Ecological Modelling 478 (2023) 110299

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Modelling the influence of mechanical-ecohydrological feedback on the nonlinear dynamics of peatlands

Adilan W. Mahdiyasa [a,b,*], David J. Large [a,*], Bagus P. Muljadi [a], Matteo Icardi [c]

[a] Department of Chemical and Environmental Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[b] Department of Mathematics, Bandung Institute of Technology, Bandung 40132, Indonesia
[c] School of Mathematical Sciences, University of Nottingham, University Park, Nottingham NG7 2RD, UK

ARTICLE INFO

Keywords:
Ecohydrology
Nonlinear dynamics
Poroelasticity
Regime shifts
Surface motion
Peat volume change

ABSTRACT

Peatlands are complex systems that exhibit nonlinear dynamics due to internal and external feedback mechanisms. However, the feedback of vegetation on peat volume changes that potentially affect peatland dynamics is not well understood. Here, we analyse the consequences of coupling between plant functional types with peat stiffness on a nonequilibrium model of a peatland by developing MPeat model. In this formulation, the peat systems prefer to exist in two possible states defined by two limit cycles, one corresponding to a wet and the other to a dry attractor. These states can also coexist under the same net rainfall indicating bistability in which a crucial drying threshold leads to a tipping point and associated regime shift from soft-wet to stiff-dry states with related changes in rates of carbon storage. While the shift from wet to dry states constitutes a tipping point, to shift from the dry to wet states requires more sustained increases in net rainfall, indicating that dry state is the more stable attractor as the peatland grows. As the model peatland evolves, the response of surface motion, carbon accumulation, and water table depth to the same external forcing becomes increasingly higher amplitude indicating that a degree of caution may be required when interpreting the paleorecord. Investigation of the behaviour of these states in response to seasonal variations in water budget suggests that the wet state will display high amplitude and later peak timing when compared to the dry state, a phenomenon that is observed in measures of surface motion. Our study highlights the possible importance of mechanical-ecohydrological feedback and, in particular, the role of the coupling between the proportion of plant functional types, peat Young's modulus, plant weight, and water table position in influencing peatland regime shifts, critical thresholds or tipping points, and both short- and long-term peatland dynamical behaviour.

1. Introduction

Peatland mechanics, including the swelling and shrinking of peat pore space due to mechanical deformation, produce significant feedbacks because they influence water budgets and carbon stocks (Mahdiyasa et al., 2022; Price, 2003; Waddington et al., 2015; Whittington and Price, 2006). These mechanical feedbacks are affected by vegetation (Malmer et al., 1994; Whittington et al., 2007), which potentially provides an essential element of peatland nonlinear behaviour. The purpose of this paper is to explore the consequences of coupling between mechanics and plant functional types (PFT) for nonequilibrium models of peatland dynamics in multiple timeframes. The model simulates an ombrotrophic peat body accumulating between fixed, free-draining boundaries on an impermeable substrate and presumed to experience uniform surface load on a square metre basis on account of the surface vegetation. Deformation of the peat body is free to occur due to gravity and the poroelastic behaviour of peat as a porous medium. Plant functional types are assumed to be a mix of *Sphagnum*, sedge, and shrub, as equations exist to calculate the exact composition of this mixture relative to water table depth. However, what matters is that this range of plant functional types provides a varied range of mechanical properties (soft *Sphagnum* to stiff shrubs) that enable feedback mechanisms to be considered. These constraints mean that the model does not provide a simulation of forested peatland as the loading would be much more complex; peatland that experiences substantial snowfall as the surface loading would be much more variable; permafrost peatland or peatland that is frozen for a significant period as the presence of ice would completely change the mechanical behaviour of the system. In essence,

* Corresponding authors.
E-mail addresses: adilan.mahdiyasa@nottingham.ac.uk, adilan@math.itb.ac.id (A.W. Mahdiyasa), david.large@nottingham.ac.uk (D.J. Large).

https://doi.org/10.1016/j.ecolmodel.2023.110299
Received 21 November 2022; Received in revised form 20 January 2023; Accepted 22 January 2023
Available online 30 January 2023

the results of the model will be most applicable to temperate peatlands.

Peatland behaviour is affected by the interplay between positive (destabilising) and negative (stabilising) feedback from internal and external factors. These feedbacks lead to nonlinear dynamics, which in turn create the possibility of peatlands having more than one equilibrium state and experiencing abrupt shifts to alternative states with fundamental differences in characteristics and structures (Belyea, 2009; Belyea and Baird, 2006; Hilbert et al., 2000). Understanding the nonlinear dynamics of peatlands, and in particular tipping points, is important because of the possibility that a sudden shift in behaviour could release a large amount of carbon stored in the peatland (Berg et al., 2009; Jackson et al., 2017; Loisel et al., 2017; Lunt et al., 2019; Yu et al., 2010), or may put the peatland into a less resilient state, with consequences for the global carbon cycle (Chaudhary et al., 2020; Dise, 2009; Kleinen et al., 2012).

Models of nonlinear peatland dynamics (e.g., Baird et al., 2012; Frolking et al., 2010; Heinemeyer et al., 2010; Morris et al., 2012, 2015, 2011; Swindles et al., 2012; Yu et al., 2001) take an ecohydrological approach and assume constant or partial changes of peat physical properties within an equilibrium condition. For example, Hilbert et al. (2000) proposed the bistability of both wet and dry peatland states potentially coexist through the nonlinear interactions between water balance and mass accumulation. Hilbert et al. (2000) also propose a tipping point could arise due to slight variability in water input, which leads to the change in peatland behaviour from carbon sinks to carbon sources. Similarly, van der Velde et al. (2021) developed a model to analyse regime shifts across biomes, from peatland to forest, indicating bistability conditions and major release of carbon when the switch occurs. Both Hilbert et al. (2000) and van der Velde et al. (2021) use the peatland water budget as the primary variable to determine the critical threshold before the regime shifts take place. However, peatland internal feedback mechanisms that can maintain the water budget are not considered and are sources of uncertainty in their models. In particular, these models ignore mechanical feedback, and the equilibrium assumption is not realised in peatlands where sustained growth continually changes the ecology, hydrology, and mechanics of the peatland system.

MPeat (Mahdiyasa et al., 2022) is a one-dimensional model of peatland dynamics that incorporates mechanical, ecological, and hydrological feedbacks through the coupling between fluid flow and solid deformation, which is known as poroelasticity (Biot, 1941; Coussy, 2004; de Boer, 2000; Detournay and Cheng, 1993; Wang, 2000). MPeat simulates peatland growth by adding a new layer or cohort of peat annually above the flat, impermeable, and rigid substrate without the requirement of an initial peat depth condition. Every new layer contains information about the initial value of peat physical properties, including bulk density, active porosity, hydraulic conductivity, and Young's modulus. MPeat conceptualises peatland into two different zones the unsaturated zone above the water table, and the saturated zone below the water table. Aerobic condition in the unsaturated zone results in a high rate of decay, while in the saturated zone, peat experiences a low rate of anaerobic decay. In both zones, the decomposition process reduces Young's modulus, which indicates the stiffness of the material against tensile or compressive forces. The changes in Young's modulus lead to the mechanical deformation of the peat pore structure, which has a significant influence on the peat bulk density, active porosity, and hydraulic conductivity. However, the effect of mechanical deformation on the peat pore structure is also affected by PFT. Whittington et al. (2007) found that peatland sites dominated by shrub experience limited compressibility, leading to lower hydraulic conductivity reduction when the water table drop. These conditions allow rapid water discharge from the peatland, promoting drier conditions and maintaining the dominance of the shrub. In contrast, sites dominated by sedge or *Sphagnum* have a better ability to expand or shrink, which keeps the relative position of the water table close to the surface and supports the growth of these plant communities. Therefore, stiffer peat dominated by shrubs could become a dry attractor, while softer peat with sedge or *Sphagnum* dominance has the possibility to turn into a wet attractor.

The objectives of this paper are to (1) present a model of peatland dynamics that incorporates the feedback between mechanical processes and plant functional types, (2) investigate the peatland regime shifts and tipping points in a growing system accounting for fully coupled mechanical-ecohydrological feedback, (3) analyse both short- and long-term nonlinear dynamics of the peatland.

2. Methods

We based our model on MPeat (Mahdiyasa et al., 2022) because it includes feedback between mechanical, ecological, and hydrological processes as the peatland develops and adapts it by introducing fundamental changes in the formulation of peat stiffness and plant weight at the top surface. This was necessary as the initial formulation of MPeat does not take into account the influence of plant functional types (PFT) on the peat stiffness and assumes a constant proportion of PFT during the simulation, which significantly affects the total plant weight that acts as the source of loading. By doing this, we are able to use a modified version of MPeat to consider the interactions between Young's modulus, PFT proportion, plant weight, and water table position (Fig. 1). As most of the MPeat formulations remain unchanged, we only describe the modifications below (for the full formulation see supplementary material).

2.1. Model formulation

In this model, Young's modulus is determined not only by decomposition (Zhu et al., 2020) but also by PFT. Peat dominated by shrub becomes stiffer and has higher Young's modulus compared to *Sphagnum* peat because the geotechnical behaviour of peat, including Young's modulus, is related to its origin (Farrell, 2012), which shrub produces stiffer plant litter than *Sphagnum* (Ämmälä, 2019; Wagner et al., 2012). Furthermore, shrub roots provide a supporting matrix in the unsaturated zone, reducing the compression effect (Malmer et al., 1994). To accommodate this behaviour, Young's modulus of all layers in the unsaturated zone increases to a value determined by PFT. In contrast, if the condition is *Sphagnum* dominant, the effect of PFT on Young's modulus only occurs at the top surface (Fig. 2). We propose an equation that includes the influence of decomposition and PFT on the peat Young's modulus as follows

$$E = \chi\left(1+\theta_t^{\zeta}\right)(b_1c_1+b_2c_2+b_3c_3) \quad (1)$$

where E is the Young's modulus (Pa), θ is the remaining mass $(-)$ which can be obtained from the mass per unit area that has experienced decay m_t (kg m^{-2}) divided by the initial mass per unit area m_0 (kg m^{-2}) or mathematically can be written as $\theta_t = m_t/m_0$, χ is the first Young's modulus parameter (Pa), ζ is the second Young's modulus parameter $(-)$, $b_1,\ b_2,\ b_3$ are the coefficient to couple PFT with Young's modulus $(-)$, $c_1, c_2,\ c_3$ are the PFT proportions $(-)$ with the indices 1,2,3 indicating shrub, sedge, and *Sphagnum*, respectively. Due to the uncertainties in the range value of peat Young's modulus (e.g., Dykes, 2008; Price et al., 2005; Reeve et al., 2013), we choose the parameters in Eq. (1) such that Young's modulus value is in agreement with the data provided by Boylan et al. (2008), Mesri and Ajlouni (2007), and Long (2005) in the range of $8\times10^4 - 1.6\times10^6$ Pa. Through this range value of Young's modulus, we enable to investigate the effect of mechanical feedback on the peatland dynamics.

Our model formulates the water table position at the centre of a circular domed peatland which is constrained by the rivers based on the equation from Childs (1969) (see also Morris et al., 2015; Swindles et al., 2012). In this formulation, a peatland receives the water from net rainfall that is defined as precipitation minus evapotranspiration and loses water due to lateral discharge towards the rivers, which is affected

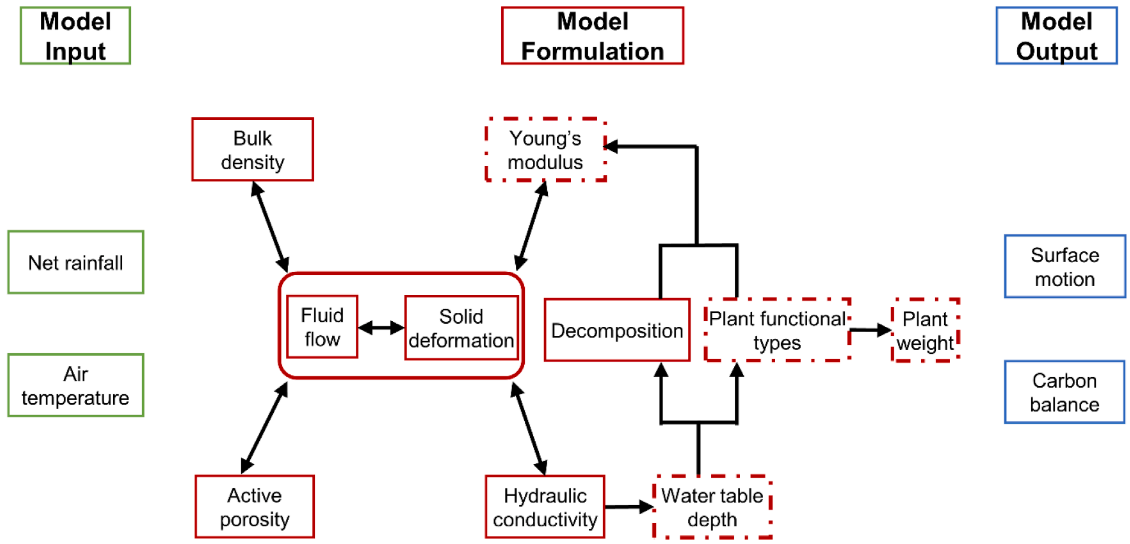

Fig. 1. Conceptual diagram of the proposed model. The green boxes indicate the climatic input to the proposed model, consisting of net rainfall, which is defined as precipitation minus evapotranspiration, and annual average air temperature. The red boxes explain the model formulation, with the red dashed boxes indicating the changes in formulation from the previously published version of MPeat by Mahdiyasa et al. (2022). In this formulation, the proportion of plant functional types depends on the water table depth, which in turn influences Young's modulus together with the decomposition process. Through this approach, we can incorporate the influence of the plant functional types on peat stiffness. Furthermore, the proportion of plant functional types also affects the total plant weight at the top surface, which provides loading and compression on the peat pore space. The changes in peat volume due to compression lead to the surface motion and influence carbon balance of the peatland, which are the outputs of the proposed model (blue boxes). Based on these outputs, we analyse regime shifts, tipping points, and both short- and long-term nonlinear dynamics of the peatland. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

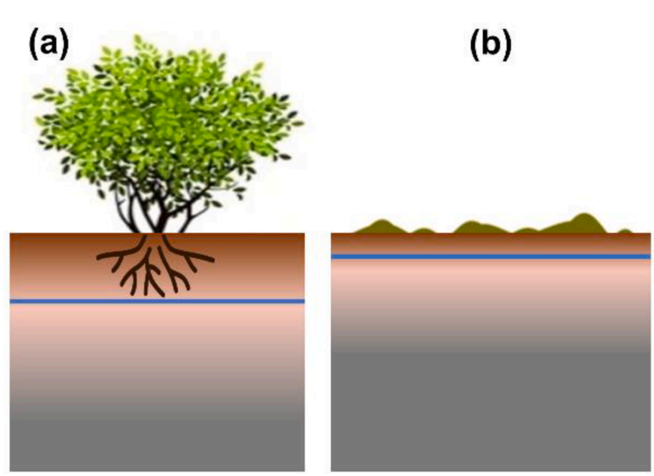

Fig. 2. The root effect of plant functional types (PFT) on peat Young's modulus. The blue line indicates the position of the water table, which leads to the different compositions of PFT. The lower water table position supports the growth of shrubs, while the higher position of water table increases the proportion of *Sphagnum* in the peatland vegetation communities. (a) If shrub is dominant, Young's modulus value in the unsaturated zone above the water table changes because shrub roots increase the stiffness of the unsaturated zone. (b) If *Sphagnum* is dominant, only Young's modulus value at the top surface is affected due to the absence of root effect on the peat stiffness. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by the active porosity, hydraulic conductivity, and the distance from the centre to the river or peatland radius

$$\frac{d\Gamma}{dt} = \frac{r}{\phi} - \frac{2\kappa\Gamma^2}{l^2\phi} \quad (2)$$

where Γ is the water table height (m), r is the net rainfall (m yr^{-1}) that is defined as precipitation minus evapotranspiration, l is the peatland radius (m), ϕ is the active porosity ($-$), and κ is the hydraulic conductivity (m s^{-1}). Water table position influences peat production, decomposition rate, and PFT composition. Moore et al. (2002) measured the relationship between the proportion of PFT with the position of the water table and found a strong negative relationship between water table position and shrub proportion. Where the water table was low, PFT composition was dominated by shrub. We apply linear regression to estimate the PFT proportion based on the minimum value of water table depth in each interval from Moore et al. (2002) data, as follows

$$c_1 = 2.23z - 0.28 \quad (3)$$

$$c_2 = -1.42z + 0.63 \quad (4)$$

$$c_3 = -0.81z + 0.64 \quad (5)$$

where c_1, c_2, c_3 are the PFT proportions $(-)$ with the indices 1,2,3 indicating shrub, sedge, and *Sphagnum*, respectively, and z is the water table depth (m) with the range value between $0.2 - 0.5$ m based on Moore et al. (2002) measurements. We assume the PFT proportion outside the range of the water table depth is equal to the estimated value when the water table depth is located in the limit range. The value of the coefficient of determination R^2 from the linear regression model for shrub, sedge, and *Sphagnum* proportions are 0.95, 0.78, and 0.82, respectively. These values of R^2 indicate that the linear fitting is appropriate to model the relationship between water table depth and PFT proportion.

The dependency of PFT proportion on the water table depth that is formulated in this model provides a more reasonable approach for investigating the influence of PFT on peatland mechanics compared to the constant proportion of PFT in the initial version of MPeat. PFT proportion affects the plant weight at the top surface, which represents the total weight of the living plants that set up the community. Plant weight becomes the source of loading in this system and is calculated through the following equations (Mahdiyasa et al., 2022; Moore et al., 2002)

$$Y = c_1\left(10^{\frac{\log_{10}(\psi)+0.409}{0.985}}\right)(1+d_1)g + c_2\left(10^{\log_{10}(\psi)+0.001}\right)(1+d_2)g + (c_3 0.144)(1+d_3)g \quad (6)$$

where Y is the plant weight (Pa), ψ is the peat production (kg m^{-2} yr^{-1}), g is the acceleration of gravity (m s^{-2}), c_1, c_2, c_3 are the PFT proportions (−) and d_1, d_2, d_3 are the constants for plant wet condition (−) with the indices 1,2,3 indicating shrub, sedge, and *Sphagnum*, respectively.

2.2. Model implementation

We run two groups of simulations with different time scales. In the first group, we simulated long-term peatland development under a constant radius of 500 m and flat substrate over a period of 6000 years, with the parameter values summarised in Table 1. We employed an annual time series of net rainfall (Fig. 3a), and annual average air temperature (Fig. 3b) generated from a sinusoidal function with some noise to create variable wet or dry climatic conditions. The range value of net rainfall and average air temperature used in our model are in line with the reported data from Morris et al. (2015), Young et al. (2019), and Young et al. (2021). In this group, the water is added evenly in small increments with timesteps equal to 0.1 years to produce a stable and convergent simulation. The boundary conditions of the model were an impermeable layer with no displacement at the bottom and a fully drained condition of the top layer. The rate of surface motion is obtained from the annual changes in peatland height, which is affected by mechanical, ecological, and hydrological feedback.

In the second group, we decoupled peat production and decomposition processes, and focused on the mechanical and hydrological feedback on a shorter time scale. We used peat properties that had been simulated from the first group to model short-term peatland surface motion with weekly timesteps over 150 weeks. We chose peat properties between the ages of 4000 − 3900 years BP and 2000 − 1900 years BP to represent the dry and wet conditions of the peatland based on the position of the water table (Fig. 4b). Unlike the first set of simulations, where peat production and decomposition influence the mechanical deformation through the changes in Young's modulus (Eq. (1)), the swelling and shrinking in the short-term simulations are affected by the plant weight at the top surface and water table position through the effective stress. Effective stress has an essential role in this model because it can explain the relationship between the total stress received by peat with excess pore water pressure (Biot, 1941; Price, 2003; Terzaghi, 1943) and the effect of compaction on the peat physical properties (Mahdiyasa et al., 2022; Schlotzhauer and Price, 1999; Whittington and Price, 2006). The model in this group was driven by climatic input in the form of weekly net rainfall only because all variables are not affected by air temperature (Fig. 3c). Therefore, throughout the year, the water is added unevenly to the peatland in the short-term simulation.

Table 1
Parameter default values for the simulations.

Name	Symbol	Value	Unit	Reference
Unsaturated zone decay rate	η_{un}	5×10^{-2}	yr^{-1}	(Clymo, 1984)
Saturated zone decay rate	η_{sa}	8×10^{-5}	yr^{-1}	(Clymo, 1984)
Biot's coefficient	α	1	–	(Terzaghi, 1943)
Bulk density initial value	ρ_0	50	kg m^{-3}	(Lewis et al., 2012)
Carbon content	C	0.47	–	(Loisel et al., 2014)
Active porosity initial value	ϕ_0	0.8	–	(Quinton et al., 2000)
Bulk density and active porosity parameter	β	2	m^{-1}	Present study
Hydraulic conductivity initial value	κ_0	1×10^{-2}	m s^{-1}	(Hoag and Price, 1995)
Hydraulic conductivity parameter	ξ	15	–	(Mahdiyasa et al., 2022)
Degree of saturation of water	S_w	0.4	–	(Mahdiyasa et al., 2022)
Water retention empirical constant 1	λ	0.5	–	(Mahdiyasa et al., 2022)
Water retention empirical constant 2	μ	0.4	m^{-1}	(Mahdiyasa et al., 2022)
Specific storage	S_s	1.4×10^{-2}	m^{-1}	(Hogan et al., 2006)
Specific weight of water	γ_w	9800	N m^{-3}	(Cheng, 2020)
Peatland radius	l	500	m	(Mahdiyasa et al., 2022)
Young's modulus parameter 1	χ	2×10^5	Pa	(Mahdiyasa et al., 2022)
Young's modulus parameter 2	ζ	0.1	–	(Mahdiyasa et al., 2022)
Shrub-Young's modulus parameter	b_1	1.25	–	Present study
Sedge-Young's modulus parameter	b_2	1	–	Present study
Sphagnum-Young's modulus parameter	b_3	0.75	–	Present study
Shrub constant	d_1	0.4	–	(Mahdiyasa et al., 2022)
Sedge constant	d_2	0.4	–	(Mahdiyasa et al., 2022)
Sphagnum constant	d_3	20	–	(McNeil and Waddington, 2003)

2.3. Sensitivity analysis

Model sensitivity to input parameters was evaluated by changing the value of parameters that couple PFT with Young's modulus (Eq. (1)). We chose to explore the effect of these parameters because of the shortage of information on how significant PFT is on the peat stiffness, which in turn influences the dynamics of the peatland. We increased the value of b_1 to represent the condition that shrubs control the peat stiffness by producing a higher Young's modulus. In contrast, the decreasing value of b_3 simulated the condition that *Sphagnum* was the essential PFT in reducing peat stiffness.

We performed one at a time sensitivity analysis or changed the value of one parameter, and all others remained the same as the baseline value (Table 1) for each simulation. The sensitivity analysis outputs consist of the relationship between peat stiffness with the dynamics of surface motion and the peatland carbon balance, including carbon input, carbon output, and net carbon accumulation.

3. Results

3.1. Long-term dynamical behaviour

Once the unsaturated zone has developed, the PFT proportion fluctuates depending on the water table position, which in turn affects the plant weight at the top surface. For instance, from 5200 − 4302 years BP, water table depth is around 0.24 m (Fig. 4b), *Sphagnum* is the dominant PFT (44%) compared to the shrub (27%) and sedge (29%) (Fig. 4a), and the value of plant weight is about 22.14 kg m^{-2} (Fig. 4c). Contrastingly, from 4274 − 3375 years BP, the water table depth is around 0.32 m, shrub proportion increases to 43%, while *Sphagnum* and sedge decrease to the value of 38% and 19% respectively, and plant weight increases to 26.65 kg m^{-2}. The differences in the PFT composition, water table depth, and plant weight lead to variations in the rate of surface motion (Fig. 5a and b).

The rate of surface motion is obtained from the average rate of motion over an entire year, essentially the net swelling and shrinking of a surface after a complete annual cycle, with positive values indicating that the peatland surface is going up, while the negative values indicate the peatland surface is going down. We use the rate of surface motion to explain the movement of the peatland surface rather than the absolute

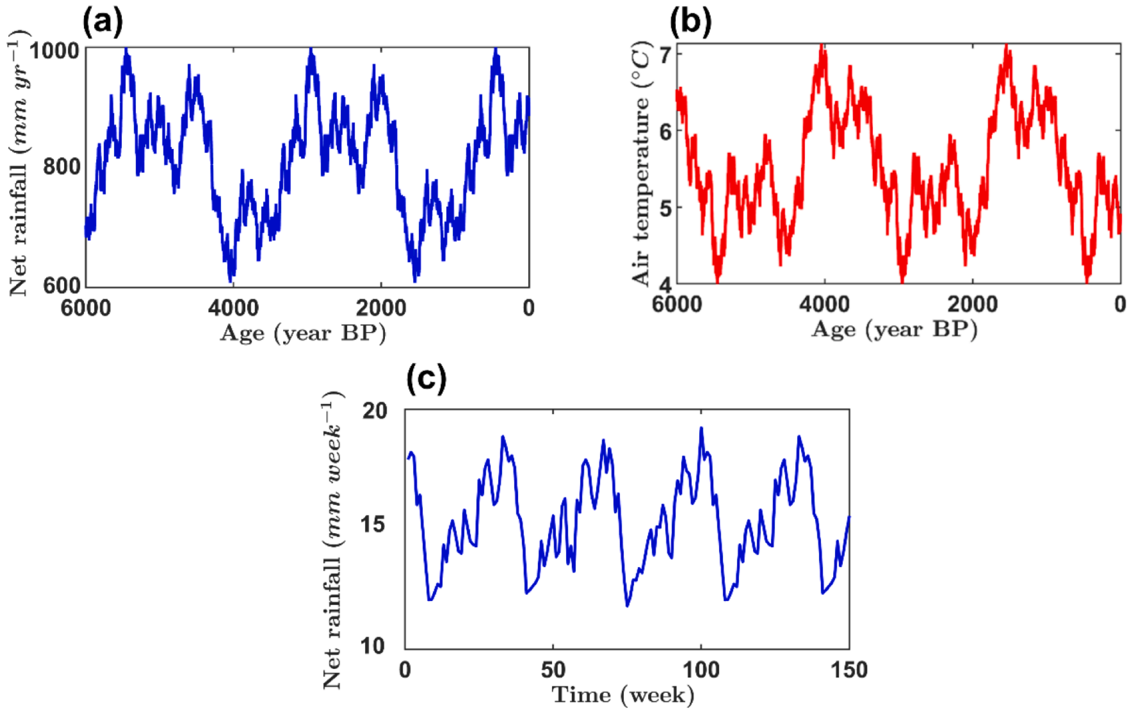

Fig. 3. The climate profile for long-term and short-term simulations. Long-term simulation is driven by the fluctuations of (a) net rainfall, which is defined as precipitation minus evapotranspiration, and (b) annual average air temperature with the value in the interval of 600 – 1000 mm yr^{-1} and 4 – 7 °C, respectively, over 6000 years. (c) Short-term simulation over 150 weeks depends only on net rainfall with the value ranging between 12 – 19 mm $week^{-1}$ because we exclude peat production and decomposition processes.

position because the reference point will change over time. This approach provides a more robust and efficient calculation process because it can be simulated without specifying some arbitrary datum. As the peatland develops, five distinct clusters of the rate of surface motion are produced, three corresponding to wetter conditions (5200 – 4302, 3199 – 1793, and 699 – 0 years BP), and two corresponding to drier conditions (4274 – 3375 and 1764 – 876 years BP) (Fig. 5a). The range of the rate of surface motion in the dry state is from -0.51 until 0.23 mm yr^{-1}, with the net rainfall fluctuating around 600 – 790 mm yr^{-1}. Conversely, if the net rainfall varies about 750 – 1000 mm yr^{-1}, peatland is attracted to the wet state, represented by the high rate of surface motion in the range of −1.64 and 1.52 mm yr^{-1}. The overlap between these two ranges of net rainfall, around 750 – 790 mm yr^{-1}, allows the dry attractor and wet attractor to coexist, which indicates the possibility of a bistability condition (Fig. 5d). Dry or wet attractors are the oscillatory states of the peatland toward which that peatland system tends to evolve, which have fundamental differences in characteristics and structures. Furthermore, the transition time from dry to wet state (wet shift) persists for around 174 years (Fig. 5b) and requires 90 mm yr^{-1} change in net rainfall (Fig. 5c), whereas the transition time from wet to dry (dry shift) is about 26 years, involving about 50 mm yr^{-1} change in net rainfall.

Long-term carbon input, output, and net accumulation are affected significantly by the peatland state. For example, the transition from wet to dry condition that occurs around 4301 to 4275 years BP increases the rate of carbon input from 0.33 to 0.39 kg C m^{-2} yr^{-1} due to the enhancement of productivity (Fig. 6a). However, this condition also leads to a substantial rise in the rate of peatland carbon release from 0.30 to 0.36 kg C m^{-2} yr^{-1} over the same time interval as the consequence of increasing the depth of the unsaturated zone (Fig. 6b). In contrast, the transition from dry to wet state about 3374 to 3200 years BP reduces the rate of carbon addition from 0.39 to 0.33 kg C m^{-2} yr^{-1} and carbon output from 0.37 to 0.31 kg C m^{-2} yr^{-1} because of the lower peat production and decomposition process as the water table is closer to the surface, from 0.31 to 0.26 m. The average value of the net rate of carbon accumulation, obtained from the difference between the rate of carbon input and output, is about 0.024 kg C m^{-2} yr^{-1} over the simulation time (Fig. 6c), which is in line with reported measurements between 0.021 – 0.025 kg C m^{-2} yr^{-1} (Chaudhary et al., 2020; Loisel et al., 2017; Loisel et al., 2014; Treat et al., 2016; Yu et al., 2010).

3.2. Short-term dynamical behaviour

Peat that grows in dry conditions has different characteristics, including the physical properties, compared to the wet peat, which results in distinct behaviour of short-term surface motion. During 4000 – 3900 years BP, shrub proportion increased due to the low net rainfall between 610 – 660 mm yr^{-1} (Fig. 3a) which led to the high Young's modulus value in the range of 3.53 $\times 10^5$ – 3.65 $\times 10^5$ Pa (Fig. 7d). Furthermore, the decrease in water input produced a deep position of the water table (0.35 – 0.32 m) from the surface (Fig. 4b), resulting in a more considerable effect of compaction, which is represented by the high value of bulk density (115 – 119 kg m^{-3}) and low value of active porosity (0.33 – 0.35) and hydraulic conductivity (2.3 $\times 10^{-8}$ – 4.9 $\times 10^{-8}$ m s^{-1}) in that period (Fig. 7a-c).

The condition was different during 2000 – 1900 years BP when peatland experienced high net rainfall (910 – 950 mm yr^{-1}), which resulted in a shallow water table position (0.18 – 0.20 m), and consequently led to the *Sphagnum* dominance condition. In this situation, peat stiffness decreased, indicated by the low value of Young's modulus (3.14 $\times 10^5$ – 3.22 $\times 10^5$ Pa). The high position of the water table reduced the effective stress, which produced peat with lower bulk density (93 –95 kg m^{-3}) and higher active porosity (0.41 –0.43) and hydraulic conductivity (5.8 $\times 10^{-7}$ – 7.8 $\times 10^{-7}$ m s^{-1}). Moreover, the surface loading from plant weight during 4000 – 3900 years BP (dry period) and 2000 – 1900 years BP (wet period) was around 26.12 – 28.92 kg m^{-2} and 19.38 – 20.44 kg m^{-2}, respectively (Fig. 4c).

Peat characteristics between the ages of 4000 – 3900 years BP and

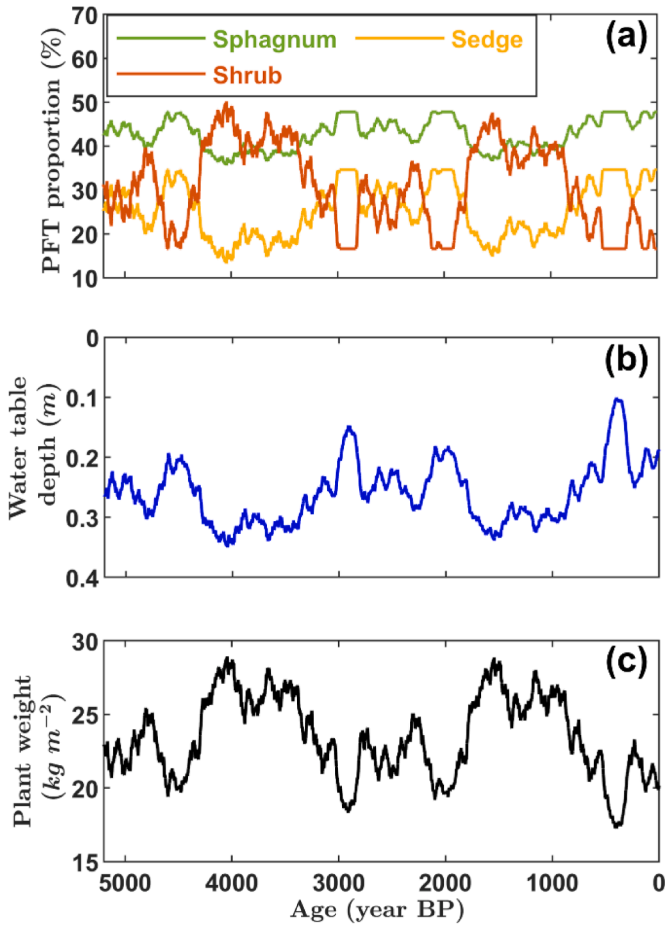

Fig. 4. (a) The proportion of plant functional types (PFT), including *Sphagnum*, shrub, and sedge, (b) the water table depth, and (c) the plant weight at the top surface over 5200 years or after the unsaturated zone is developed. Between the ages of 3000–2850, 2100–1900, and 500–300 years BP, the simulated water table depth is lower than 0.2 m, exceeds the limit range of Moore et al. (2002) measurements, which results in a constant proportion of PFT in these periods.

2000 – 1900 years BP, which represent dry and wet periods, were employed to simulate short-term surface motion. The amplitude of surface motion and peak timing varied between dry and wet peat over 150 weeks. Surface displacement ranged from −0.11 to 0.04 m for peat formed in dry condition, while for peat developed in a wet environment it fluctuated between −0.21 and 0.05 m (Fig. 8a). The negative or positive values indicate shrinkage or swelling of the peat surface from the initial elevation, which was 1.52 m for the dry peat and 2.36 m for the wet peat. Periods of peak timing of surface motion were not synchronized across the two time series, with wet peat experiencing a delay in peak timing relative to the dry peak of around five weeks. In addition, the hysteresis of surface elevation with the water level also appears for both dry peat (Fig. 8b) and wet peat (Fig. 8c). This phenomenon suggests the water level drops faster than the pore structure can collapse and the opposite happens when water is added to the peatland.

3.3. Sensitivity analysis

The parameter b_1 (Eq. (1)) controls the effect of the shrub proportion on the peat Young's modulus as the PFT composition changes because of the fluctuation in water table depth. Increasing parameter b_1 to 3.75 (Fig. 9) led to a higher Young's modulus with a value between 4.07 $\times 10^5$ – 7.92 $\times 10^5$ Pa, which in turn reduced the rate of surface motion to the range of -1.48 until 1.12 mm yr^{-1}. This condition, on average, results in a higher rate of carbon addition and carbon output with a value of about 2.2% and 5.6%, compared to the baseline value. Because the increasing rate of carbon output is higher than carbon input, the net rate of carbon accumulation decreases by around 39%. Moreover, a higher value of Young's modulus leads to a lower amplitude of surface motion for both dry peat (0.07 m) and wet peat (0.17 m), but the shift in peak timing is the same with the short-term baseline simulation, around five weeks.

The changes in Young's modulus value due to the variation in *Sphagnum* proportion are determined by b_3 parameter (Eq. (1)). Decreasing b_3 parameter to 0.375 resulted in a lower Young's modulus value (2.43 $\times 10^5$ – 3.13 $\times 10^5$ Pa), and as a consequence, the range of surface motion rate increased to the value between −1.48 and 1.69 mm yr^{-1}. This condition reduced the rate of carbon addition and carbon output by around 1.5% and 3.2% compared to the baseline simulation. The net carbon accumulation rate increased by approximately 19% due to a greater reduction in carbon output than carbon input. Furthermore, a lower Young's modulus value led to a higher amplitude of surface motion for both dry peat and wet peat in the short-term simulation, with the value of about 0.20 m and 0.32 m, respectively, and produced a more extended shift in peak timing about six weeks.

4. Discussion

The most significant observation arising from this model is the apparent bistability of the peatland with respect to net rainfall (Fig. 5d), with both wet and dry states being possible for the same net rainfall, but at different times. Another view of this is that as net rainfall varies over time, the peatland jumps between attractors characterised by two limit cycles. In comparison to the bistability predicted by Hilbert et al., (2000), who consider equilibrium states, our model is more complex because the system is continually evolving. By definition, an equilibrium state can be achieved if the state variable does not change with time. However, interactions between internal and external feedback mechanisms will prevent the peatland from reaching that condition because the peat physical properties, including bulk density, active porosity, hydraulic conductivity, and Young's modulus, change in time and space (Boylan et al., 2008; Fraser et al., 2001; Hogan et al., 2006; Lewis et al., 2012). This dynamic view of an evolving system is potentially more useful as there is no indication that Holocene peatlands are close to an equilibrium state. It can also be seen (Figs. 5b and 6c) that as the model peatland grows, the amplitude of oscillations, particularly in the wet state, increases. This is not surprising as growth between the fixed lateral boundaries in the model will steepen hydrological gradients over time, generating increasing extreme responses to the same changes in net rainfall. It should also, in the long term, favour the dry state, assuming that the processes of decay do not impose an earlier limit. If these modelled results have a bearing on reality, then some caution should also be exercised when interpreting the response of the peat to palaeoclimatic change, as the same climate forcing could generate quite different outcomes in the evolving peatland system. The inference of a permanent state of disequilibrium also raises the important question as to whether it would ever be possible for an observer on the surface of a peatland to determine if the system was tending to a long-term stable carbon balance as might be expected if they were to assume a constant decay rate.

Another key observation that operates on different time frames is the hysteretic behaviour of surface elevation with the water level. Short-term hysteresis is a well-known consequence of the filling and draining of porous matter and is obtained from field measurement. The data from Fritz et al. (2008) showed that delayed response of the surface motion to the changes in water level results in a hysteresis loop, with a positive relationship between these two variables, and this observation is in agreement with our simulation results (Fig. 10). The slope of surface elevation with water level decreases in the dry period, which may indicate that peat is stiffer at depth in the study area measured by Fritz

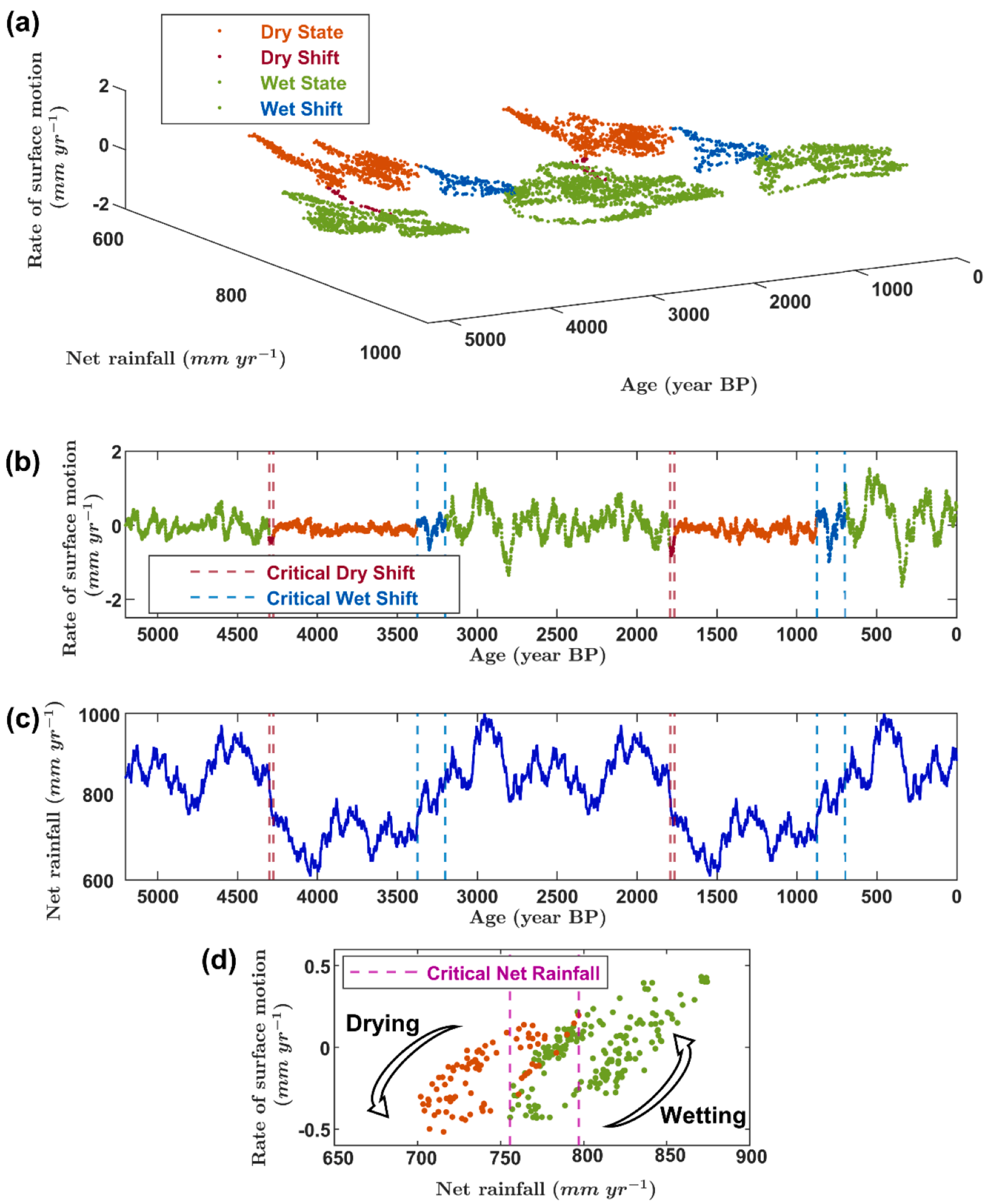

Fig. 5. (a) The rate of surface motion (positive value indicates the peatland surface is going up while the negative value is going down) with net rainfall and time in three-dimensional space, (b) the projections to two-dimensional space between rate of surface motion with time, (c) the changes in net rainfall that is required to shift peatland from one state to another, and (d) the projections to two-dimensional space between rate of surface motion with net rainfall to show the possibility of bistability condition because wet and dry attractors could appear under the same range of net rainfall.

et al. (2008), because the enhancement of peat stiffness will produce lower surface displacement and results in a flatter curve. In our simulations, stiffer peat that formed in dry conditions has a smaller slope of surface elevation with water level (0.3) compared to the wet peat (0.6), while Fritz et al. (2008) data show that the slope in the dry and wet conditions are around 0.2 and 0.8, respectively. The more pronounced difference between dry and wet conditions in the Fritz et al. (2008) data might be related to the peat characteristics in that specific site, including the restiad PFT composition compared to our model and possibly the influence of this on the microporosity (Rezanezhad et al., 2010; Silins and Rothwell, 1998). However, the main reason for comparison with Fritz et al. (2008) data is to demonstrate how the model provides an interpretative framework for analysing their observation of a peatland which in other respects (e.g., uniform surface loading and reduction in elasticity with decay) can be considered comparable to our model. Furthermore, this comparison also indicates the ability of our model to capture the heterogeneity and nonlinearity of peatland behaviour, provide a context for interpreting field data, and suggest that our chosen physical properties appear to be reasonable for the purpose of analysing peatland behaviour.

The long-term nonlinear hysteretic response to oscillatory changes in net precipitation may reflect fundamental differences in the behaviour of the wetting and drying system that result from a change in the state of the peatland (Fig. 5d). Intuitively, differences in the response of peatland to wetting and drying are reasonable as it should be easier to lose potential energy by lowering a water table than to build potential energy. This result may also indicate that the production of peat by compaction is a nonlinear process on multiannual timescales, with periods of either net growth (accumulation) or subsidence (compaction) of the peat occurring in response to longer terms changes in weather or climate. Some evidence of such longer-term oscillatory mechanical behaviour can be observed in the field observations of Howie and Hebda (2018), whose data, when plotted on an appropriate scale, appears to display evidence of multiannual oscillations in surface motion.

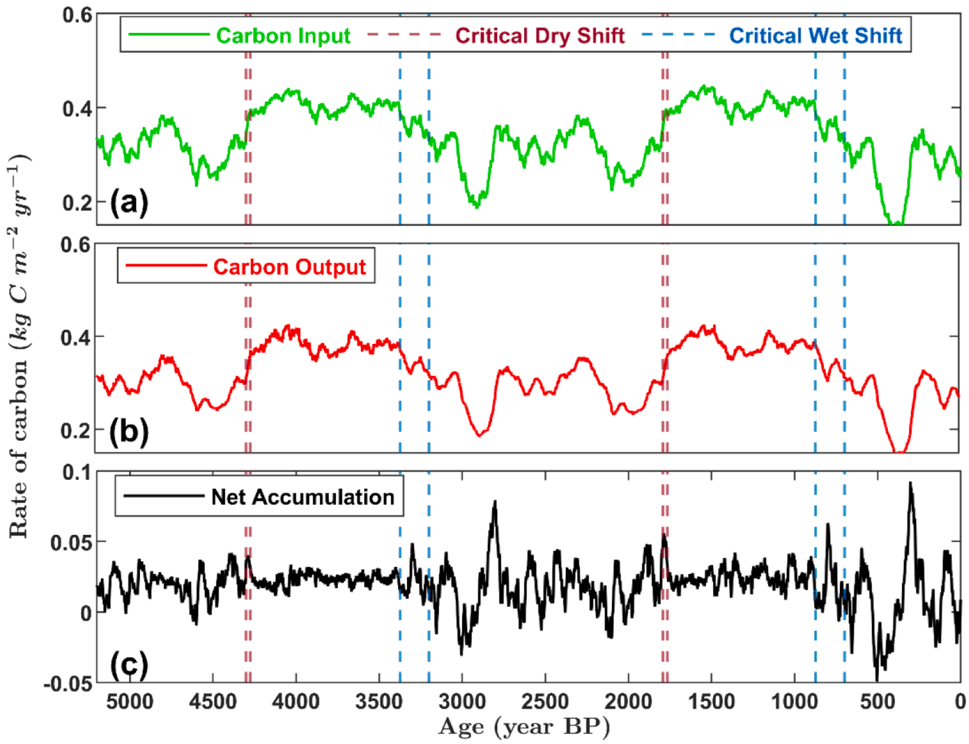

Fig. 6. Long-term peatland carbon balance over 5200 years. (a) The carbon input is obtained from peat production multiplied by carbon content with a value of 47% based on the data from Loisel et al. (2014). (b) The carbon output is calculated from mass loss due to the decomposition multiplied by the carbon content. (c) The difference between carbon input and carbon output leads to the net carbon accumulation in the peatland. The fluctuation of the net carbon accumulation rate is increasing as the system evolves, particularly in the wet state when subject to the same external forcing.

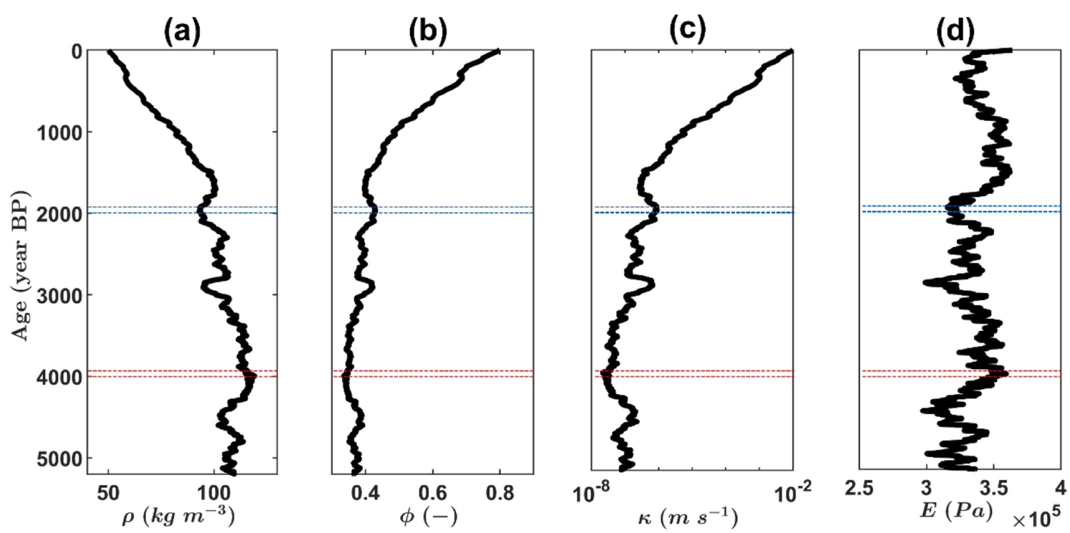

Fig. 7. The profile of peat physical properties with age-depth, including (a) bulk density ρ, (b) active porosity ϕ, (c) hydraulic conductivity κ, and (d) Young's modulus E over 5200 years. Red and blue dashed lines indicate the dry period 4000 − 3900 years BP and wet period 2000 − 1900 years BP, respectively. The range of bulk density calculated in our model between 50 − 119 kg m^3 is in line with the reported value around 30 − 120 kg m^3 (Clymo, 1984; Lewis et al., 2012). The range of active porosity from the simulation about 0.33 − 0.8 is consistent with the reported measurement between 0.1 − 0.8 (Hoag and Price, 1997; Quinton et al., 2000; Quinton et al., 2008). The simulation result of hydraulic conductivity in the range of 2.2 $\times 10^{-8}$ − 1 $\times 10^{-2}$ m s^{-1} align with reported measurements 7 $\times 10^{-9}$ − 1.6 $\times 10^{-2}$ m s^{-1} (Clymo, 2004; Fraser et al., 2001; Hoag and Price, 1995). Finally, the simulation result of Young's modulus in our model around 2.9 $\times 10^5$ −3.6 $\times 10^5$ Pa is in agreement with reported values about 8 $\times 10^4$ − 1.6 $\times 10^6$ Pa (Boylan et al., 2008; Long, 2005; Mesri and Ajlouni, 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Peatland regime shifts and tipping points

We found that a more substantial change in net rainfall is required to move the peatland from a dry state to wet state, than the other way around (Fig. 5a and c). A significant increase in water input is necessary to produce higher excess pore water pressure and expand the pore space, leading to more substantial peat water storage, which is the requirement for the regime shift from dry to wet states. However, as the dry state develops, the flow of water on the near-surface will be more favourable because the compaction effect is less significant for the stiffer material, and consequently, near-surface hydraulic conductivity will remain high, preventing the peatland from accumulating more water. Therefore, a dry state turns into a more dominant attractor that can accommodate greater perturbations and potentially becomes a preferable state in the long-term as the peatland grows.

It is notably difficult to predict when the regime shifts will appear in

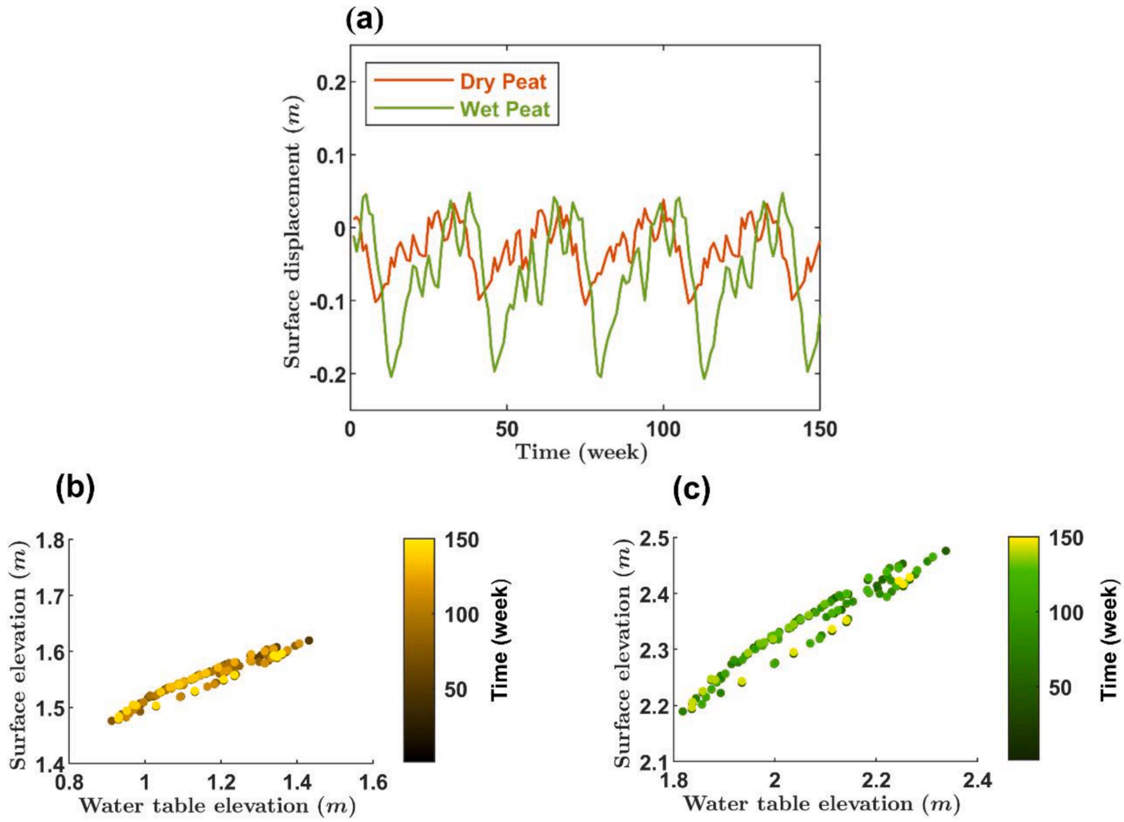

Fig. 8. (a) The difference in the characteristics of surface motion, including the amplitude and peak timing, between peat that grows in dry and wet conditions over 150 weeks, (b) hysteretic behaviour of surface elevation with water table elevation for dry peat, and (c) wet peat. Water table elevation shows the height of the water table from the base of the peatland. The surface moves with time in the anticlockwise direction.

complex dynamical systems (Scheffer et al., 2009; Scheffer and Carpenter, 2003), including peatlands (Belyea, 2009; Belyea and Baird, 2006), because they involve heterogeneous processes and nonlinear feedbacks. However, as the system approaches a tipping point, the variability of state behaviour changes (Carpenter and Brock, 2006; Kleinen et al., 2003; Oborny et al., 2005; van Nes and Scheffer, 2003), in our case is the rate of surface motion, that can be used as an early warning signal. For instance, before the regime shift around 3200 years BP, the standard deviation in the rate of surface motion increased from 0.07 to 0.27 mm yr^{-1} (Fig. 11), indicating the upcoming major transition from dry state to wet state. This is because the ability of the system to recover from perturbations and track fluctuations is decreasing near the critical threshold (Berglund and Gentz, 2002).

The proposed model shows how the feedback between internal and external factors affects peatland states and regime shifts under uniform landscape conditions. However, the state behaviour is also influenced by the spatial topography of the peatland. Assuming a sufficiently complex landscape (e.g., blanket bog with variable slopes, drainage lines, and local hydrology), and then on account of lateral flow with variations in the net water budget, it appears to be quite likely that wet and dry states could coexist in a landscape, and particularly, if the net rainfall were to fall within the region of bistability. This conclusion is supported by satellite observation of surface motion that indicates the bimodal wet state or dry state behaviour in such landscape (Bradley et al., 2022) with a mean annual net rainfall of around 800 mm yr^{-1} a value that is remarkably close to the 760 to 790 mm yr^{-1} annual net rainfall range in which bistability occurs within our model. However, in practice the situation is potentially far more complex, for example, microtopography of hummocks and hollows also exerts an influence on peatland mechanical behaviour (Marshall et al., 2022) at a much smaller scale ($1-10$ m) than the 90 m scale observations of Bradley et al., (2022).

A complex landscape, together with the variability of the peat physical properties throughout the peatland area, may also promote one state to be more stable than the other. Slope variabilities in a complex landscape have a major impact on the peatland hydrology (Holden, 2005; Holden and Burt, 2003), where the areas with a steeper slope experiences a higher rate of water discharge. This condition results in a smaller decrease in net rainfall required to shift from wet state to dry state than would be the case if the substrate was flat. Moreover, higher bulk density and lower hydraulic conductivity at mesotope margins (Baird et al., 2008; Lapen et al., 2005; Lewis et al., 2012) suggest smaller peat water storage in that location, which supports the dry state becoming more stable. Conversely, lower hydraulic gradients at mesotope centres will promote the accumulation of water, resulting in the wet condition becoming a dominant state. The state should change rapidly at a transition region between these two areas (margin and centre), and this is consistent with satellite observations (Bradley et al., 2022).

4.2. Peatland characteristics in different states

Our simulation results show apparent differences in the characteristics of peatland surface motion between the wet state and dry state over long-term and short-term periods. In the long-term simulations, the rate of surface motion of dry peat is lower compared to wet peat (Fig. 5a and b). The plant community composition in the dry state is dominated by shrub (Alshammari et al., 2020; Moore et al., 2002; Sottocornola et al., 2009; Wierda et al., 1997), which increases peat stiffness (Fig. 7d) and loading from plant weight at the top surface (Fig. 4c). The presence of shrub roots provides a supporting matrix (Malmer et al., 1994), particularly in the unsaturated zone where mechanical deformation mainly occurs (Fenton, 1980; Mahdiyasa et al., 2022; Quinton et al., 2000; Waddington et al., 2010; Whittington and Price, 2006), which limits the expansion and contraction of peat volume and prevent the

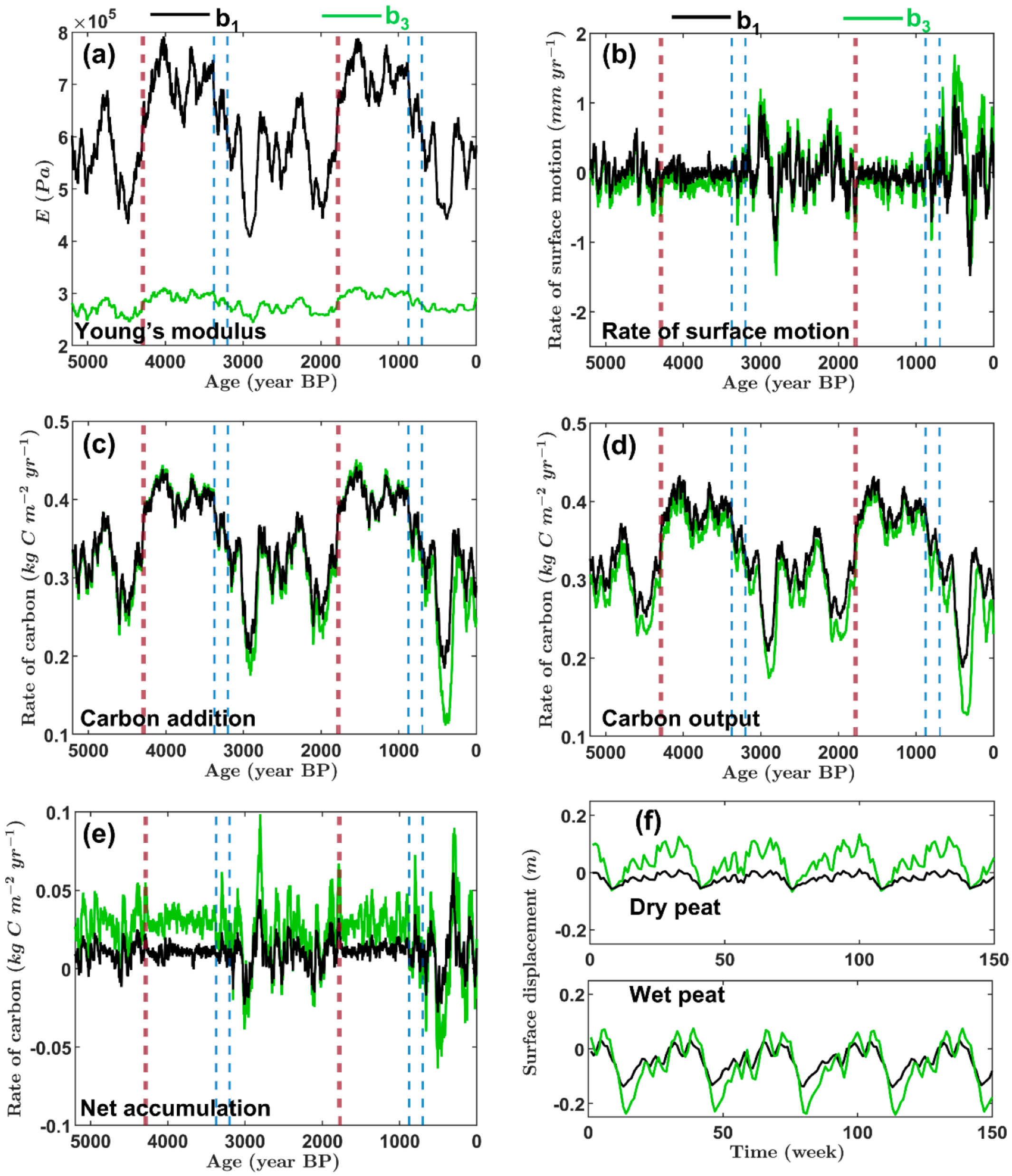

Fig. 9. The sensitivity analysis by changing the value of parameter b_1 to 3.75 (black line) or b_3 to 0.375 (green line) with the output variables are (a) Young's modulus E, (b) rate of surface motion, (c) rate of carbon addition, (d) rate of carbon output, (e) net rate of carbon accumulation, and (f) short-term surface motion. The parallel dashed red and blue lines indicate a critical dry and wet shift, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

peatland surface from oscillating with a higher amplitude.

In the short-term simulation, the differences between wet and dry states are not only the magnitude but also the peak timing of surface motion. Generally, if we exclude the effect of peat addition and decomposition, the main drivers in short-term surface motion are the interactions between effective stress, excess pore water pressure, and peat physical properties. The peat physical properties of short-term simulations are obtained between the ages of 4000 – 3900 BP and 2000 – 1900 BP to represent the dry and wet states, respectively (Fig. 7). The different values of Young's modulus between the two states result in a considerable distinction in the amplitude of surface motion, which corroborates the result from Reeve et al., (2013), indicating that lower Young's modulus produces more substantial changes in elevation of peat surface. Moreover, the wet peat has a lower bulk density and higher active porosity (Waddington et al., 2010; Whittington and Price, 2006), which lead to more significant water storage due to the larger pore size. These characteristics delay the effect of effective stresses on the reduction or expansion of peat volume because the process of expulsion or infiltration of water requires more time, resulting in a shift in the peak timing of surface motion. Another possible explanation for this is that the variation in hydraulic conductivity between wet and dry peat leads to the difference in time for excess pore water pressure to reach equilibrium (Biot, 1941; Ferronato et al., 2010; Moradi et al., 2019; Terzaghi, 1943), producing the delayed effect of compression.

Our short-term simulation result, which is developed from the coupling between mechanical and hydrological feedbacks, agrees in general with the satellite measurements from Bradley et al., (2022), who found that wet peat dominated by *Sphagnum* tends to experience a delay in peak timing. As opposed to that characteristic, peat in the dry state, typically dominated by shrub, undergoes earlier time to reach the peak of surface elevation. These distinct behaviours of surface motion, including amplitude and peak timing, between wet and dry peat could

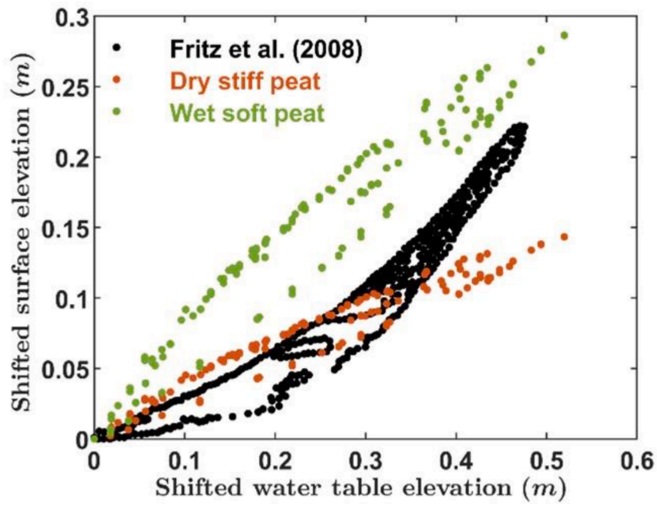

Fig. 10. Comparison with Fig. 4 Fritz et al. (2008) related to the hysteretic response of surface elevation with water table elevation. Shifted water table elevation is obtained from the water table elevation minus its minimum value, and shifted surface elevation is obtained from the surface elevation minus its minimum value.

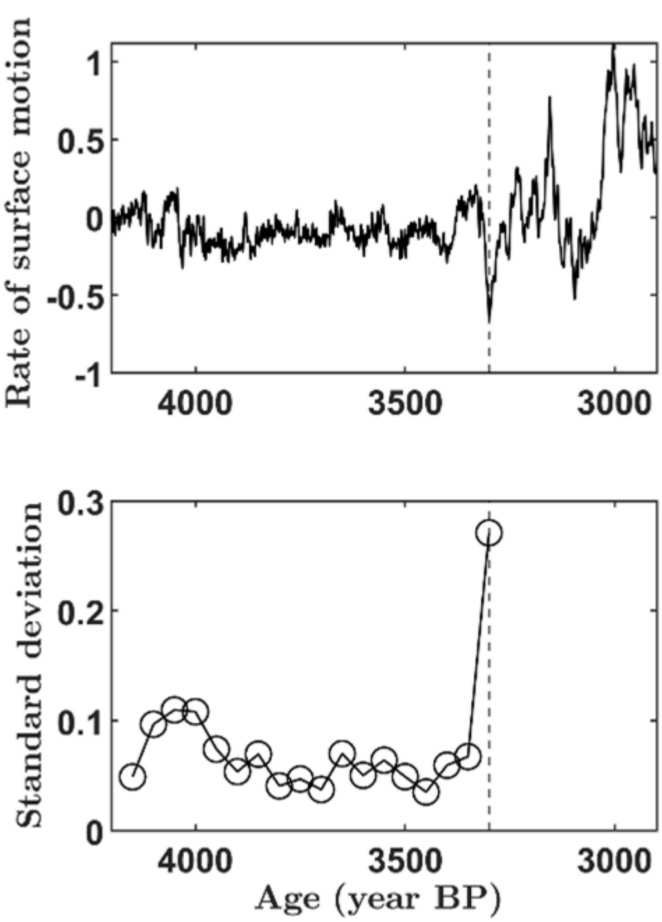

Fig. 11. The standard deviation of the rate of surface motion (mm yr^{-1}) increases significantly before the regime shift from dry state to wet state around 3200 years BP.

be used as a reliable indicator to assess peatland conditions. However, the shifts in peak timing are more evident in the satellite observations compared to our simulation, with a difference of about ten weeks. This discrepancy could be attributed to the seasonal growth and dieback of plants that are not included in our short-term simulation, peat physical properties variation between model simulation and the study location, and possibly the accuracy of signal processing undertaken by Bradley et al., (2022).

4.3. Peatland carbon balance and resilience

Our simulations show that the peatland accumulates carbon more effectively in the drier states, with the water table depth fluctuating in the range of 0.3 – 0.35 m, because at that interval, peat production reaches the maximum value, as shown by Belyea and Clymo (2001) from observational studies, and Morris et al., (2012) from the theoretical model DigiBog (Fig. 6). Therefore, the significant increase in peat production cancels out the effect of a considerable rise in peat decomposition. Furthermore, this result indicates the important contribution of vascular plants, as the unsaturated zone thickness increases, to peat production that provides a significant amount of above-ground biomass and root biomass (Moore et al., 2002; Wallén, 1986; Wallèn, 1987; Wallén et al., 1988). Charman et al., (2013) support our results and found that peatlands become stronger carbon sinks under a warming climate because the net primary productivity is a more critical variable than decomposition for determining long-term peatland carbon accumulation. However, as the peatland in the stiffer, drier state is less able to adjust its surface height to a falling water table, it is more susceptible to periods of drought and fire damage and becomes less resilient.

Conversely, although peatlands in the wetter state will accumulate less carbon, it is more resilient to further changes in the climate, as the peatland surface experiences more oscillation in the wetter state and can adjust more effectively to the fluctuations of water input (Alshammari et al., 2020; Bradley et al., 2022). The drop in water input will be accompanied by a decrease in surface elevation due to the compaction, which maintains the relative position of the water table from the surface (Mahdiyasa et al., 2022; Whittington and Price, 2006).

5. Conclusion

At the heart of this paper is an empirical and straightforward relationship between Young's modulus and plant functional types, in which shrubs should produce stiffer peat compared to *Sphagnum*. This simplicity, combined with a scarcity of Young's modulus data, results in a number of sources of uncertainty in the simulations. However, despite these limitations, the results are supported by both field and satellite data, and as better data become available, the inputs to the model can be modified to improve the accuracy of the results. For example, more realistic results may be achieved by the inclusion of the leaf drop term for shrubs and sedges on the total plant weight formulation or by adapting the formulation of plant functional type and above-ground biomass to encompass a greater range of environmental conditions and peatland types.

The proposed model shows that the interactions between mechanical processes and plant functional types exercise considerable influence on peatland dynamics. By considering the effect of plant functional types on the peat stiffness as the peatland grows, the limit cycles of wet and dry attractors could coexist under the same net rainfall, which potentially provides a more realistic approach to understanding bistability because the interactions between internal and external feedback mechanisms will prevent peatland from reaching the equilibrium state. The condition of a continuously evolving system, indicated by the increasing oscillation rate of surface motion, carbon balance, and water table depth over time under the same climatic influence, also suggests that caution might be needed to interpret the paleorecord data from the peatland. Finally, we demonstrate how the application of fully coupled mechanical-ecohydrological feedback could help explain the regime shift, tipping point, and nonlinear dynamics of the peatland in multiple timeframes.

CRediT authorship contribution statement

Adilan W. Mahdiyasa: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **David J. Large:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Bagus P. Muljadi:** Methodology, Resources, Writing – review & editing. **Matteo Icardi:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The codes that support the findings of this study are openly available in zenodo at https://doi.org/10.5281/zenodo.7335037 (Mahdiyasa, 2022)

Acknowledgments

This work was funded by RISPRO-UKICIS (United Kingdom - Indonesia Consortium for Interdisciplinary Sciences) with the grant number 4345/E4/AL.04/2022. We would like to thank Savvas Triantafyllou for interesting discussions on an earlier version of the model. We also thank Nigel Roulet and anonymous reviewers for their insightful and constructive comments.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2023.110299.

References

Alshammari, L., Boyd, D.S., Sowter, A., Marshall, C., Andersen, R., Gilbert, P., Marsh, S., Large, D.J., 2020. Use of surface motion characteristics determined by InSAR to assess peatland condition. J. Geophys. Res. 125 (1), e2018JG004953 https://doi.org/10.1029/2018JG004953.

Ämmälä, A.P.P., 2019. Sphagnum moss as a functional reinforcement agent in castor oil-based biopolyurethane composites. Mires Peat 24 (28), 1–11. https://doi.org/10.19189/MaP.2019.OMB.397.

Baird, A.J., Eades, P.A., Surridge, B.W.J., 2008. The hydraulic structure of a raised bog and its implications for ecohydrological modelling of bog development. Ecohydrology 1 (4), 289–298. https://doi.org/10.1002/eco.33.

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

Belyea, L.R., 2009. Nonlinear dynamics of peatlands and potential feedbacks on the climate system. In: Baird, A.J., Belyea, L.R., Comas, X., Reeve, A., Slater, L.D. (Eds.), Carbon Cycling in Northern Peatlands. American Geophysical Union, pp. 5–18. https://doi.org/10.1029/2008GM000829.

Belyea, L.R., Baird, A.J., 2006. Beyond the "limits to peat bog growth": cross-scale feedback in peatland development. Ecol. Monogr. 76 (3), 299–322. https://doi.org/10.1890/0012-9615(2006)076[0299:BTLTPB]2.0.CO;2.

Belyea, L.R., Clymo, R.S., 2001. Feedback control of the rate of peat formation. Proc. R. Soc. Lond. B Biol. Sci. 268 (1473), 1315–1321. https://doi.org/10.1098/rspb.2001.1665.

Berg, E.E.B.E., Hillman, K.M.M., Dial, R., DeRuwe, A., 2009. Recent woody invasion of wetlands on the Kenai Peninsula Lowlands, south-central Alaska: a major regime shift after 18 000 years of wet Sphagnum–sedge peat recruitment. Can. J. For. Res. 39 (11), 2033–2046. https://doi.org/10.1139/x09-121.

Berglund, N., Gentz, B., 2002. Metastability in simple climate models: pathwise analysis of slowly driven Langevin equations. Stochastics Dyn. 02 (03), 327–356. https://doi.org/10.1142/s0219493702000455.

Biot, M.A., 1941. General theory of three-dimensional consolidation. J. Appl. Phys. 12 (2), 155–164. https://doi.org/10.1063/1.1712886.

Boylan, N., Jennings, P., Long, M., 2008. Peat slope failure in Ireland. Q. J. Eng. Geol. Hydrogeol. 41 (1), 93–108. https://doi.org/10.1144/1470-9236/06-028.

Bradley, A.V., Andersen, R., Marshall, C., Sowter, A., Large, D.J., 2022. Identification of typical ecohydrological behaviours using InSAR allows landscape-scale mapping of peatland condition. Earth Surf. Dynam. 10 (2), 261–277. https://doi.org/10.5194/esurf-10-261-2022.

Carpenter, S.R., Brock, W.A., 2006. Rising variance: a leading indicator of ecological transition. Ecol. Lett. 9 (3), 311–318. https://doi.org/10.1111/j.1461-0248.2005.00877.x.

Charman, D.J., Beilman, D.W., Blaauw, M., Booth, R.K., Brewer, S., Chambers, F.M., Christen, J.A., Gallego-Sala, A., Harrison, S.P., Hughes, P.D.M., Jackson, S.T., Korhola, A., Mauquoy, D., Mitchell, F.J.G., Prentice, I.C., van der Linden, M., De Vleeschouwer, F., Yu, Z.C., Alm, J., Bauer, I.E., Corish, Y.M.C., Garneau, M., Hohl, V., Huang, Y., Karofeld, E., Le Roux, G., Loisel, J., Moschen, R., Nichols, J.E., Nieminen, T.M., MacDonald, G.M., Phadtare, N.R., Rausch, N., Sillasoo, Ü., Swindles, G.T., Tuittila, E.S., Ukonmaanaho, L., Väliranta, M., van Bellen, S., van Geel, B., Vitt, D.H., Zhao, Y., 2013. Climate-related changes in peatland carbon accumulation during the last millennium. Biogeosciences 10 (2), 929–944. https://doi.org/10.5194/bg-10-929-2013.

Chaudhary, N., Westermann, S., Lamba, S., Shurpali, N., Sannel, A.B.K., Schurgers, G., Miller, P.A., Smith, B., 2020. Modelling past and future peatland carbon dynamics across the pan-Arctic. Glob. Chang. Biol. 26 (7), 4119–4133. https://doi.org/10.1111/gcb.15099.

Cheng, A.H.D., 2020. A linear constitutive model for unsaturated poroelasticity by micromechanical analysis. Int. J. Numer. Anal. Methods Geomech. 44 (4), 455–483. https://doi.org/10.1002/nag.3033.

Childs, E.C., 1969. An Introduction to the Physical Basis of Soil Water Phenomena. John Wiley & Sons Ltd.

Clymo, R.S., 1984. The limits to peat bog growth. Philosop. Trans. R. Soc. London. B, Biol. Sci. 303 (1117), 605–654. https://doi.org/10.1098/rstb.1984.0002.

Clymo, R.S., 2004. Hydraulic conductivity of peat at Ellergower Moss, Scotland. Hydrol. Process 18 (2), 261–274. https://doi.org/10.1002/hyp.1374.

Coussy, O., 2004. Poromechanics. John Wiley & Sons Ltd.

de Boer, R., 2000. Theory of Porous Media. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-59637-7.

Detournay, E., Cheng, A.H.D., 1993. Fundamentals of poroelasticity. In: Fairhurst, C. (Ed.), Analysis and Design Methods. Pergamon, pp. 113–171. https://doi.org/10.1016/B978-0-08-040615-2.50011-3.

Dise, N.B., 2009. Peatland response to global change. Science 326 (5954), 810–811. https://doi.org/10.1126/science.1174268.

Dykes, A.P., 2008. Tensile strength of peat: laboratory measurement and role in Irish blanket bog failures. Jisuberi 5 (4), 417–429. https://doi.org/10.1007/s10346-008-0136-1.

Farrell, E.R., 2012. Organics/peat soils. In: Burland, C.T., Skinner H, J., Brown, M. (Eds.), ICE Manual of Geotechnical engineering: Volume I. ICE Publishing, pp. 463–479. https://doi.org/10.1680/moge.57074.0463.

Fenton, J.H.C., 1980. The rate of peat accumulation in Antarctic Moss Banks. J. Ecol. 68 (1), 211–228. https://doi.org/10.2307/2259252.

Ferronato, M., Castelletto, N., Gambolati, G., 2010. A fully coupled 3-D mixed finite element model of Biot consolidation. J. Comput. Phys. 229 (12), 4813–4830. https://doi.org/10.1016/j.jcp.2010.03.018.

Fraser, C.J.D., Roulet, N.T., Moore, T.R., 2001. Hydrology and dissolved organic carbon biogeochemistry in an ombrotrophic bog. Hydrol. Process 15 (16), 3151–3166. https://doi.org/10.1002/hyp.322.

Fritz, C., Campbell, D.I., Schipper, L.A., 2008. Oscillating peat surface levels in a restiad peatland, New Zealand—magnitude and spatiotemporal variability. Hydrol. Process 22 (17), 3264–3274. https://doi.org/10.1002/hyp.6912.

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

Heinemeyer, A., Croft, S., Garnett, M.H., Gloor, E., Holden, J., Lomas, M.R., Ineson, P., 2010. The MILLENNIA peat cohort model, predicting past, present and future soil carbon budgets and fluxes under changing climates in peatlands. Climate Res. 45 (1), 207–226. https://doi.org/10.3354/cr00928.

Hilbert, D.W., Roulet, N., Moore, T., 2000. Modelling and analysis of peatlands as dynamical systems. J. Ecol. 88 (2), 230–242. https://doi.org/10.1046/j.1365-2745.2000.00438.x.

Hoag, R.S., Price, J.S., 1995. A field-scale, natural gradient solute transport experiment in peat at a Newfoundland blanket bog. J. Hydrol. (Amst.) 172 (1), 171–184. https://doi.org/10.1016/0022-1694(95)02696-M.

Hoag, R.S., Price, J.S., 1997. The effects of matrix diffusion on solute transport and retardation in undisturbed peat in laboratory columns. J. Contam. Hydrol. 28 (3), 193–205. https://doi.org/10.1016/S0169-7722(96)00085-X.

Hogan, J.M., van der Kamp, G., Barbour, S.L., Schmidt, R., 2006. Field methods for measuring hydraulic properties of peat deposits. Hydrol. Process 20 (17), 3635–3649. https://doi.org/10.1002/hyp.6379.

Holden, J., 2005. Controls of soil pipe frequency in upland blanket peat. J. Geophys. Res. (F1), 110. https://doi.org/10.1029/2004JF000143.

Holden, J., Burt, T.P., 2003. Runoff production in blanket peat covered catchments. Water Resour. Res. (7), 39. https://doi.org/10.1029/2002WR001956.

Howie, S.A., Hebda, R.J., 2018. Bog surface oscillation (mire breathing): a useful measure in raised bog restoration. Hydrol. Process 32 (11), 1518–1530. https://doi.org/10.1002/hyp.11622.

Jackson, R.B., Lajtha, K., Crow, S.E., Hugelius, G., Kramer, M.G., Piñeiro, G., 2017. The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. Annu. Rev. Ecol. Evol. Syst. 48 (1), 419–445. https://doi.org/10.1146/annurev-ecolsys-112414-054234.

Kleinen, T., Brovkin, V., Schuldt, R.J., 2012. A dynamic model of wetland extent and peat accumulation: results for the Holocene. Biogeosciences 9 (1), 235–248. https://doi.org/10.5194/bg-9-235-2012.

Kleinen, T., Held, H., Petschel-Held, G, 2003. The potential role of spectral properties in detecting thresholds in the Earth system: application to the thermohaline circulation. Ocean Dyn. 53 (2), 53–63. https://doi.org/10.1007/s10236-002-0023-6.

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

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

Loisel, J., van Bellen, S., Pelletier, L., Talbot, J., Hugelius, G., Karran, D., Yu, Z., Nichols, J., Holmquist, J., 2017. Insights and issues with estimating northern peatland carbon stocks and fluxes since the Last Glacial Maximum. Earth Sci. Rev. 165, 59–80. https://doi.org/10.1016/j.earscirev.2016.12.001.

Loisel, J., Yu, Z., Beilman, D.W., Camill, P., Alm, J., Amesbury, M.J., Anderson, D., Andersson, S., Bochicchio, C., Barber, K., Belyea, L.R., Bunbury, J., Chambers, F.M., Charman, D.J., De Vleeschouwer, F., Fiałkiewicz-Kozieł, B., Finkelstein, S.A., Gałka, M., Garneau, M., Hammarlund, D., Hinchcliffe, W., Holmquist, J., Hughes, P., Jones, M.C., Klein, E.S., Kokfelt, U., Korhola, A., Kuhry, P., Lamarre, A., Lamentowicz, M., Large, D., Lavoie, M., MacDonald, G., Magnan, G., Mäkilä, M., Mallon, G., Mathijssen, P., Mauquoy, D., McCarroll, J., Moore, T.R., Nichols, J., O'Reilly, B., Oksanen, P., Packalen, M., Peteet, D., Richard, P.J., Robinson, S., Ronkainen, T., Rundgren, M., Sannel, A.B.K., Tarnocai, C., Thom, T., Tuittila, E.-S., Turetsky, M., Väliranta, M., van der Linden, M., van Geel, B., van Bellen, S., Vitt, D., Zhao, Y., Zhou, W., 2014. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. Holocene 24 (9), 1028–1042. https://doi.org/10.1177/0959683614538073.

Long, M., 2005. Review of peat strength, peat characterisation and constitutive modelling of peat with reference to landslides. Stud. Geotech. Mech. 27 (3–4), 67–90.

Lunt, P.H., Fyfe, R.M., Tappin, A.D., 2019. Role of recent climate change on carbon sequestration in peatland systems. Sci. Total Environ. 667, 348–358. https://doi.org/10.1016/j.scitotenv.2019.02.239.

Mahdiyasa, A.W., 2022. MPeat-PFT. Zenodo. https://doi.org/10.5281/zenodo.7335037.

Mahdiyasa, A.W., Large, D.J., Muljadi, B.P., Icardi, M., Triantafyllou, S., 2022. MPeat—A fully coupled mechanical-ecohydrological model of peatland development. Ecohydrology 15 (1), e2361. https://doi.org/10.1002/eco.2361.

Malmer, N., Svensson, B.M., Wallén, B., 1994. Interactions between Sphagnum mosses and field layer vascular plants in the development of peat-forming systems. Folia Geobot. Phytotaxon. 29 (4), 483–496. http://www.jstor.org/stable/4181306.

Marshall, C., Sterk, H.P., Gilbert, P.J., Andersen, R., Bradley, A.V., Sowter, A., Marsh, S., Large, D.J., 2022. Multiscale variability and the comparison of ground and satellite radar based measures of peatland surface motion for peatland monitoring. Remote Sens (Basel) 14 (2), 336. https://www.mdpi.com/2072-4292/14/2/336.

McNeil, P., Waddington, J.M., 2003. Moisture controls on Sphagnum growth and CO2 exchange on a cutover bog. J. Appl. Ecol. 40 (2), 354–367. https://doi.org/10.1046/j.1365-2664.2003.00790.x.

Mesri, G., Ajlouni, M., 2007. Engineering properties of fibrous peats. J. Geotech. Geoenviron. Eng. 133 (7), 850–866. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:7(850.

Moore, T.R., Bubier, J.L., Frolking, S.E., Lafleur, P.M., Roulet, N.T., 2002. Plant biomass and production and CO2 exchange in an ombrotrophic bog. J. Ecol. 90 (1), 25–36. https://doi.org/10.1046/j.0022-0477.2001.00633.x.

Moradi, M., Keshavarz, A., Fazeli, A., 2019. One dimensional consolidation of multi-layered unsaturated soil under partially permeable boundary conditions and time-dependent loading. Comput. Geotech. 107, 45–54. https://doi.org/10.1016/j.compgeo.2018.11.020.

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

Morris, P.J., Baird, A.J., Young, D.M., Swindles, G.T., 2015. Untangling climate signals from autogenic changes in long-term peatland development. Geophys. Res. Lett. 42 (24) https://doi.org/10.1002/2015GL066824, 10788-710,797.

Morris, P.J., Belyea, L.R., Baird, A.J., 2011. Ecohydrological feedbacks in peatland development: a theoretical modelling study. J. Ecol. 99 (5), 1190–1201. https://doi.org/10.1111/j.1365-2745.2011.01842.x.

Oborny, B., Meszéna, G., Szabó, G., 2005. Dynamics of Populations on the Verge of Extinction. Oikos 109 (2), 291–296. http://www.jstor.org/stable/3548746.

Price, J.S., 2003. Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. Water Resour. Res. 39 (9) https://doi.org/10.1029/2002WR001302.

Price, J.S., Cagampan, J., Kellner, E., 2005. Assessment of peat compressibility: is there an easy way? Hydrol. Process 19 (17), 3469–3475. https://doi.org/10.1002/hyp.6068.

Quinton, W.L., Gray, D.M., Marsh, P., 2000. Subsurface drainage from hummock-covered hillslopes in the Arctic tundra. J. Hydrol. (Amst.) 237 (1), 113–125. https://doi.org/10.1016/S0022-1694(00)00304-8.

Quinton, W.L., Hayashi, M., Carey, S.K., 2008. Peat hydraulic conductivity in cold regions and its relation to pore size and geometry. Hydrol. Process 22 (15), 2829–2837. https://doi.org/10.1002/hyp.7027.

Reeve, A.S., Glaser, P.H., Rosenberry, D.O., 2013. Seasonal changes in peatland surface elevation recorded at GPS stations in the Red Lake Peatlands, northern Minnesota, USA. J. Geophys. Res. 118 (4), 1616–1626. https://doi.org/10.1002/2013JG002404.

Rezanezhad, F., Quinton, W.L., Price, J.S., Elliot, T.R., Elrick, D., Shook, K.R., 2010. Influence of pore size and geometry on peat unsaturated hydraulic conductivity computed from 3D computed tomography image analysis. Hydrol. Process 24 (21), 2983–2994. https://doi.org/10.1002/hyp.7709.

Scheffer, M., Bascompte, J., Brock, W.A., Brovkin, V., Carpenter, S.R., Dakos, V., Held, H., van Nes, E.H., Rietkerk, M., Sugihara, G., 2009. Early-warning signals for critical transitions. Nature 461 (7260), 53–59. https://doi.org/10.1038/nature08227.

Scheffer, M., Carpenter, S.R., 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. Trends Ecol. Evol. (Amst.) 18 (12), 648–656. https://doi.org/10.1016/j.tree.2003.09.002.

Schlotzhauer, S.M., Price, J.S., 1999. Soil water flow dynamics in a managed cutover peat field, Quebec: field and laboratory investigations. Water Resour. Res. 35 (12), 3675–3683. https://doi.org/10.1029/1999WR900126.

Silins, U., Rothwell, R.L., 1998. Forest peatland drainage and subsidence affect soil water retention and transport properties in an Alberta peatland. Soil Sci. Soc. Am. J. 62 (4), 1048–1056. https://doi.org/10.2136/sssaj1998.03615995006200040028x.

Sottocornola, M., Laine, A., Kiely, G., Byrne, K.A., Tuittila, E.-S., 2009. Vegetation and environmental variation in an atlantic blanket bog in South-Western Ireland. Plant Ecol. 203 (1), 69–81. http://www.jstor.org/stable/40305716.

Swindles, G.T., Morris, P.J., Baird, A.J., Blaauw, M., Plunkett, G., 2012. Ecohydrological feedbacks confound peat-based climate reconstructions. Geophys. Res. Lett. 39 (11) https://doi.org/10.1029/2012GL051500.

Terzaghi, K., 1943. Theoretical Soil Mechanics. John Wiley & Sons, Inc.

Treat, C.C., Jones, M.C., Camill, P., Gallego-Sala, A., Garneau, M., Harden, J.W., Hugelius, G., Klein, E.S., Kokfelt, U., Kuhry, P., Loisel, J., Mathijssen, P.J.H., O'Donnell, J.A., Oksanen, P.O., Ronkainen, T.M., Sannel, A.B.K., Talbot, J., Tarnocai, C., Väliranta, M., 2016. Effects of permafrost aggradation on peat properties as determined from a pan-Arctic synthesis of plant macrofossils. J. Geophys. Res. 121 (1), 78–94. https://doi.org/10.1002/2015JG003061.

van der Velde, Y., Temme, A.J.A.M., Nijp, J.J., Braakhekke, M.C., van Voorn, G.A.K., Dekker, S.C., Dolman, A.J., Wallinga, J., Devito, K.J., Kettridge, N., Mendoza, C.A., Kooistra, L., Soons, M.B., Teuling, A.J., 2021. Emerging forest–peatland bistability and resilience of European peatland carbon stores. Proc. Natl. Acad. Sci. 118 (38), e2101742118 https://doi.org/10.1073/pnas.2101742118.

van Nes, E.H., Scheffer, M., 2003. Alternative attractors may boost uncertainty and sensitivity in ecological models. Ecol. Modell. 159 (2), 117–124. https://doi.org/10.1016/S0304-3800(02)00278-8.

Waddington, J.M., Kellner, E., Strack, M., Price, J.S., 2010. Differential peat deformation, compressibility, and water storage between peatland microforms: implications for ecosystem function and development. Water Resour. Res. 46 (7) https://doi.org/10.1029/2009WR008802.

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

Wagner, S.T., Isnard, S., Rowe, N.P., Samain, M.-S., Neinhuis, C., Wanke, S., 2012. Escaping the lianoid habit: evolution of shrub-like growth forms in Aristolochia subgenus Isotrema (Aristolochiaceae). Am. J. Bot. 99 (10), 1609–1629. https://doi.org/10.3732/ajb.1200244.

Wallén, B., 1986. Above and below ground dry mass of the three main vascular plants on hummocks on a subarctic peat bog. Oikos 46 (1), 51–56. https://doi.org/10.2307/3565379.

Wallèn, B., 1987. Growth pattern and distribution of biomass of calluna vulgaris on an ombrotrophic peat bog. Holarctic Ecol. 10 (1), 73–79. http://www.jstor.org/stable/3682127.

Wallén, B., Falkengren-Grerup, U., Malmer, N., 1988. Biomass, productivity and relative rate of photosynthesis of sphagnum at different water levels on a South Swedish Peat Bog. Holarctic Ecol. 11 (1), 70–76. http://www.jstor.org/stable/3682591.

Wang, H.F., 2000. Theory of Linear Poroelasticity With Applications to Geomechanics and Hydrogeology. Princeton University Press.

Whittington, P., Strack, M., Haarlem, R.v., Kaufman, S., Stoesser, P., Maltez, J., Price, J. S., Stone, M., 2007. The influence of peat volume change and vegetation on the hydrology of a Kettle-Hole wetland in Southern Ontario, Canada. Mires Peat 2.

Whittington, P.N., Price, J.S., 2006. The effects of water table draw-down (as a surrogate for climate change) on the hydrology of a Fen Peatland, Canada. Hydrol. Processes 20 (17), 3589–3600. https://doi.org/10.1002/hyp.6376.

Wierda, A., Fresco, L.F.M., Grootjans, A.P., van Diggelen, R., 1997. Numerical assessment of plant species as indicators of the groundwater regime. J. Veg. Sci. 8 (5), 707–716. https://doi.org/10.2307/3237376.

Young, D.M., Baird, A.J., Charman, D.J., Evans, C.D., Gallego-Sala, A.V., Gill, P.J., Hughes, P.D.M., Morris, P.J., Swindles, G.T., 2019. Misinterpreting carbon accumulation rates in records from near-surface peat. Sci. Rep. 9 (1), 17939. https://doi.org/10.1038/s41598-019-53879-8.

Young, D.M., Baird, A.J., Gallego-Sala, A.V., Loisel, J., 2021. A cautionary tale about using the apparent carbon accumulation rate (aCAR) obtained from peat cores. Sci. Rep. 11 (1), 9547. https://doi.org/10.1038/s41598-021-88766-8.

Yu, Z., Campbell, I.D., Vitt, D.H., Apps, M.J., 2001. Modelling long-term peatland dynamics. I. Concepts, review, and proposed design. Ecol. Modell. 145 (2), 197–210. https://doi.org/10.1016/S0304-3800(01)00391-X.

Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W., Hunt, S.J., 2010. Global peatland dynamics since the Last Glacial Maximum. Geophys. Res. Lett. 37 (13) https://doi.org/10.1029/2010GL043584.

Zhu, J., Wang, Y., Wang, Y., Mao, Z., Langendoen, E.J., 2020. How does root biodegradation after plant felling change root reinforcement to soil? Plant Soil 446 (1), 211–227. https://doi.org/10.1007/s11104-019-04345-x.