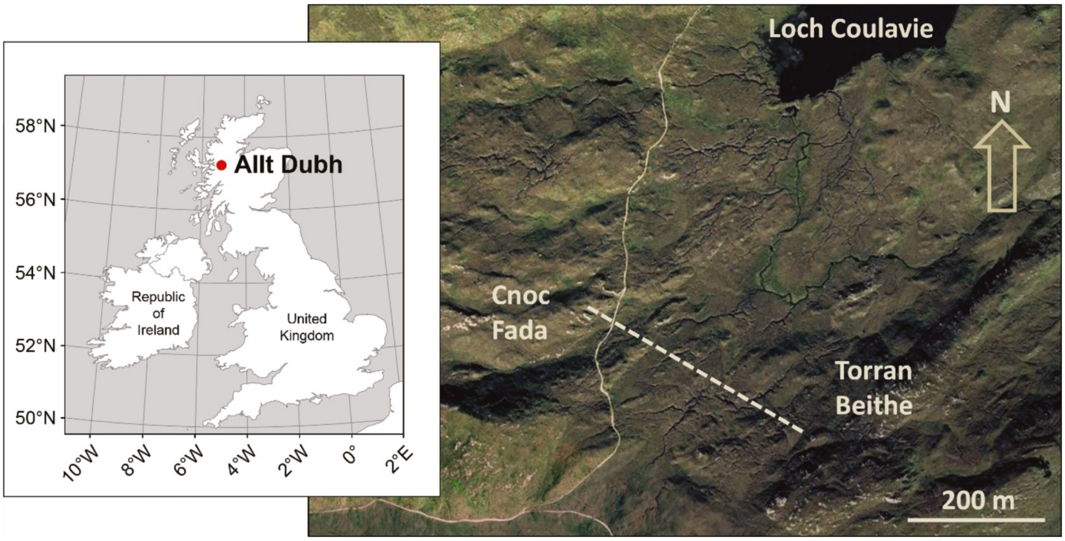

Figure 1. Location of the Allt Dubh transect (dashed line). Background aerial image credit: Getmapping from Google Earth. Inset shows site location within the United Kingdom.

as the Allt Dubh ("black stream") and is the name we use henceforth for the transect. The Allt Dubh transect was chosen because it has been the subject of previous study: peat thicknesses and ^{14}C-dated basal ages along the transect have been measured at 26 and eight locations respectively (R. M. Tipping et al., 2003; R. Tipping, 2008; Table S1-1 in Supporting Information S1). The Allt Dubh transect also contains many of the topographic features typical of blanket peatlands that affect the movement and storage of water, such as variations in slope angle, breaks in slope, convex and concave slopes, depressions (basins), and a mostly flat central area (the main basin) into which two opposing slopes drain (Figure 2). In combination, these make it particularly suitable for testing Winter's model. Due to an error in the original calculation of the transect profile, the altitudes we used are different from those shown in R. Tipping (2008). The corrected values are given Table S1-1 in Supporting Information S1, which we interpolated using the pracma (Borchers, 2022) function "interp1" in R (R Core Team, 2022) to produce a continuous surface that was discretized into 45 8 × 8 m peat columns (Figure 2a) for the application of DigiBog. The model boundaries at 0 and 360 m were set to no-flow conditions to represent drainage divides.

Along the Allt Dubh transect, peat depths were subtracted from the ground-level elevations to provide a mineral surface in DigiBog upon which simulated peat could accumulate. The simulation was set to start at 10,500 BP (early Holocene) because that is (approximately) the oldest peat basal age found along the transect (R. Tipping, 2008) (details of the basal ages along the transect are given in Figure 2a in the Results; see also Section 3.2 and Table S1-1 in Supporting Information S1).

DigiBog includes a water-holding or "ponding" layer on top of each column of peat so that water can be stored on the peatland surface. Any water that exceeds the depth of the pond is lost from the model domain like overland flow. We tuned the ponding layer in the main basin (Figure 2a) to achieve peat thicknesses comparable to the observations from the site. By setting the pond to 0.08 m, water flowing from upslope columns and net precipitation were allowed to build up in the way described by Winter (2000). We could have further modified pond thicknesses across the landscape to create a closer match between our simulation and observations, but this was not our aim and could have led to overfitting. For the remaining parameter values, we used those shown in Table S1-2 (Supporting Information S1), which show some overlap with the values used in previous DigiBog simulations (e.g., Morris et al., 2012; Young et al., 2017).

Ideally, we would also have had detailed peat core information (e.g., downcore peat ages, peat humification, and water-table proxies—Booth et al., 2010; Chambers et al., 2011; Piotrowska et al., 2011) for multiple locations across the transect to compare with DigiBog's outputs, but we are not aware of any studies that contain this level of detail for this site or others in the UK.

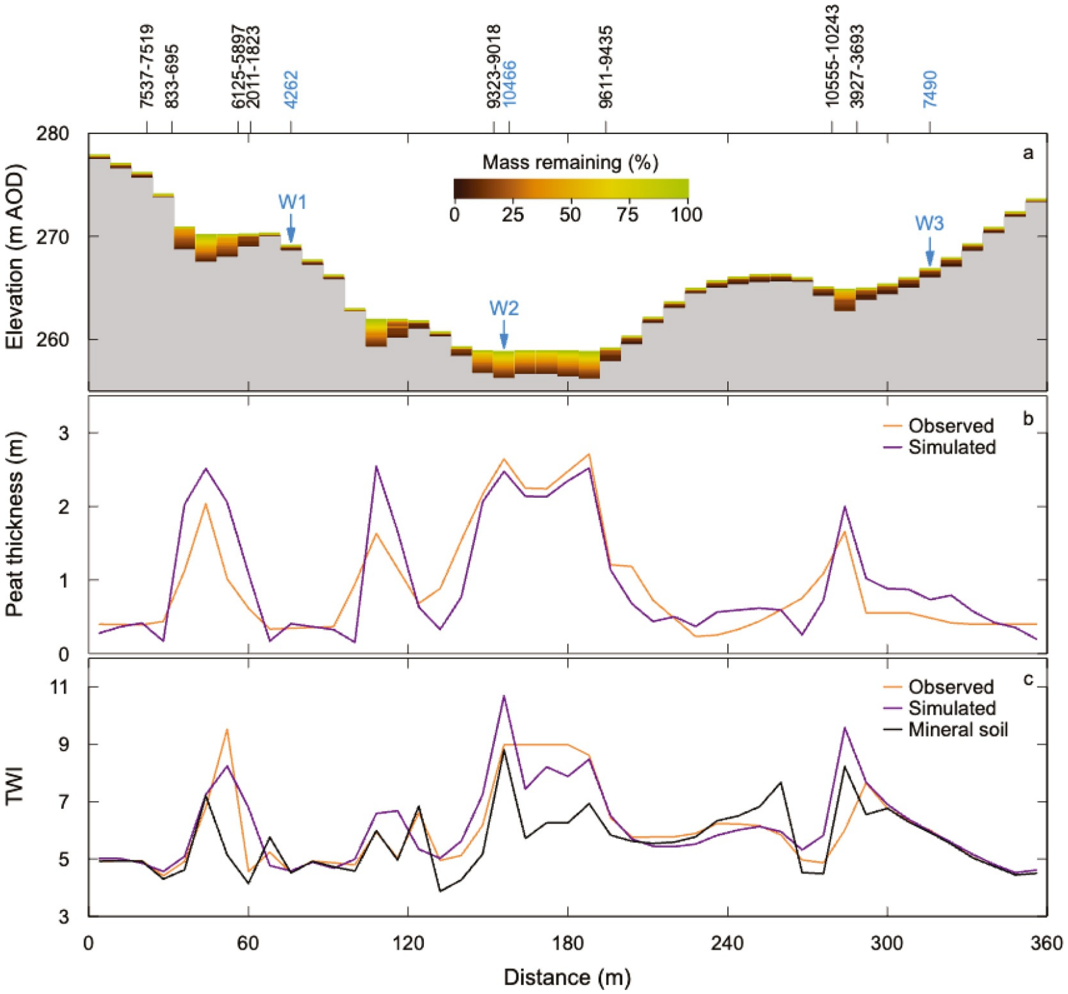

Figure 2. Observed and modeled peat across the Allt Dubh transect from Cnoc Fada (left) to Torran Beithe (right) (see Figure 1). (a) Simulated peat thickness and proportion of original mass remaining in each peat column. Darker colors indicate the peat is more decomposed (less original peat mass remaining). W1, W2 and W3 are watchpoints discussed later, with data from them shown in Figure 4. The numbers at the top of the plot are the measured (black) and modeled (blue—shown for the watchpoints only) basal dates. (b) Observed and simulated peat thicknesses. (c) Topographic Wetness Index for the observed and simulated peat surface and for the top of the mineral surface underlying the peat.

Finally, as we show later, peat formed synchronously across the modeled landscape from the start of the simulation, but rates of net accumulation varied according to topographic setting, with substantial differences in peat thickness between thin peat on some slopes and thick peat in the basins. Peat initiation in the model is not forced or pre-determined; modeled peat will only accumulate if litter production by plants exceeds decay of previous cohorts of litter/peat. The significance of the synchronous modeled initiation of peat across the transect is considered in Section 3.2 and Section 4.

2.2. Past and Future Climates Driving DigiBog

We constructed time series of air temperature and net precipitation (precipitation minus evapotranspiration, cm yr^{-1}) to drive DigiBog, running for 10,650 years from the early Holocene (10.5 ka BP), through to 0 BP (i.e., 1950 CE), and then on to 2100 CE under four Representative Concentration Pathway scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). The numbers in each RCP name relate to the projected increase in radiative forcing, measured in W m^{-2}, between 1750 CE (considered pre-industrial) and 2100 CE. RCP2.6 is the lowest-magnitude scenario, in terms of both anthropogenic emissions and warming, commonly used; while RCP8.5 is the highest magnitude scenario. Our choice of scenarios therefore covers a large range of possible future climates.

We generated four climate series, one for each RCP. The four series have identical Holocene climates between 10.5 ka and 0 BP (1950 CE), and diverge from one another between 0 BP and 2100 CE according to the four RCPs. Each time series consists of a sequence of four component phases which we joined together to form a continuous series of smooth, mainly slowly-changing climate, lacking realistic inter- and intra-annual variability. We used a weather generator model, calibrated for the 1961–1990 observed climate data, to add realistic inter- and intra-annual variability to all phases of the temperature and net rainfall series.

For the period 10.5 ka to 0 BP, we used equilibrium-type climate hindcasts from the UK Met Office Hadley Centre's HadCM3 coupled atmosphere-ocean general circulation model with dynamic vegetation (Gordon et al., 2000; Pope et al., 2000; Valdes et al., 2017) to simulate long-term changes in local palaeoclimate at our study site at 500-year timesteps. HadCM3 is forced by boundary conditions, updated every 500 simulated years, that include orbitally-determined solar insolation, atmospheric greenhouse gas concentrations, ice-sheet characteristics, and associated palaeogeographies. The boundary conditions are broadly consistent with the PMIP4 protocol for 23–0 ka BP (Ivanovic et al., 2016), but are held constant in time for each 500-year equilibrium-type hindcast and do not include freshwater forcing. We downscaled monthly and annual climate means from the model's native resolution (3.75° longitude × 2.5° latitude) to a 0.5° × 0.5° grid using bi-cubic spline interpolation, and regionally bias-corrected the climate simulations using instrumental climate data for the period 1961–1990 CE (New et al., 1999). These simulations provide monthly and annual average air temperature and total precipitation at 500-year intervals for 0.5° × 0.5° spatial grid cells. The grid cell that contains the Allt Dubh transect is centered on 57.25°N, 5.25°W. Morris et al. (2018) provide a full description of the HadCM3 paleoclimate simulations used here. We interpolated all climate variables linearly between HadCM3's steady-state 500-year intervals to provide an annual series. The HadCM3 data do not include representations of abrupt changes in climate at sub-Milankovitch timescales, such as the 8.2 ka BP event, Roman warming, the Medieval climate anomaly, or the Little Ice Age. Evidence for these past climatic episodes is sometimes recorded in peat stratigraphy, and DigiBog can simulate a peatland's response to such events (Morris et al., 2015). However, as noted in Section 2.1, we lacked the peat core data to undertake a detailed model-data comparison. Therefore, we sought instead to validate, in a broader sense, the model's simulation of Holocene peat accumulation to the current day and used this to help understand the vulnerability of different parts of the peatland to future climate changes and according to their landscape setting.

Between 1951 and 1965 CE, we assumed that monthly and annual climate means, and between-month standard deviations, were stationary at the study site, equal to observed statistics for the period 1961 to 1990 CE, based on the hourly ERA5 product (Hersbach et al., 2020). Between the years 1966 and 2000 CE, we forced temperature and net precipitation to follow observed trends by linearly increasing temperature, and adjusting precipitation, on decadal time intervals in all four climate time series. Doing so provided a seamless join between the palaeoclimate time series and the beginning of the RCP scenarios.

For the final—mostly future—part of the time series between 2001 and 2100 CE, we used the UKCP18 (United Kingdom Climate Projections: https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index) future climate projections. These simulations provide projected changes in annual and monthly mean temperature and net precipitation (Figure S2-1 in Supporting Information S1).

We then used the AWE-GEN weather generator model (Fatichi et al., 2011, 2021) to add realistic inter- and intra-annual variability to the interpolated time series. Although all four component phases of the time series contain a seasonal cycle, with monthly values of temperature and net precipitation, they lack realistic, stochastic seasonal and inter-annual variability. AWE-GEN reads in observational weather data for a calibration period (1961–1990 in our case; Hersbach et al., 2020), for which climatic variability is characterized and parameterized at hourly, monthly and annual scales. The method preserves the co-correlation between temperature and net precipitation, and produces realistic weekly, seasonal and inter-annual variabilities (Peleg et al., 2019). AWE-GEN then superimposes this inter- and intra-annual variability onto the longer, smooth time series of simulated climate.

The hourly time series of temperature and net precipitation produced by AWE-GEN were aggregated to coarser temporal scales to drive DigiBog. In the version of DigiBog used here, net precipitation (always assumed to be net rainfall) is read into the simulation on a weekly timestep, while air temperature is read in both weekly (for oxic decay only) and annually (for plant production and anoxic decay). As noted above (Section 2.1), we assumed that the temperature of oxic peat would respond to weekly changes in air temperature, and that the temperature of anoxic (mostly deeper) peat would respond to annual variations.

2.3. Peatland Development and the Hydrologic Landscape

To provide a formal test of Winter's conceptual model, we investigated whether the TWI provided a good indication of peat thickness across the measured and modeled landscape. TWI is a measure of water accumulation on slopes and was first proposed by Beven and Kirkby (1979). It is given by:

$$\mathrm{TWI} = \ln(\alpha / \tan \beta)$$

where α is the upslope area draining through a unit length of contour, and $\tan \beta$ is the local gradient. If Winter's model applies, we would expect areas with higher values of TWI to have thicker peat than areas with lower TWI values.

3. Results

3.1. Landscape Controls on Peat Thickness and Peatland Development Along the Allt Dubh Transect

DigiBog's simulation of peat accumulation across the Allt Dubh transect is mostly in good agreement with observations of peat thickness (Figure 2). Lin's Concordance Correlation Coefficient (Lin, 1989) was 0.86 (0.77–0.92, 95% CI) while observed thickness regressed on simulated thickness (in meters) (Piñeiro et al., 2008) gave observed = 0.9526 × simulated + 0.0897 ($r^2 = 0.75$). In general, measured and modeled peat at topslope and midslope locations is thinner than that at the base of slopes or in hillslope basins (Figure 2b), and modeled peat in the basins is better preserved (less decomposed) than the peat elsewhere along the transect (Figure 2a).

Figures 2b and 2c suggest a broad correspondence between peat thickness and TWI (see also Figure 3). A regression of observed peat thickness versus the TWI for the observed peat surface yielded an r^2 value of 0.45, which rose to 0.67 for simulated peat thickness versus the TWI for the simulated peat surface. The r^2 is 0.15 for observed peat thickness versus mineral surface TWI and 0.23 for simulated peat thickness versus mineral surface TWI (Figure 3).

3.2. Basal Ages Across the Allt Dubh Transect and Modeled Peat Accumulation History in Different Landscape Features

The basal peat in the Allt Dubh transect varies substantially in measured age between landscape features. For example, from 10,555 to 10243 cal BP in one of the basins to 833–695 cal BP on the steepest slope in the transect (Figure 2a, Table S1-1 in Supporting Information S1). The modeled data likewise show considerable variability in basal age between different landscape features (Figures 4a and 4b). However, measured basal ages also show high variability within landscape features such as the basin at ∼280 m along the transect (Figure 2a). Although DigiBog produces a wide range of basal dates, only three, perhaps four, out of eight correspond reasonably closely to the measured dates (Figure 4c).

The modeled peat accumulation history varies substantially across the different landscape elements (Figure 4a) represented by the three watch points (W1–W3) shown in Figure 2. There is a monotonic increase in modeled peat thickness in the main basin (W2), although the rate of increase declines over time. For the topslope and midslope watch points (W1 and W3) the rate of increase in peat thickness is generally much lower and the peat in both locations remains thin (<40 cm) for millennia. Both locations also experience net loss of peat (a thinning of the peat) several times during the simulation, notably between 3 and 2 ka BP.

DigiBog predicts a continuous presence of peat at all three locations from 10.5 ka BP (Figure 4b), but, despite this, the age-depth curves for W1 and W3 show much younger basal dates of 4262 BP and 7490 BP respectively (Figure 4a; see also Figure 2a). We explain this apparent anomaly in the Discussion.

3.3. The Allt Dubh Transect Under Future Climates

Under all RCPs, DigiBog predicts a net accumulation of peat across all of the landscape (Figure 5). The rates of accumulation are highly variable across the transect, and some areas that Winter (2000) would class as vulnerable, such as steeper slopes, are predicted to gain more peat than areas that would not be classed as vulnerable such as the main basin in the center of the transect.

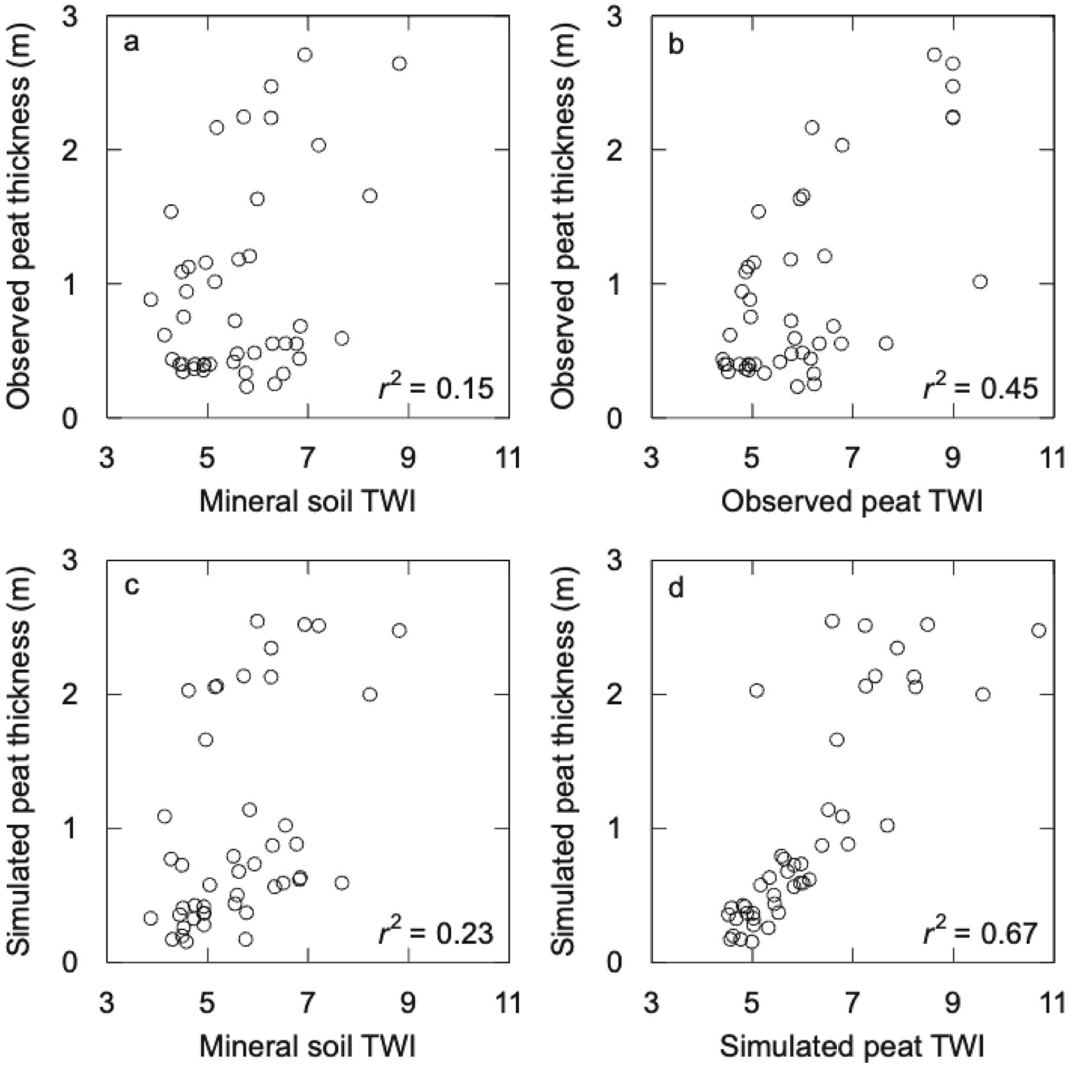

Figure 3. Observed and modeled peat thickness versus the Topographic Wetness Index for the observed (a and b) and simulated (c and d) peat thicknesses in the Allt Dubh transect.

4. Discussion

DigiBog accurately predicts peat thickness across the Allt Dubh transect (as demonstrated by high values of Lin's Concordance Correlation Coefficient (Lin, 1989)). The model does not consistently over- or under-predict peat thickness across the landscape, which may be taken to mean that it does not have any obvious bias. This lack of bias is also reflected in the high concordance correlation value, and the success of the model in this regard suggests it can be used to explore blanket peatland response to future climate change (Figure 5; see below).

The depth-TWI relationships (Figure 3) suggest (but see below this section) that Winter's model is moderately useful for identifying vulnerability in blanket peatlands. It is notable that the depth-TWI relationship is better when the TWI of the contemporary surface is used rather than the TWI of the underlying mineral surface. As the elevation of the ground surface changes in response to peat accumulation, so does the TWI. For example, steep, reasonably well-drained slopes on the sides of basins with relatively low TWIs, can become buried by the growing peat, which tends to flatten the gradient and increase the TWI (Figure 2). In other words, the presence of a peatland makes the landscape wetter. It is notable too that there is a cluster of thin peats with relatively high values of TWI (Figure 3b) indicating a poor relationship between the two in some parts of the peatland. The explanation may lie in the mineral status of water flowing down the hillslope. Even on impermeable rocks such as those found on the transect, some water flowing downslope through the base of the peat may acquire a "mineral signature" via

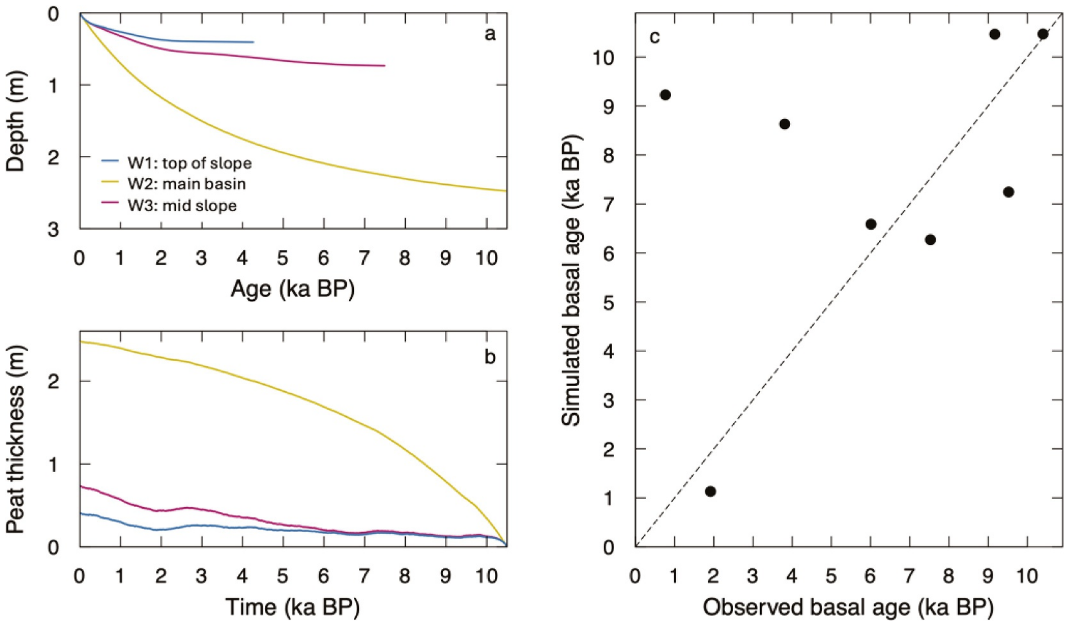

Figure 4. Modeled age-depth curves (a) and annually-resolved peat thickness (b) for the three watchpoints (Figure 2a) on the Allt Dubh transect. (c) Simulated versus observed basal ages (dashes denote the 1:1 line).

dissolution of the rock. The mineral load in the water may be sufficient to reduce rates of peat formation by increasing rates of peat decay (e.g., Ehnvall et al., 2025). DigiBog doesn't explicitly simulate the mineral status of the water or its effect on peat decay, and this omission may partly explain why the model overpredicts peat thickness in three of the four basins which might be expected to be sinks for dissolved minerals. Despite this omission, decay rates can be adjusted in DigiBog and other models such as HPM to reflect a mineral influence (e.g., Frolking et al., 2010). However, as we explain later in this section when discussing differences in peat accumulation between the basins and slopes, a lack of correspondence between both measured and modeled thickness and TWI may also be because of complex eco-hydrological interactions.

Peatland basal dates are usually taken to be the initiation date—the date peat started forming at the location of a peat core. In a landscape like the Allt Dubh, peat may be expected to form first in wetter parts of the landscape

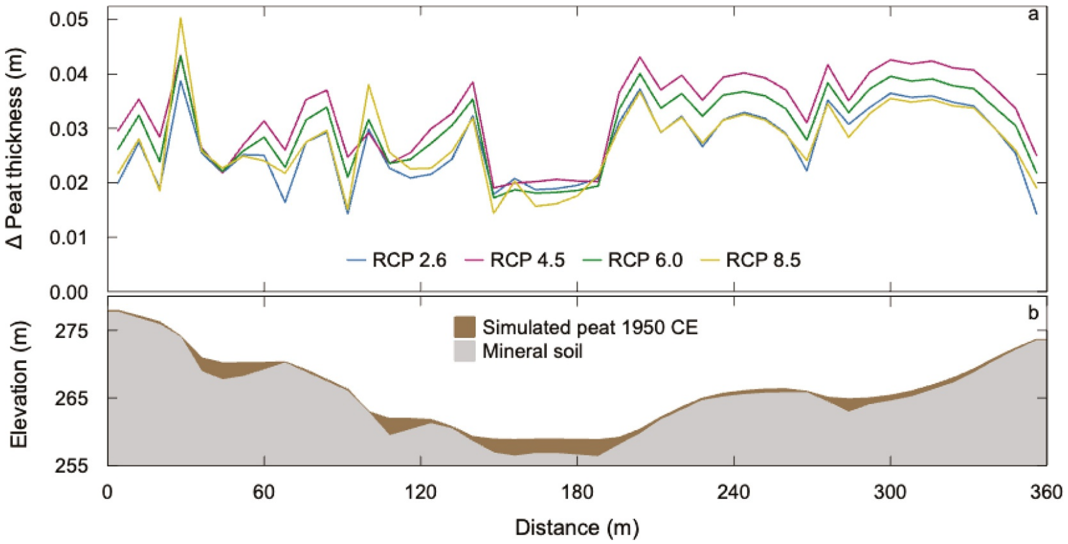

Figure 5. The effect of climate change on peat thickness across the Allt Dubh transect. (a) Changes in peat thickness by 2100 CE. (b) Simulated peat thickness at 1950 CE.

such as basins. Younger basal dates may arise when peat spreads upslope from basins after peat has formed in those locations first. Alternatively, younger basal dates may occur because thinner peat on the slopes has been completely lost through decomposition during droughts, with new peat re-establishing later in its place when conditions allowed. We have too few measurements to determine whether basal dates get progressively younger away from the basins along the Allt Dubh transect (Figure 2a). In DigiBog, peat started forming from 10,500 BP across all of the Allt Dubh transect and has been ever-present since then, so the same basal date should apply everywhere in the model's outputs. Figure 4b shows continuous peat cover at the three watch points in contrasting topographic locations. Such a continuous presence of peat is not a DigiBog artifact; complete peat loss is also possible in the model, given the right conditions. Despite the continuous presence of peat in the modeled transect, the simulated basal peat at W1 (topslope) and W3 (midslope) is younger than that in the main basin (W2) (Figures 2a and 4a). Clearly, the two explanations above (peat spreading out from basins, and peat re-establishing after being completely lost) cannot be invoked here. Instead, the following explanation applies. Because basins are in the wettest part of the landscape, and because they quickly develop thick peat (Figure 4b), drought water tables do not reach the basal peat which remains anoxic, decaying very slowly. Where thin peat forms on slopes, the drought year water table can fall to the base of the profile, exposing older peat to more rapid decay. Given enough time and exposure to drought, this ongoing basal decay leads to the complete loss of the oldest peat. Nevertheless, peat remains on the slopes because new litter production is generally able to keep pace with the peat loss or slightly exceed it. This explanation for variations in basal dates is only likely to apply to blanket peatlands like the Allt Dubh where the peat on the slopes remains thin for millennia.

Peat erosion is common in blanket peatlands and can lead to complete peat loss and exposure of the underlying mineral material (e.g., Bragg & Tallis, 2001; M. Evans & Warburton, 2007). Past episodes of peat erosion may not be immediately evident if new peat has later established when conditions allowed. Thus, even if there is no evidence of contemporary erosion, which is the case along our study transect, there may have been past erosion-re-establishment episodes and these may explain the variation in basal dates. A record of peat erosion is often preserved in lacustrine and marine deposits (e.g., Stevenson et al., 1990), where the timing and extent of the erosion can be established through stratigraphic analysis and ^{14}C dating. The sedimentary record from the nearest lake to the Allt Dubh transect—Loch Coulavie (Figure 1)—has been investigated by Tisdall (2003). Cores from the lake contain peat deposits but these are derived from lake-marginal fens, and not from the wider catchment, suggesting erosion has not occurred on the study site and therefore cannot explain the variation in basal dates. Nevertheless, it is worth noting that DigiBog is unable to simulate erosion—in the model complete peat loss of old peat is only possible via in situ decay as discussed above—so it is limited in its application to sites where erosion has not occurred.

Our RCP simulations suggest that the Allt Dubh peatland will be a carbon sink over the next ~80 years. During this time, net rainfall is stable but temperature increases (Figure S2-1 in Supporting Information S1). Net peat accumulation occurs when the rate of litter addition exceeds the depth-integrated decay of the extant peat. The seemingly counter-intuitive result whereby less net peat accumulation occurs in the basins than on some of the hillslopes, is a continuation of a trend shown in the palaeo part of the simulation. Between ~2 ka BP and the present (Figure 4b), the gradient of increasing peat thickness over time is greater for W1 (topslope) and W3 (midslope) than for W2 (basin).

Rates of litter production are low in inundated peats increasing with water-table depth to depths of about 30 cm. Rates of decay also increase with water-table depth, such that net peat accumulation tends to be lowest for inundated conditions, rising to a peak at intermediate water-table depths, and then falling again (Belyea & Clymo, 2001; C. D. Evans et al., 2021; Morris et al., 2012). This relationship helps explain why rates of net peat accumulation are higher on the drier slopes than in the wetter basins (Figure S3-1 in Supporting Information S1) from ~2 ka BP and into the future. Nevertheless, the relationship is complicated by (a) peat thickness below the water table, (b) temperature, which affects litter production and peat decay differently, (c) intra- and inter-annual variations in water-table depth, and (d) peat hydraulic conductivity, which affects subsurface water movement and water-table dynamics and which declines as peat decays. Therefore, it is difficult to identify exactly why the basins accumulate peat at a greater rate than the slopes prior to ~2 ka BP. Nevertheless, these results help show why the relationship between peat thickness and TWI is relatively modest, and why the assumption behind Winter's model—that "wetter is better"—is not always true.

The accumulation of peat across the transect under all RCPs contrasts with the thinning of peat on the slopes between ~3 and 2 ka BP (Figure 4b). The thinning appears to be related to a period of declining temperatures, and also a slight climatic drying (Figure S2-1 in Supporting Information S1). The lower temperatures would cause reductions in litter production and decay. However, the effect of temperature on decay may have been more than offset by deeper water tables (Figure 3-1 in Supporting Information S1) causing a switch from anoxic to oxic decay. Therefore, the decline in peat thickness may have been the result of both a reduction in litter inputs and an increase in decay.

It is widely expected that the area suitable for continued peatland development in temperate environments will shrink as the climate changes (e.g., Gallego-Sala & Prentice, 2013). Some statistical bioclimatic envelope models (BEMs) predict that, by 2080, the Allt Dubh transect will remain within the climatic envelope for blanket peatlands in accordance with our results, while others suggest it will lie outside (see Ferretto et al., 2019). These alternative outcomes arise from differences in the BEMs themselves and not because of the uncertainties in the future climates used to drive them. Although useful in showing where peatlands may be at risk in future, BEMs are not designed to simulate peatland carbon balance. They cannot account for how much carbon stocks will increase in areas that remain within the shrinking envelope, or the speed with which peatlands outside the envelope will lose their carbon. The latter may take many decades, and peatlands may undergo internal changes and feedbacks that allow them to stabilize under a new climatic regime (Belyea, 2009; Swindles et al., 2012). Therefore, we recommend that landscape-scale peatland development models such as DigiBog are used in multiple locations in concert with BEMs to provide an indication of peatland vulnerability and of changes in C stock over time.

5. Conclusions

Using both field data and the DigiBog peatland development model, we explored Winter's (2000) concept of the “hydrologic landscape” and its relation to wetland vulnerability to climate change in a Scottish blanket peatland. We find that:

1. The DigiBog model accurately reproduced peat thicknesses across a topographically-complex landscape. Simple conceptual models like Winter's are also capable of indicating—broadly—how peat thickness may vary across a landscape, and it is notable, although not unexpected, that peat accumulation acts to make a landscape wetter via reducing surface gradients. Nevertheless, Winter's model is based solely on the assumption that “wetter is better.” This aphorism is not always true, as shown by the future climate simulations and the greater rate of increase in peat thickness at the watch points on the slopes compared to the watch point in the main basin from ~2 ka BP. Peatland behavior is complex and involves non-linear relationships between wetness and net peat accumulation. These relationships can only be represented in peatland development models.
2. In a similar vein, while very useful in showing regions where blanket peatlands may be vulnerable to climate change, BEMs do not simulate what happens to the peatland carbon store for areas inside and outside the shrinking envelope. Process-based models such as DigiBog are again needed. We recommend that both types of model are used when assessing peatland response to climate change.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The DigiBog code and files for the model runs shown in the paper are on Zenodo at: https://doi.org/10.5281/zenodo.13793405. Data concerning the Allt Dubh transect are also presented in the Supporting Information.

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