Review of revision to Mahdiyasa *et al*.: 'MPeat2D –A fully coupled mechanical-ecohydrological model of peatland development in two dimensions' submitted to *EGUSphere*

Overview

This is a revised version of a paper I reviewed in December 2023. The authors are thanked for their efforts in responding to my original comments; the revision is an improvement on the original. However, I feel the authors' responses in places fall short of addressing the original concerns that I raised. Below I reproduce my original comments in black, the authors' rebuttal in green, and my response in brown. I use the authors' numbering.

1. The authors present the results from a single model parameterisation. In a previous paper on the 1D model, Mahdiyasa et al. (2023) report modelled fluctuations of surface level of as much as 25 cm in response to variations in water-table position of about 50 cm. Such a large range in surface elevation seems generally implausible for *Sphagnum* peats, except floating mats in bog pools. In my experience, variations in surface elevation are typically a factor of four to five less than simulated by the 1D model. The authors cite Whittington and Price (2006) who report substantial changes in the position of the peat surface relative to the tubes of unanchored piezometers, but such instruments cannot be taken as reliable indicators of surface elevation.

Although this paper does not present the 1D model, the comment is worth considering. The range of surface motion simulated from 1D model of MPeat (Mahdiyasa et al., 2023) is in agreement with the field observation from Howie and Hebda (2018), who measured the surface oscillation of the raised bog with different plant communities. The range of surface motion reported by Howie and Hebda (2018) from peatland sites dominated by *Sphagnum* is about 15-30 cm. Furthermore, it should also be noted that the actual magnitude of the surface oscillation will depend on the specific site history, which we have not yet attempted to model.

The authors are right that Howie and Hebda (2018) report large oscillations in peat surface level for *Sphagnum* peat. I admit to being surprised by the values reported, but am also satisfied that Howie and Hebda used robust techniques for measuring surface levels. Notwithstanding, the authors must also know that, in many cases, the amount of fluctuation is very much less than 20-30 cm. For example, co-author Large has measured directly much smaller oscillations in areas of *Sphagnum* blanket bog (Marshall *et al*. 2022: file:///C:/Users/User/Downloads/remotesensing-14-00336.pdf). Howie and Hebda also cite Mawby (1995) (Effects of damming peat cuttings on Glasson Moss and Wedholme Flow, two lowland raised bogs in northwest England. In B. D. Wheeler, S. C. Shaw, W. J. Fojt, & R. A. Robertson (eds), *Restoration of Temperate Wetlands*. New York: John Wiley & Sons Ltd.) who measured fluctuations of 3-3.5 cm on raised bogs in northern England. Relatively small annual ranges of a few cm are also reported for *Sphagnum* peat bogs in west Wales including for central bog areas in a near-natural condition (Hrysiewicz et al., 2023: file:///C:/Users/User/Downloads/remotesensing-14-00336.pdf). My point is that surface motion and poro-elastic effects may, in many cases, be much smaller than simulated by the authors; in other words their findings about the importance of poro-elasticity in peatland

development may be exaggerated. It would be very useful if they could indicate what levels of surface motion are simulated in the model runs that they present in the paper so that readers can place the results in the context of published data on surface motion.

2. The parameterisation used in the current paper is different from that in Mahdiyasa et al. (2023) and the surface motion across the 2D model is not presented or discussed. However, I'd be interested in knowing what happens when the poro-elastic effect is 'dialled down'. How different are the model results? At what point does the poro-elastic effect become of secondary importance compared to the ecological and hydrological processes? I think the paper would benefit from a short section looking at model sensitivity to the degree of poro-elasticity.

We have added a short section related to the sensitivity analysis of the model (**lines 341-345 and 443-459**). We changed the peat Young's modulus, which determines the peat stiffness and is an important variable in the poroelasticity model. A more detailed analysis of the poroelastic effect is beyond the scope of this paper as it would ideally be done relative to field measures and specific peatland types. Our objective in this paper is to present the structure of a fully coupled mechanical-ecohydrological model for peat growth in two dimensions and consider the potential implications of feedback within this model system. This is discussed throughout the manuscript, and this message is strengthened in the discussion to indicate clearly the importance of mechanical-ecohydrological processes together with the spatial variability of water table depth, plant functional types composition, and peat physical properties on peatland behaviour.

I appreciate the authors wishing to showcase their model, but their point about saving a more detailed analysis of the poro-elastic effect doesn't make sense because in the paper they compare their model with the original version of DigiBog which does not contain the effect. I comment later on the problems of the comparison with DigiBog. Surely, the best way of gauging the importance of the poro-elastic effect is to run their model with the effect switched off and with the effect turned on such that it gives surface motions that are in the range of typical values noted above. I don't understand why the authors won't do this; it should be a key part of evaluating and presenting the new model. Hence, I disagree with their closing comment above suggesting their model "indicate[s] clearly the importance of mechanical-ecohydrological processes".

3. The authors compare the spatial pattern in their data with data from a blanket bog in Ireland. Although there is some overlap between raised bogs – which is what the authors simulate – and blanket bogs, the two peatland types can be quite different, and I am not sure it makes sense to compare the model of one type with the field results of the other. The authors also report that their simulated peat properties fall within the ranges reported in the literature. I don't think such a comparison is that useful because properties such as hydraulic conductivity can show enormous variation across different peats – 'peat' is not a single soil type. This means that, almost regardless of the values simulated by the model, it will fit within the observed range.

Although the peatland type from Lewis et al. (2012) is different from our simulations, the main reason for the comparison is to demonstrate the ability of the model to produce

reasonable outputs of the spatial variability on peat physical properties, including bulk density and hydraulic conductivity. We do not parameterise the model to simulate specific peatland sites and focus on developing a general peatland model. Therefore, we compare our results with the typical range of peat physical properties obtained from the previous studies. We added a few lines to clarify this issue (**lines 522-524**).

The authors do not address my concern. It doesn't make sense to suggest the model is reasonable because its values of hydraulic conductivity fall within the several orders of magnitude range of hydraulic conductivities recorded for peats.

4. A somewhat different point applies to the model-data comparison for the rate of peat and carbon accumulation. As shown by Young *et al*. (2021) (https://www.nature.com/articles/s41598-021-88766-8) it is not possible to obtain past rates of net peat and carbon accumulation from the first derivative of the age-depth curve. Studies that purport to do so are, unfortunately, in error and shouldn't be used for model-data comparisons.

We do not take the first derivative of the age-depth curve. We calculate the long-term rate of carbon accumulation based on the total amount of carbon and the total time of simulations. After that, we compare the results with available data from the previous study. We added a few lines to clarify this issue (**lines 539-540**).

I understand the authors do not take the first derivative of the age-depth curve. However, the studies to which they compare their model results do, and it is these studies that are in error; they should not be used to validate the net C balance of MPeat2D. So, again, I caution against comparing model results to these other studies.

5. The authors don't compare their predictions of peatland shape with data. Many raised bogs approximate a hemi-ellipse in cross section, but the MPeat2D results shown in Figures 5 and 8 show what seems to be a very different profile. I am not convinced the model has that much skill in representing overall peatland form. The authors are encouraged to compare the modelled cross-sectional shape with real raised bogs.

The hemi-ellipse shape of the peatland in the cross-section is proposed by Ingram (1982) through the Groundwater Mound Hypothesis (GMH). This shape is obtained by assuming constant hydraulic conductivity throughout the profile, which is not true because the field observation from Baird et al. (2008) and Lewis et al. (2012) showed that hydraulic conductivity changes in the vertical and horizontal directions. Armstrong (1995) modified the GMH by proposing non-uniform hydraulic conductivity that exponentially decreases with depth, showing different predictions of peatland shape and thickness. This model produces a lower hydraulic gradient at the margin, which is in agreement with our model MPeat2D. Comparing MPeat2D with the shape of a real raised peatland requires specific parameterisation of that site, including peat physical properties, substrate characteristics, and information about peatland age, which might reduce the generalisation obtained from MPeat2D simulations. Note that the primary purpose of this paper is to present a model that can then be developed for a wide range of purposes. We added a few lines to clarify this issue (**lines 578-584**).

The authors do not address my concern. My original point is that many raised bogs (most?) are approximately hemi-elliptical in cross section, and that MPeat seems to predict very different shapes from this common form. It is interesting to consider whether peatlands fit or don't fit Ingram's and Armstrong's models, but that is not the point I am making. I am concerned that MPeat doesn't give the right general shape as revealed by data from topographic surveys across many raised bogs. I agree with the authors' desire to avoid, at this stage, a detailed comparison with a specific site (see 6 below), but I think it would be useful for them to comment on the general realism of their model predictions.

6. I understand the desire of the authors to produce some 'generic' model results, but it would also be useful, whether in this paper or a follow-up paper, to apply the model to a particular site to see how well it simulates overall peatland shape, peat properties, and the age-depth curve.

We agree with the referee's comments that a comparison with the particular site would also be useful. However, we believe the site comparison should be conducted after the conceptual and generic model is developed.

I agree with the authors and look forward to their papers on such detailed comparisons.

7. In the discussion section the authors compare their model's predictions with those from DigiBog. I can't be sure, but they seem to have used an early prototype of DigiBog from 2012 which has long been superseded (since 2014). More recent versions of DigiBog produce a more realistic margin to raised bogs. The authors do not indicate how DigiBog was parameterised, so it is unclear what is being compared here. The DigiBog team, of which I am a member, would be happy to share more recent model code with the authors should they want to use it. Finally, the comparison with DigiBog should be reported in the Model Implementation and Results sections, and not just the Discussion; it is odd to report results in a discussion section.

We compare MPeat2D with the earlier version of DigiBog because both models have similar characteristics, including the flat and impermeable substrate with the symmetric assumption of peatland growth. Moreover, both models also assume that water ponding was lost immediately to the margin. We have tried to use more recent versions of DigiBog by contacting the DigiBog team. However, because of the different and complex parametrisation and setup, the more recent DigiBog versions produce incomparable simulation results to the MPeat2D. The more recent DigiBog versions employ a layer lumping system after some specific time and thickness. This approach results in faster simulation because it reduces the number of layers that become the domain of calculation. However, the different parametrisation of the layer lumping appears to change the results and stability of the DigiBog. Furthermore, the more recent version includes the parameter of mineral soil and water ponding thickness, which also influences the model outputs. These additional features and parameters lead to incomparable conditions with MPeat2D. We agree that the comparison with DigiBog should be reported in the Model Implementation and Results sections. We added a few lines to explain the reason for choosing the earlier version of DigiBog and provide the DigiBog parameter in the Implementation and Results sections (**lines 326-338 and 428-440**).

I find these comments disappointing and somewhat unbecoming. I am quite happy for DigiBog to be criticised. However, the comments above are based on a lack of understanding of how the model works*. The original and now obsolete version of DigiBog was based on running the hydrological model to a steady state for each ecological time step. The new version of the model is fully dynamic hydrologically, and, for that reason, can be expected to give different results from the original. The DigiBog team have thoroughly tested the lumping part of the code and it produces near-identical results to unlumped versions provided the maximum lumping layer thickness is not set too high. The current version of the model can, of course, simulate flat landscapes as well as sloping ones, and can account for situations where no water is stored on the peatland surface (as with the original obsolete version of the model). The model can experience instability if the hydrological timesteps are set too low. Spatial oscillations can also occur in the model depending on how flows to the model boundary are set and how surface ponding levels are chosen. Dealing with such issues is a normal part of numerical modelling.

A bigger concern is that DigiBog is not equivalent to MPeat in all respects apart from having no poro-elastic effect. The results from DigiBog will depend on what values are set for drainable porosity, dry bulk density, and the hydraulic conductivity function. Very different results are possible for the model depending on how these parameters are set. This parametrisation issue is not discussed at all by the authors. As noted earlier (point 2 above), if the authors wish to know how poro-elasticity affects model outputs, they should simply run a version of MPeat with the effect removed – surely, they can parameterise the model in this way. If they do this and can show that ignoring the poro-elastic effect leads to significant differences in model output, then it is fine for them in their discussion to criticise models such as DigiBog for not including the effect. Therefore, I recommend they remove the comparison with DigiBog and run their model with the poro-elastic effect turned off.

*The DigiBog team provided the authors with the new DigiBog code and help with running it. The authors had some difficulties in setting up the parameters and getting the model to work properly. We were, and are, happy to continue helping them, but they have not followed up on this invitation.

8. When building a model, modellers usually try and include all the key processes, leaving out those to which the model is not sensitive. There are many ways in which models such as DigiBog might be improved, such as the decay routines which are heavily empirical. The decision on what to include and exclude is also dependent on how much is known about a process. If information on the process is sparse then it will be difficult to include. I welcome the authors looking at the effects of poro-elasticity on peatland development, but I think there remains considerable uncertainty about the importance of the process.

Peat is a mechanically weak poroelastic material due to the low value of Young's modulus (Dykes, 2008; Mesri & Ajlouni, 2007), shear, and tensile strength (Boylan et al., 2008; Dykes, 2008; Dykes & Warburton, 2008; Hendry et al., 2011; O'Kelly, 2015). As a result, the changes in peat pore structure, which significantly influence hydraulic properties, are not only determined by progressive decomposition (Moore et al., 2005; Quinton et al., 2000) but also compression. Hydraulic conductivity decreases when the water table drops due to the

mechanical deformation in the pore structure (Whittington & Price, 2006), an important process that can reduce water discharge from peatland. In addition, compression also reduces peat volume, causing the peatland surface to drop. This drop in the peat surface acts to maintain the relative position of the water table, which in turn helps sustain PFTs associated with wet surface conditions (Schouten, 2002; Waddington et al., 2015). The detailed explanation related to the importance of poroelasticity on peatland development is presented in the Mahdiyasa et al. (2022) and Mahdiyasa et al. (2023).

The authors do not address my concern here. They seem to be saying that, because peat is a poro-elastic medium, the poro-elastic effect *has* to be important. If they run their model with a poro-elastic effect set to reproduce a reasonable degree of surface motion and show that that produces a very different peatland from one where the effect is turned off (see 7 above) then I think they are in a position to say that the effect is important. I know from my own work on measuring hydraulic conductivity using piezometer slug tests that sometimes the peat around the piezometer intake behaves like a rigid soil, and sometimes it doesn't; just because the medium is poro-elastic does not mean the effect is important. I am quite happy to acknowledge that it is, but want that to be demonstrated using the MPeat comparisons I recommend above. In particular, I think it is important to know at what degree of poro-elasticity does the effect become significant.

9. Other processes about which quite a lot is known include the build up, release, and dissolution of biogenic gas bubbles below the water table on an annual cycle. Bubbles may occupy more than 20% of the total peat volume, blocking pores and reducing the peat's hydraulic conductivity, and also making the peat more buoyant. To me, these effects would seem to equal or perhaps exceed the effects of poro-elasticity and I would be interested in hearing, via the discussion section, what the authors thought about this possibility.

We agree that entrapped gas bubbles could have a significant influence on the peatland behaviour. The entrapped gas bubbles influence hydraulic conductivity (Baird & Waldron, 2003; Beckwith & Baird, 2001; Reynolds et al., 1992) and pore pressure (Kellner et al., 2004), which results in variations of effective stress. Consequently, the mechanical deformation of peat pore space, including the shrinking or swelling, is also affected by the presence of gas bubbles. The simulation from Reeve et al. (2013) suggested that a higher gas content results in a more significant peatland surface deformation. We could expand the poroelasticity formulation below the water table to accommodate more than one fluid, for example, water and gas mixture (Kurzeja & Steeb, 2022). This modification requires generalisation in Biot's theory of consolidation to model multiphase fluid saturation. We added a paragraph to provide a brief discussion related to this possibility (**lines 605-613**).

What the authors say here seems reasonable. I would add that variations in bubble contents may or may not cause changes in peat volume. This is an interesting area of research that requires more work.

The authors also responded to the comments I made directly on the manuscript. I comment below on only a selection of the responses. I have retained the numbering used by the authors in their rebuttal.

20. Line 225 How does this equation compare to what is revealed in the meta-analysis of Morris et al. (2022)?

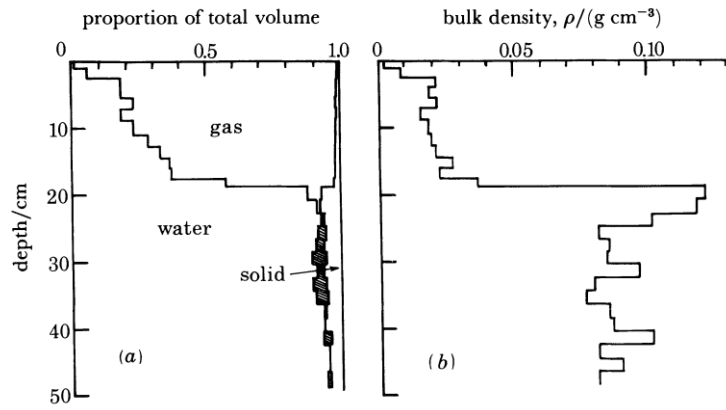
The Equation (19) in the MPeat2D is developed based on the exponential relationship between hydraulic conductivity and active porosity through the generalized Kozeny-Carman equation. The basic idea for this relationship is that changing active porosity due to compression affects hydraulic conductivity because water cannot move easily as the pore size becomes smaller. Contrastingly, Morris et al. (2022) developed a linear model to predict hydraulic conductivity from other independent variables, including depth, bulk density, von Post score, and categorical information. We added a few lines to provide the explanation related to the comparison with Morris et al. (2022) (lines 239-242).

The authors don't answer my question. For similar dry bulk densities and degree of decay, does MPeat2D produce a similar value of K to the Morris *et al*. (2022) model, which, of course, is data-based? Also, Morris *et al*. (2022) developed a model that predicts log-linear and log-log relationships with other physical variables, so it is not a simple linear model as implied in the authors' response above.

32. Line 396 I don't think this paper is cited correctly here. Clymo (2004) actually shows bulk density being constant while K declines with depth, which is contrary to what is predicted by MPeat.

In the manuscript, we cite Clymo (1984), who provides the data of bulk density with depth, as shown by Figures 1, 8, and 16. The bulk density profile from Clymo (1984) is in agreement with MPeat2D simulations, which indicates an increasing value from the top surface to the bottom layer. For Clymo (2004), we agree to delete this reference from the paper (line 491).

I agree that I wrongly highlighted Clymo (1984) and then discussed Clymo (2004). However, Clymo (2004) was referenced in the same parentheses, so my point surely remains. And why now delete reference to Clymo (2004)? It contains data that don't conform with the authors' model so should cited as counter-evidence that the model is producing the right patterns.

I looked again at Clymo (1984) to check the authors' claim that it supports their model. I reproduce below Figures 1, 8, and 16 from Clymo (1984) as cited by the authors. Figure 1 shows a short section of a peat profile. There is a step increase in bulk density at a depth of 20 cm and then a decline to a depth of 50 cm, with no data from deeper in the profile, so I am not sure the pattern is as expected from MPeat2D. Figure 8 shows a general increase in bulk density with depth over a depth range of several metres. However, between the ground surface and a depth of ~2.7 metres the bulk density is constant. Again, this seems to be inconsistent with MPeat2D. Figure 16 shows data to a depth of ~90 cm and shows a general increase in bulk density. It is noteworthy that Clymo (1984) includes other datasets – in Figures 7 and 12, which are also reproduced below – some of which show no depth trend in bulk density values. It is not clear why the authors ignore these figures in their rebuttal. Clymo (1984) is perhaps not as supportive of the authors' claims as they suggest.

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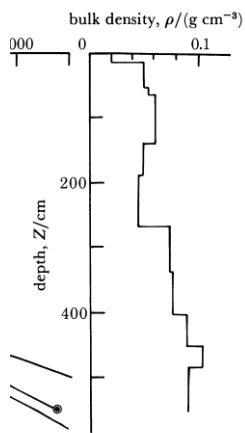
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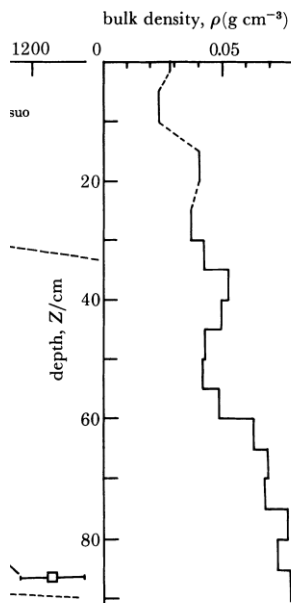
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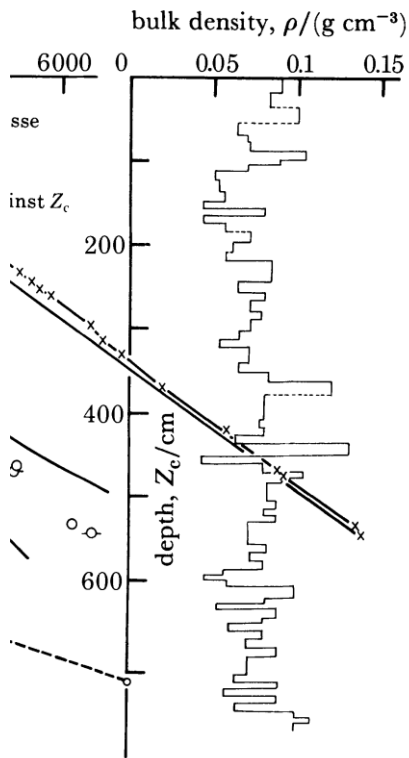
Figure 7.
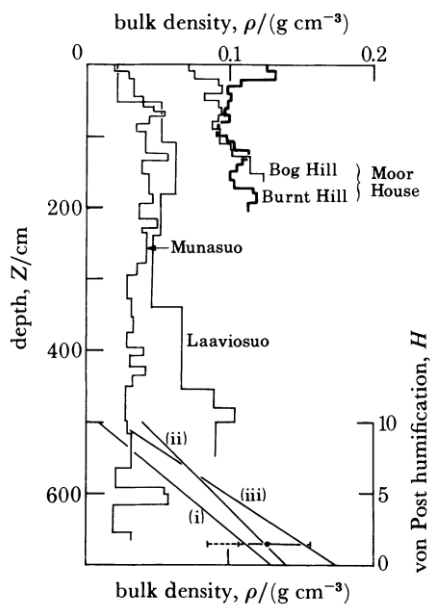
Figure 12 (Munasuo data).

39. Line 460 What parameterisation was used for DigiBog? What bulk density was used, and was *K* set to be comparable to the values used in MPeat2D?

We used the parameterisation from Morris *et al.* (2012) with the value of bulk density equal to 100 kg m^{-3} and the hydraulic conductivity parameters a and b equal to 1×10^{-5} m s^{-1} and 8, respectively.

The authors are thanked for their response here, but they still don't compare the *K* values – how different were the two models in this respect?

I have also added comments to the track-changed version of the revised manuscript; these comments are for both the editor and authors. In conclusion, I note:

- The authors' work is scientifically interesting and certainly deserves to be published in some form.
- The authors appear to assume that because peat is a poro-elastic medium, the poro-elastic effect must be an important control on peatland development. In some (perhaps many) circumstances it may not be.
- Despite the authors' claims, some features of the model's output – for example, peatland shape and the depth distribution of peatland properties such as dry bulk density and hydraulic conductivity – don't appear to have strong empirical support. I think the authors could have been more explicit about what the model seems to do well and what it doesn't do so well, and possible reasons for the latter.

As before, and in the spirit of scientific openness, I ask that my name be revealed to the authors.

Andy Baird,
Chair of Wetland Science, University of Leeds, UK;
24th April 2024.

MPeat2D − A fully coupled mechanical-ecohydrological model of peatland development in two dimensions

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Abstract. Higher dimensional models of peatland development are required to analyse the influence of spatial heterogeneity and complex feedback mechanisms on peatland behaviour. However, the current models exclude the mechanical process that leads to uncertainties in simulating the spatial variability of water table position, vegetation composition, and peat physical properties. Here, we propose MPeat2D, a peatland development model in two dimensions, which considers mechanical, ecological, and hydrological processes together with the essential feedback from spatial interactions. MPeat2D employs poroelasticity theory that couples fluid flow and solid deformation to model the influence of peat volume changes on peatland ecology and hydrology. To validate the poroelasticity formulation, the comparisons between numerical and analytical solutions of Mandel's problems for two-dimensional test cases are conducted. The application of MPeat2D is illustrated by simulating peatland growth over 5000 years above ~~the~~ a flat and impermeable substrate with free-draining boundaries at the edges, using constant and variable climate. In both climatic scenarios, MPeat2D produces lateral variability of water table depth, which results in the variation of vegetation composition. Furthermore, the drop of the water table at the margin increases the compaction effect, leading to a higher value of bulk density and a lower value of active porosity and hydraulic conductivity. These spatial variations obtained from MPeat2D are consistent with the field observations, suggesting plausible outputs from the proposed model. By comparing the results of MPeat2D to a one-dimensional model and a two-dimensional model without the mechanical process, we argue that ~~the significance of~~ mechanical-ecohydrological feedbacks are important ~~on~~ for analysing spatial heterogeneity, ~~peatland~~ shape, carbon accumulation, and resilience of the peatland. ~~is highlighted.~~

1 Introduction

In this paper, we provide a fully coupled mechanical-ecohydrological model of peatland development in two dimensions (2D). The continuum representation of the peatland employed by the proposed model results in the advancement of peatland modelling, particularly if we consider questions relating to the phenomena for which mechanical process and feedback are

essential components. Examples of these phenomena include the analysis of mechanical limits to peatland stability and the relationship between topography, peat physical properties, and carbon accumulation. The purpose ~~emphasis~~ of this paper is to explain the formulation of the model, which is developed from an earlier one-dimensional (1D) mechanical-ecohydrological model~~s~~ (Mahdiyasa et al., 2023; Mahdiyasa et al., 2022). Its application is illustrated through the simulations of the long-term peatland growth over millennia under idealised conditions. To consider the consequences of incorporating spatial variability and mechanical process on the peatland behaviour, we compare our results with the existing peatland growth models, including a 1D model without spatial variability MPeat (Mahdiyasa et al., 2023; Mahdiyasa et al., 2022) and a 2D stiff non-continuum model DigiBog (Baird et al., 2012; Morris et al., 2012).

The spatial variability of ~~on~~ the peatland is widely evidenced by the changes in the horizontal and vertical directions of peat physical properties, including bulk density, active porosity, and hydraulic conductivity. The horizontal variation of hydraulic conductivity was observed by Lapen et al. (2005), who found that hydraulic conductivity is lower at the margin than at the centre based on the field measurements and analysis of a ~~the~~ peatland groundwater flow model. Field observations from Baird et al. (2008) and Lewis et al. (2012), who measured lateral variability of the hydraulic conductivity in a raised and a blanket peatland, respectively, agree with the Lapen et al. (2005) finding. Lewis et al. (2012) also observed the lateral variability in bulk density, which increased from the centre toward the margin. In the vertical direction, deeper peat exhibits a higher value of bulk density and a lower value of active porosity and hydraulic conductivity, with abrupt changes occurring between the unsaturated and saturated zones (Clymo, 2004, 1984; Hoag and Price, 1997; Hoag and Price, 1995; Quinton et al., 2008; Quinton et al., 2000; Fraser et al., 2001). Moreover, the meta-analysis from Morris et al. (2022) with an extensive database of hydraulic conductivity and bulk density also indicates that depth significantly affects these peat physical properties.

The spatial variations of peat physical properties occur because of the fully coupled mechanical-ecohydrological processes. As a porous medium with a low value of Young's modulus (Long, 2005; Mesri and Ajlouni, 2007; Boylan et al., 2008; Dykes and Warburton, 2008), the peat body is susceptible to deformation. The deformation is non-uniform throughout the peatland area due to the spatial variations of water table depth that influence the effective stress (Whittington and Price, 2006; Price, 2003; Price et al., 2005; Waddington et al., 2010). For example, the increase in water table depth at the margin leads to higher bulk density and lower active porosity and hydraulic conductivity, preventing greater water discharge from the deeper peat. Consequently, Lapen et al. (2005) posited that a lower hydraulic conductivity at the margin has a significant influence on maintaining the wet condition at the centre, which in turn affects peat accumulation. Therefore, the spatial variations of peat physical properties potentially provide essential feedback as the peatland develops.

Higher dimensional models of peatland development ~~assume constant or limited spatial variations of peat physical properties and~~ ignore mechanical feedback (e.g., Ingram, 1982; Winston, 1994; Armstrong, 1995; Korhola et al., 1996; Borren and Bleuten, 2006; Baird et al., 2012; Morris et al., 2012; Swinnen et al., 2019) and assume constant or limited spatial variations of peat physical properties. For example, Borren and Bleuten (2006) proposed a three-dimensional model (3D) of peatland development based on the groundwater flow model (Boussinesq, 1871) and focused on the ecohydrological feedback between water table position with peat production and decomposition following the Clymo (1984) model. The mechanical compaction

is assumed to be negligible, and the spatial variations in the bulk density and hydraulic conductivity are obtained based on the empirical relationship between different peatland types, consisting of bog, throughflow fen, and fen. DigiBog (Baird et al., 2012; Morris et al., 2012) is a 1D, 2D, or 3D model of peatland development that accommodates the spatial changes in hydraulic conductivity through the differences in remaining mass that are affected by water table position and decomposition processes (Moore et al., 2005; Quinton et al., 2000). Although DigiBog captures more complex feedback between ecological and hydrological processes than the model from Borren and Bleuten (2006), the omission of mechanical feedback leads to the assumption of constant active porosity and bulk density as the peatland grows. Cobb et al. (2017) developed a 2D tropical peatland growth model to analyse the influence of climate, particularly the rainfall pattern, on carbon storage. This model simulates the dynamics of the water table and peat accumulation through the groundwater flow model (Boussinesq, 1871) and the difference between peat production and decomposition. The carbon storage is estimated from the stable peat surface Laplacian that is affected by the rate of peat production and decomposition. The peat surface Laplacian indicates the curvature of the peat surface, calculated as the sum of second derivatives of surface elevation. Although surface Laplacian provides information related to the peatland morphology, this model ignores the mechanical feedback and assumes a constant value of hydraulic conductivity that becomes the source of uncertainty in estimating the peatland carbon storage.

This paper, therefore, sets out to (1) provide the formulation of a fully coupled mechanical-ecohydrological model of peatland development in 2D called MPeat2D, (2) investigate model outputs in the idealised peatland growth scenario, (3) analyse the potential consequences of mechanical-ecohydrological feedback on the long-term peatland carbon accumulation and resilience by comparison with ~~the~~ other peatland development models. The structure of this paper is presented in three main parts. First, we consider the mathematical formulation, consisting of mechanical, ecological, and hydrological submodels, together with the numerical verification of the MPeat2D. Second, we explain how to implement MPeat2D to simulate long-term peatland growth over millennia and provide examples of model outputs. Third, we examine the implications obtained from MPeat2D to understand peatland behaviour and conclude the analysis by addressing the areas in which further development from the model is required. Although MPeat2D is focused on ombrotrophic peatlands with temperate climates, the framework proposed in this paper could be employed to model the other peatland types.

2 Model formulation and verification

MPeat2D is a fully coupled mechanical, ecological, and hydrological model of long-term peatland growth in two dimensions, which takes spatial variability and structure into consideration. MPeat2D is developed based on the continuum concept (Irgens, 2008; Jog, 2015) that assumes peatland constituents, both solid and fluid particles, entirely fill the peatland body. Through this approach, the conservation of mass can be appropriately defined to formulate mechanical processes on the peatland obtained from the coupling between solid deformation and fluid flow or known as poroelasticity that becomes the core of the model (see the mechanical submodel) (Biot, 1941; Detournay and Cheng, 1993; De Boer, 2000; Wang, 2000; Coussy, 2004). The mechanical deformation of peat pores space affects physical properties, including bulk density, active porosity, and hydraulic

conductivity, resulting in different peatland behaviour (Fig. 1). For example, the changes in active porosity and hydraulic

100   conductivity influence the water table position, which in turn determines peat production and decomposition processes (Belyea and Clymo, 2001; Clymo, 1984). Furthermore, the proportion of plant functional types (PFT) and the plant weight are also affected because they are a function of the water table depth (Moore et al., 2002; Munir et al., 2015; Peltoniemi et al., 2016; Kokkonen et al., 2019; Laine et al., 2021). The plant weight at the top surface produces loading that leads to compaction and provides feedback on the peat physical properties. By having fully coupled mechanical, ecological, and hydrological processes,

105   MPeat2D incorporates realistic spatial variability on the peatland and allows for more significant insights into the interplay between these complex feedback mechanisms. As explained below, the formulation of MPeat2D is divided into mechanical, ecological, and hydrological submodels.
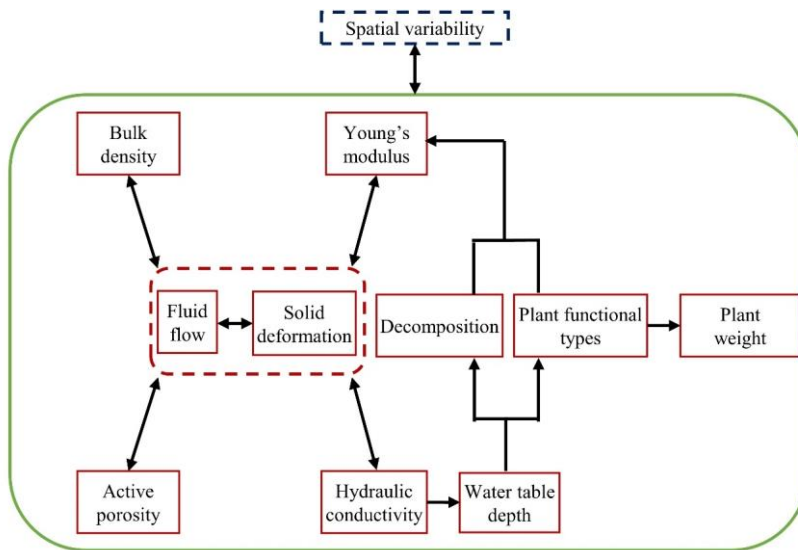
Figure 1: Illustrative formulation of MPeat2D that involves mechanical, ecological, and hydrological processes together with the
110   **feedback from spatial variability on the peatland under a single mathematical and numerical framework.**

2.1 Mechanical submodel

The mechanical deformation on the peat body is influenced by the stiffness of the peat solid skeleton and the behaviour of the pore fluid. Reeve et al. (2013) found that a higher value of Young's modulus, which represents the stiffness of the material, leads to a lower deformation effect on the peat body. Furthermore, the characteristics of fluid contained in the peat pore space,

115   including gas content and degree of saturation, also significantly affect the deformation due to the presence of pore fluid

pressure (Boylan et al., 2008; Price and Schlotzhauer, 1999; Price, 2003). Therefore, the mechanical submodel is developed based on the poroelasticity theory, which couples solid deformation and fluid flow.

We employ a fully saturated poroelasticity in 2D (Biot, 1941) to model the saturated zone of the peatland below the water table, with the governing equations as follows. The equation of equilibrium can be formulated by considering the stress tensor

120 acting on a small elementary area, as written below

$$\overline{\nabla}^{\mathrm{T}}\boldsymbol{\sigma} + \mathbf{b} = 0, \tag{1}$$

with $\overline{\nabla} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix}$ and $\mathbf{b} = \begin{bmatrix} 0 & (\rho_w\phi + \rho(1-\phi))g \end{bmatrix}^{\mathrm{T}}$. In this formulation $\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx}, \sigma_{yy}, \sigma_{xy} \end{bmatrix}^{\mathrm{T}}$ is the total stress tensor

(Pa), $\mathbf{b}$ is the body force (N m^{-3}), ρ_w is the water density (kg m^{-3}), ρ is the peat bulk density (kg m^{-3}), ϕ is the active porosity (–) and g is the acceleration of gravity (m s^{-2}). The presentation in terms of matrix form provides convenient

125 notation for the derivation of weak form and numerical calculation (Jha and Juanes, 2014).

The stresses on the peat body are distributed to the solid skeleton and pore fluid, resulting in solid displacement and pore fluid pressure. The stress associated with solid displacement is known as effective stress, and it is defined as

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \alpha\mathbf{m}p, \tag{2}$$

where $\boldsymbol{\sigma}' = \begin{bmatrix} \sigma'_{xx}, \sigma'_{yy}, \sigma'_{xy} \end{bmatrix}^{\mathrm{T}}$ is the effective stress tensor (Pa), $\boldsymbol{\sigma} = \begin{bmatrix} \sigma_{xx}, \sigma_{yy}, \sigma_{xy} \end{bmatrix}^{\mathrm{T}}$ is the total stress tensor (Pa), α is the

130 Biot's coefficient, $\mathbf{m} = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}^{\mathrm{T}}$ is the vector form of Kronecker's delta, and p is the pore water pressure (Pa). The linear constitutive law gives the relation between effective stress tensor and strain tensor through the following equation

$$\boldsymbol{\sigma}' = \mathbf{D}\boldsymbol{\epsilon}, \tag{3}$$

with $\mathbf{D} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix}$. In this formulation $\boldsymbol{\sigma}' = \begin{bmatrix} \sigma'_{xx}, \sigma'_{yy}, \sigma'_{xy} \end{bmatrix}^{\mathrm{T}}$ is the effective stress tensor (Pa),

E is the Young's modulus (Pa), ν is the Poisson's ratio (–), and $\boldsymbol{\epsilon} = \begin{bmatrix} \epsilon_{xx}, \epsilon_{yy}, \epsilon_{xy} \end{bmatrix}^{\mathrm{T}}$ is the strain tensor (–). The relation

135 between strain tensor and displacement is provided by the kinematics relations reads

$$\boldsymbol{\epsilon} = \overline{\nabla}\mathbf{u}, \tag{4}$$

where $\boldsymbol{\epsilon} = \begin{bmatrix} \epsilon_{xx}, \epsilon_{yy}, \epsilon_{xy} \end{bmatrix}^{\mathrm{T}}$ is the strain tensor (–) and $\mathbf{u} = \begin{bmatrix} u_x, u_y \end{bmatrix}^{\mathrm{T}}$ is the displacement (m). Finally, to complete the governing equations of the mechanical submodel, we employ the conservation of mass for solid and fluid constituents. By assuming that water flow in the peat pore space follows Darcy's law and the volumetric strain is the sum of linear strains, we

140 can formulate the relation between solid deformation, pore water pressure, and the water flow in the peat pore space as

$$\alpha \frac{\partial \epsilon}{\partial t} + S_s \frac{\partial p}{\partial t} = \nabla \cdot (\kappa \nabla p),$$ (5)

where α is the Biot's coefficient $(-)$, $\epsilon = \epsilon_{xx} + \epsilon_{yy}$ is the volumetric strain $(-)$, S_s is the specific storage (m^{-1}), p is the pore water pressure (Pa), and κ is the hydraulic conductivity $(m\ s^{-1})$.

In the unsaturated zone above the water table, we assume that the air pressure is equal to the atmospheric pressure because the
145   water table depth is usually less than 0.5 m in the peatland (Ballard et al., 2011; Swinnen et al., 2019; Mahdiyasa et al., 2022). Consequently, we can expand Eq. (5) to model the unsaturated zone by introducing parameters α_w and M_w that depend on the degree of saturation of water as follows (Cheng, 2020)

$$\alpha_w \frac{\partial \epsilon}{\partial t} + \frac{1}{M_w} \frac{\partial p}{\partial t} = \nabla \cdot (\kappa \nabla p),$$ (6)

with $\alpha_w = S_w$ and $M_w = \frac{\gamma_w (1-\lambda)}{\phi \lambda \mu} S_w^{-1/\lambda} \left(1 - S_w^{1/\lambda}\right)^{\lambda}$. In this formulation $\epsilon = \epsilon_{xx} + \epsilon_{yy}$ is the volumetric strain $(-)$, p is the
150   pore water pressure (Pa), κ is the hydraulic conductivity $(m\ s^{-1})$, S_w is the degree of saturation of water $(-)$, γ_w is the specific weight of water $(N\ m^3)$, ϕ is the active porosity $(-)$, λ is the first water retention empirical constant $(-)$, and μ is the second water retention empirical constant (m^{-1}).

The discretisation is required in order to solve the partial differential equations from poroelasticity formulation. In 1D, the discretisation is relatively simple because it is conducted over a vertically oriented domain, the length of which represents the
155   height of a peatland (Mahdiyasa et al., 2023; Mahdiyasa et al., 2022). However, in 2D, the discretisation becomes more complex and is carefully done to circumvent numerical instabilities (George, 2000; Edelsbrunner, 2001; Zhu et al., 2006). We implement the Delaunay triangulation, which provides an optimal and non-overlapping connection between the neighbouring triangles from the data sets of points to create a 2D mesh (Shewchuk, 2002). The Delaunay triangulation does not require a predetermined equation for domain descriptions, which is relevant for our model because the internal and external feedback
160   mechanisms influence the shape and domain of the peatland during the development process.

The peat stiffness, represented by Young's modulus, is modelled as a function of decomposition (Zhu et al., 2020) and plant functional types (PFT) (Whittington et al., 2007), following the formulation from Mahdiyasa et al. (2023)

$$E = \chi \left(1 + \theta_t^{\zeta}\right)(b_1 c_1 + b_2 c_2 + b_3 c_3),$$ (7)

where E is the Young's modulus (Pa), χ is the first Young's modulus parameter (Pa), ζ is the second Young's modulus
165   parameter $(-)$, θ is the remaining mass $(-)$, b_1, b_2, b_3 are the coefficient to couple PFT with Young's modulus $(-)$, and c_1, c_2, c_3 are the PFT proportions $(-)$ with the indices $1, 2, 3$ indicating shrub, sedge, and *Sphagnum*, respectively. The interactions between peat stiffness and the load from plant weight, new layer addition, and body force determine the vertical and horizontal displacement of peat solid particles, which affects the bulk density and active porosity due to the changes in the peat volume. We proposed the influence of solid displacement on the peat bulk density and active porosity in 2D as follows

170 $\quad \rho_t = \frac{\rho_{t-1}}{1+\beta_\rho \nabla \cdot \mathbf{u}},$ (8)

$\phi_t = \frac{\phi_{t-1}+\beta_\phi \nabla \cdot \mathbf{u}}{1+\nabla \cdot \mathbf{u}},$ (9)

where ρ is the bulk density (kg m^{-3}), β_ρ is the bulk density parameter ($-$), ϕ is the active porosity ($-$), β_ϕ is the active porosity parameter ($-$), and $\mathbf{u} = [u_x, u_y]^T$ is the displacement (m).

2.2 Ecological submodel

175 We use the formulation from Morris et al. (2015) for the peat production model ~~that is influenced by the water table depth and air temperature~~, written as

$\psi = 0.001(9.3 + 133z - 0.022(100z)^2)^2(0.1575Temp + 0.0091),$ for $0 \le z \le 0.668$ (10)

$\psi = 0,$ for $z > 0.668,$

where ψ is the peat production (kg m^{-2} yr^{-1}), z is the water table depth (m), and $Temp$ is the air temperature (℃). Although
180 the peat production model in Eq. (10) has a limitation related to the vegetation composition, this model can couple the ecological and hydrological processes through the dependency between peat production and water table depth. Furthermore, it also includes the effect of air temperature, which leads to a more realistic model. Another approach to model peat production is through the global Thornthwaite Memorial equation (Lieth, 1975) that simulates the primary productivity of the world. However, this model might omit the unique characteristics and the important feedback from the peatland ecosystem.

185 Peat production and the PFT proportion are employed to model the plant weight at the top surface through the following equation (Mahdiyasa et al., 2023; Mahdiyasa et al., 2022; Moore et al., 2002)

$Y = c_1\left(10^{\frac{log_{10}(\psi)+0.409}{0.985}}\right)(1+d_1)g + c_2\left(10^{log_{10}(\psi)+0.001}\right)(1+d_2)g + (c_3 0.144)(1+d_3)g,$ (11)

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
190 shrub, sedge, and *Sphagnum*, respectively. The proportions of PFT vary depending on the position of the water table, with the shrub becoming the dominant PFT in the low water table condition (Moore et al., 2002; Potvin et al., 2015; Kettridge et al., 2015). Therefore, we use a linear regression model from Mahdiyasa et al. (2023), which was developed from the Moore et al. (2002) data, to model the relationship between PFT proportions with the water table

$c_1 = 2.23z - 0.28,$ (12)

195 $c_2 = -1.42z + 0.63,$ (13)

$c_3 = -0.81z + 0.64,$ (14)

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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). We assign the minimum value of each PFT proportion equal to zero if the value is negative and normalise the total proportion.

200 The decomposition processes occur in the saturated and unsaturated zones of the peatland at different rates. In the saturated zone below the water table, the rate of decay is low due to ~~the anaerobic~~ anoxic conditions, while in the unsaturated zone above the water table, the rate of decay is significantly higher as a consequence of ~~the aerobic~~ oxic conditions that supports the decomposition processes. We follow the model from Clymo (1984) to calculate the changes in peat mass due to the decomposition

205 $$\frac{dm}{dt} = -\eta m, \tag{15}$$

where m is the mass per unit area (kg m^{-2}) and η is the rate of decay (yr^{-1}). We do not include the influence of temperature and recalcitrance in the decomposition model because they will increase the number of empirical parameters and assumptions, which might lead to a higher uncertainty of the model. The effect of temperature on the decomposition process could be employed through Q_{10} parameter (Morris et al., 2015). However, this parameter has a high range of values between 1 and 10,
210 which depends on the peatland types and temperature characteristics (Xiang and Freeman, 2009; Hardie et al., 2011). Moreover, the inclusion of the recalcitrance effect requires additional assumptions related to the changes in the rate of decay that could decline linearly or quadratically, as shown by Clymo et al. (1998).

The effect of decomposition is represented as the remaining mass, which is defined as the ratio between mass at time t, which has experienced decay, and the initial mass (Mahdiyasa et al., 2022; Baird et al., 2012; Morris et al., 2012; Morris et al., 2015)

215 $$\theta_t = \frac{m_t}{m_0}, \tag{16}$$

where θ is the remaining mass (−), m_t is the mass per unit area at time t (kg m^{-2}), and m_0 is the initial mass per unit area (kg m^{-2}).

2.3 Hydrological submodel

We model the peatland groundwater flows in 2D using the Boussinesq equation (Bartlett and Porporato, 2018) subject to net
220 rainfall that acts as a source term (Cobb et al., 2017; Baird et al., 2012; Morris et al., 2012)

$$S_y \frac{\partial W}{\partial t} = \nabla \cdot (T \nabla W) + r, \tag{17}$$

where W is the water table height (m), ~~S_s is the specific storage (m^{-1})~~ S_y is the specific yield (−), ~~κ is the hydraulic conductivity (m s^{-1})~~ T is the transmissivity (m^2 yr^{-1}), and r is the net rainfall (m yr^{-1}) that is defined as precipitation
225 minus evapotranspiration. The Boussinesq equation is ~~developed~~ based on the Dupuit and Forchheimer (D-F) assumption

(Bartlett and Porporato, 2018), which states that groundwater flows horizontally in unconfined aquifers. The D-F assumption is appropriate to model the peatland groundwater flow because the peatland lateral distance is much wider than the thickness, which leads to the dominant horizontal flow. We assume that the height of the water table cannot surpass the height of the peatland because the water will flow as surface water (Mahdiyasa et al., 2022; Morris et al., 2011). This would appear to be a realistic assumption because we do not simulate patterned peatlands. Consequently, the water table depth is obtained from the difference between peatland height and water table height as follows

$$z = h - FW, \tag{18}$$

where z is the water table depth (m), h is the peatland height (m), and FW is the water table height (m).

The mechanical deformation changes the peat pore structure, leading to variations in the active porosity (Eq. (9)) and influencing water flow through the pore space. Therefore, we implement the hydraulic conductivity model from Mahdiyasa et al. (2022), who formulate the changes in hydraulic conductivity as a function of active porosity

$$\kappa_t = \kappa_0 \left(\frac{\phi_t}{\phi_0}\right)^\xi, \tag{19}$$

where κ is the hydraulic conductivity (m s^{-1}), κ_0 is the initial value of hydraulic conductivity (m s^{-1}), ϕ is the active porosity (−), ϕ_0 is the initial value of active porosity (−), and ξ is the hydraulic conductivity parameter (−). Through this approach, we can capture the effect of mechanical deformation on the peatland hydrology. Compared to the hydraulic conductivity model developed by Morris et al. (2022) from the meta-analysis of northern peat samples, Eq. 19 provides a more straightforward approach to analyse the influence of mechanical deformation on peatland hydrology.

2.4 Numerical verification

The verification is focused on the mechanical submodel, particularly the poroelasticity formulation, by comparing numerical calculations with analytical solutions from Mandel's problem (Mandel, 1953). Uniform vertical load $2F$ is applied to a rectangular sample through a rigid and frictionless plate of width $2a$ and height $2H$, with drainage to the two sides in lateral condition as shown in Fig. 2. The deformation of the sample is forced to be in-plane strain condition by preventing all deformation in the direction perpendicular to the plane. The pore water pressure distribution will be homogeneous at the instant loading, but when drainage starts, the pore water pressure at two sides, $x = -a$ and $x = a$, are reduced to zero and followed by the pore water pressure in the interior. Because the discharge has only a horizontal component, the pore water pressure, stress, and strain are independent of the y-coordinate. Furthermore, $\sigma_{xx} = 0$, $\sigma_{xy} = 0$, u_x is independent of y, and u_y is independent of x. Since the problem is symmetric, we solve only the upper right quadrant of the xy plane. We use 441 nodes and 800 elements to generate the simulations. The data for analytical and numerical solutions of this problem are stated in Table 1.

255 The analytical solutions to Mandel's problem for the pore water pressure, horizontal, and vertical displacement are (Cheng

and Detournay, 1988; Abousleiman et al., 1996; Phillips and Wheeler, 2007)

$$p = \frac{2FB(1+\nu_u)}{3a} \sum_{i=1}^{\infty} \frac{\sin \omega_i}{\omega_i - \sin \omega_i \cos \omega_i} \left(\cos \frac{\omega_i x}{a} - \cos \omega_i \right) \exp\left(-\frac{\omega_i^2 c_v t}{a^2} \right),$$ (20)

$$u_x = \left[\frac{F\nu}{2Ga} - \frac{F\nu_u}{Ga} \sum_{i=1}^{\infty} \frac{\sin \omega_i \cos \omega_i}{\omega_i - \sin \omega_i \cos \omega_i} \exp\left(-\frac{\omega_i^2 c_v t}{a^2} \right) \right] x + \frac{F}{G} \sum_{i=1}^{\infty} \frac{\cos \omega_i}{\omega_i - \sin \omega_i \cos \omega_i} \sin \frac{\omega_i x}{a} \exp\left(-\frac{\omega_i^2 c_v t}{a^2} \right),$$ (21)

$$u_y = \left[-\frac{F(1-\nu)}{2Ga} + \frac{F(1-\nu_u)}{Ga} \sum_{i=1}^{\infty} \frac{\sin \omega_i \cos \omega_i}{\omega_i - \sin \omega_i \cos \omega_i} \exp\left(-\frac{\omega_i^2 c_v t}{a^2} \right) \right] y,$$ (22)

260 with $\tan \omega_i = \frac{1-\nu}{\nu_u - \nu} \omega_i$. In this analytical solutions p is the pore water pressure (Pa), u_x is the horizontal displacement (m),

u_y is the vertical displacement (m), F is the force (N), B is the Skempton's coefficient ($-$), G is the shear modulus (Pa), ν is

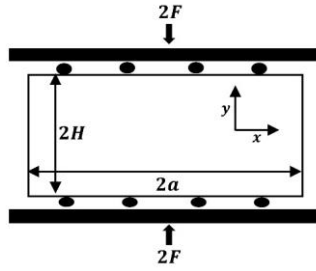
the Poisson's ratio ($-$), and ν_u is the undrained Poisson's ratio ($-$).

265 **Figure 2: The illustration of Mandel's problem for the two-dimensional poroelasticity verification.**

Table 1: Input data for numerical and analytical solutions of Mandel's problem.

Name	Symbol	Value	Unit
Horizontal and vertical distance	a	1	m
Consolidation coefficient	c_v	0.17	m^2 s^{-1}
Force	F	2×10^4	N
Initial value of pore water pressure	p_0	1×10^4	Pa
Porosity	ϕ	0.375	$-$
Poisson's ratio	ν	0.2	$-$
Undrained Poisson's ratio	ν_u	0.5	$-$
Hydraulic conductivity	κ	1×10^{-5}	m s^{-1}
Specific storage	S_s	3.5×10^{-10}	m^{-1}
Bulk modulus	K	1.2×10^8	Pa
Skempton's coefficient	B	0.95	$-$
Shear modulus	G	4×10^7	Pa

The comparison between numerical and analytical solutions for Mandel's problem for normalised pore water pressure, normalised horizontal displacement, and normalised vertical displacement are shown in Fig. 3 at various dimensionless times

270 $t^* = c_v t/a^2$. The mean absolute errors for normalised pore water pressure and displacement are small. The first variable, normalised pore water pressure, has a mean absolute error of around 3.8×10^{-3}, 3.7×10^{-4}, and 5.2×10^{-6} at dimensionless time equal to 0.01, 0.1, and 0.5, respectively. For the second variable, normalised horizontal displacement, has a mean absolute error of around 2.8×10^{-3} and 1.4×10^{-6} at dimensionless time equal to 0.1 and 0.5, respectively. Finally, the mean absolute error of normalised vertical displacement is about 1.1×10^{-3} at dimensionless time equal to 0.1 and

275 5.8×10^{-7} at dimensionless time equal to 0.5.

Mandel's problem has an interesting characteristic related to the behaviour of pore water pressure. In the centre of the sample, the pore water pressure will be higher than the initial pressure for a small time interval. The value of normalised pore water pressure is greater than one at $t^* = 0.01$ and $t^* = 0.1$ (Fig. 3a). This phenomenon is denoted as the Mandel-Cryer effect, and it occurs due to the deformation and rigid plate conditions producing an additional source term for the pore water pressure

280 distribution (Phillips and Wheeler, 2007; Duijn and Mikelic, 2021).

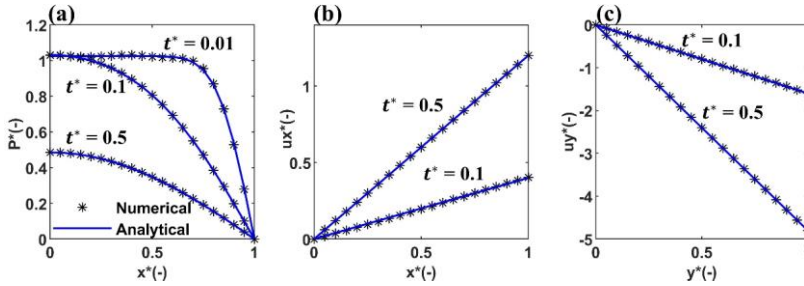



Figure 3: Numerical and analytical solutions of Mandel's problem at various dimensionless time $t^* = c_v t/a^2$ for (a) normalised pore water pressure $P^* = \frac{p}{p_0}$, (b) normalised horizontal displacement $u_x^* = \frac{u_x}{u_{x0}}$, and (c) normalised vertical displacement $u_y^* = \frac{u_y}{u_{y0}}$. The initial displacements in the horizontal and vertical directions are obtained from $u_{x0} = \frac{F v_u x}{2Ga}$ and $u_{y0} = \frac{F(1-v_u)y}{2Ga}$, respectively. In this

285 verification, $x^* = \frac{x}{a}$ is the normalised horizontal distance and $y^* = \frac{y}{a}$ is the normalised vertical distance.

3 Model implementation

We simulate long-term peatland development over 5000 years with flat, impermeable, and rigid substrates, constrained by the parallel rivers at the edges (Ingram, 1982), with the parameter values summarised in Table 2. We assume the rivers do not incise, which could affect the water discharge (Glaser et al., 2004). Therefore, we implement no displacement and no flux

290 boundary conditions at the bottom and zero pore water pressure at the edges. To reduce the computational time, we model half of the peatland domain from the central vertical axis to the one river with a distance of 500 m due to the symmetric growth assumption of the peatland (Baird et al., 2012; Morris et al., 2012). The boundary conditions for the central axis are impermeable without experiencing horizontal displacement.

The total load on this system is associated with the surficial peat addition (Eq. (10)), plant weight (Eq. (11)), and body force
295 (Eq. (1)). The surficial peat addition and plant weight are applied at the surface, while the body force acts throughout the peatland area. The surface loadings are influenced by the peat production and vegetation composition consisting of shrub, sedge, and *Sphagnum*. Different from the surface loadings that are controlled by external sources, the body force is obtained from peatland self-weight, which is determined by the peat bulk density, water density, and active porosity.

To illustrate how MPeat2D works, we run two groups of simulations ~~based on the~~ with different climate inputs. ~~climatic~~
300 ~~influence.~~ In the first group, we employ constant net rainfall (0.8 m yr^{-1}) and air temperature (6 ℃) to provide the basic simulation related to the influence of mechanical-ecohydrological feedback and spatial heterogeneity of peat physical properties, water table depth, PFT proportion, and plant weight on peatland behaviour (Fig. 4). In the second group, we use a non-constant annual time series of net rainfall and air temperature generated from sinusoidal function with some noise (Mahdiyasa et al., 2023; Mahdiyasa et al., 2022), with the range value of $0.6 - 1$ m yr^{-1} and $4 - 7$℃, respectively (Morris
305 et al., 2015; Young et al., 2021; Young et al., 2019). Through this approach, we can capture the wet and dry climatic influence on the long-term development of peatlands and maintain the simplicity of our climate reconstruction as the input variable. ~~The fluctuations of wet and dry conditions from climate input in the second group are developed to analyse the peatland response to the changing climate during the long-term development process.~~

Table 2: 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)
Poisson's ratio	ν	0.2	−	Present study
Bulk density initial value	ρ_0	50	kg m^{-3}	Lewis et al. (2012)
Bulk density parameter	β_ρ	3	−	Present study
Active porosity initial value	ϕ_0	0.8	−	Quinton et al. (2000)
Active porosity parameter	β_ϕ	2	−	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)
Specific yield	S_y	1.4×10^{-2}	−	Bourgault et al. (2017)
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)
Young's modulus parameter 1	χ	4×10^5	Pa	Present study
Young's modulus parameter 2	ζ	0.1	−	Mahdiyasa et al. (2022)

Shrub-Young's modulus parameter	b_1	1.25	–	Mahdiyasa et al. (2023)
Sedge-Young's modulus parameter	b_2	1	–	Mahdiyasa et al. (2023)
Sphagnum-Young's modulus parameter	b_3	0.75	–	Mahdiyasa et al. (2023)
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)

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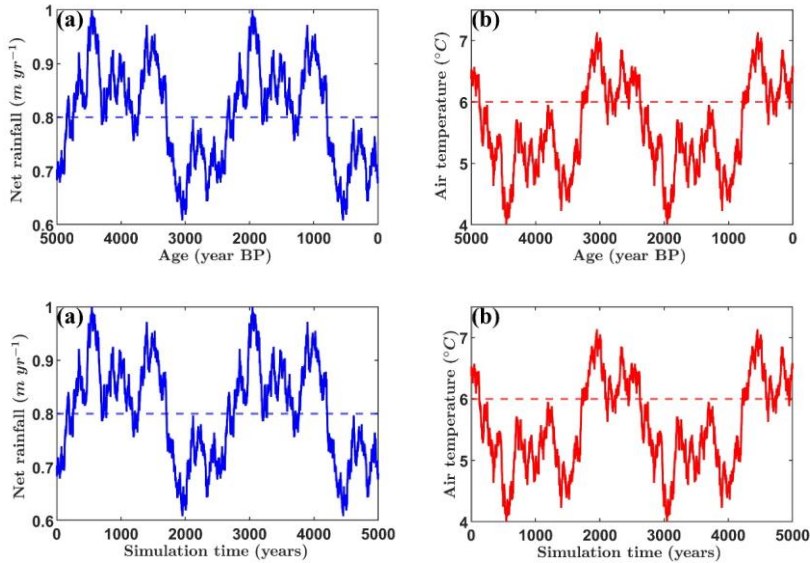

315

Figure 4: The climate profile for (a) net rainfall and (b) air temperature over 5000 years under constant and non-constant conditions. The values of constant climate are 0.8 m yr^{-1} and $6\,°C$ indicated by dashed lines, while the non-constant climate specified by continuous lines fluctuating between 0.6 and 1 m yr^{-1} for net rainfall and between 4 and $7°C$ for air temperature. $0.6 - 1$ m yr^{-1} and $4 - 7°C$ for net rainfall and air temperature, respectively.

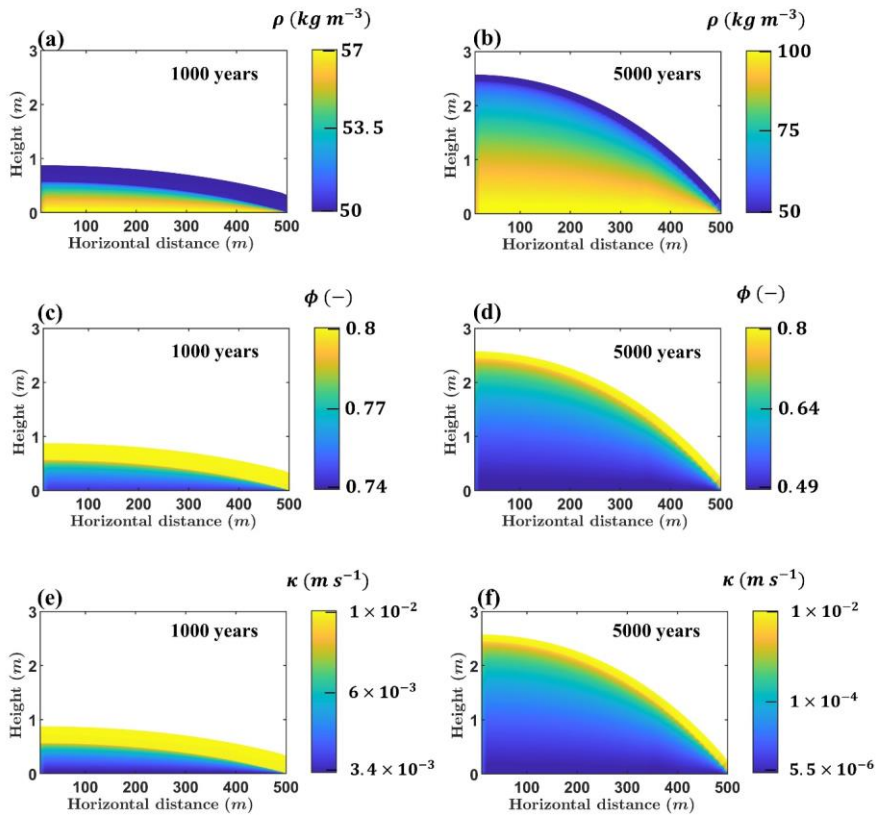
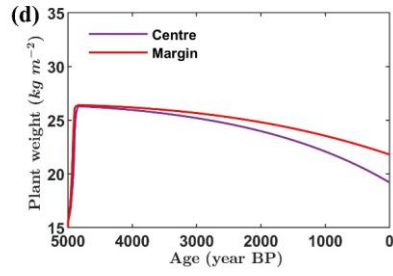
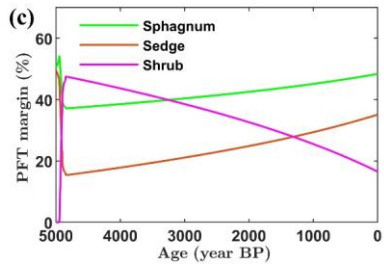
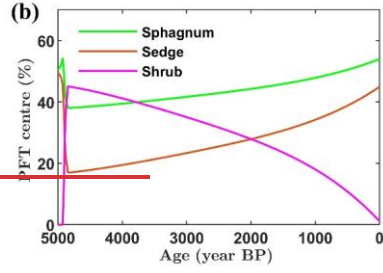
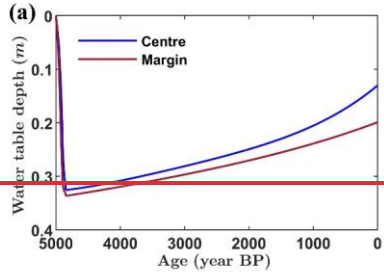
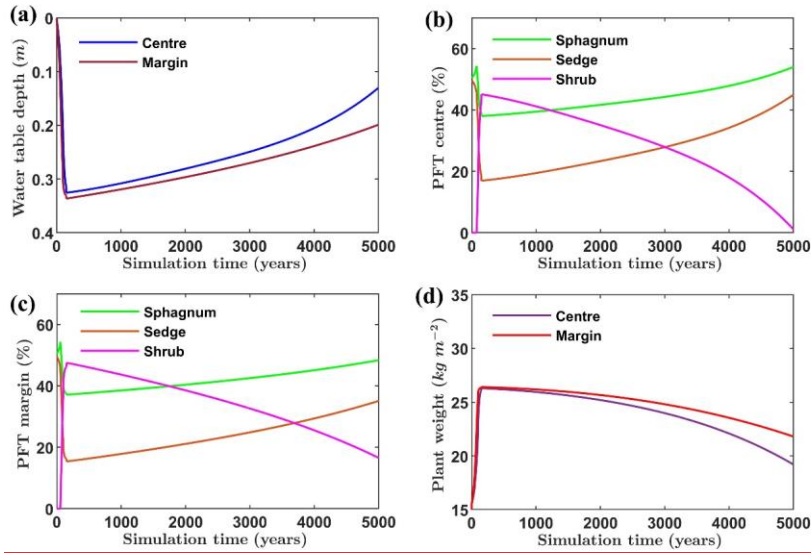
320 We compare the results obtained from MPeat2D with the previously developed mechanical-ecohydrological model of peatland development in 1D called MPeat (Mahdiyasa et al., 2022; Mahdiyasa et al., 2023) and with the 2D ecohydrological model of peatland growth that ignores the mechanical feedback DigiBog (Morris et al., 2012; Baird et al., 2012). to assess feedbacks or other physical phenomena that might be unresolved by the latter. The comparison with MPeat is conducted for the water table

depth, peatland height, and cumulative carbon from the centre area using the same parameters and climatic influence summarised in Table 2 and Fig. 4, respectively. In both models, cumulative carbon is obtained from cumulative mass multiplied by 47% of the carbon content (Loisel et al., 2014). The comparison with DigiBog employs the model version provided by Baird et al. (2012) and Morris et al. (2012), which is run under a constant climate with the value of bulk density equal to 100 kg m^{-3} and the hydraulic conductivity parameters a and b equal to 1×10^{-5} m s^{-1} and 8, respectively. We chose this model version of DigiBog because it has similar characteristics to MPeat2D, including the flat and impermeable substrate with the symmetric assumption of peatland growth. Moreover, both models also assume that water ponding was lost immediately to the margin. In contrast, the more recent DigiBog versions (e.g., Young et al., 2017; Young et al., 2019; Young et al., 2021) produce incomparable simulation results to the MPeat2D because of the different and complex parametrisation and setup. The more recent DigiBog versions employ a layer lumping system after some specific time and thickness. This approach results in faster simulation because it reduces the number of layers that become the domain of calculation. However, the different parametrisation of the layer lumping appears to change the results and stability of the DigiBog. Furthermore, the more recent version includes the parameter of mineral soil and water ponding thickness, which also influences the model outputs. These additional features and parameters lead to incomparable conditions with MPeat2D. The output variables from the comparison between MPeat2D and DigiBog are peatland shape in cross section, thickness, and water table depth.

The sensitivity analysis of MPeat2D is conducted by changing the first Young's modulus parameter χ to 3.5×10^5 Pa and 4.5×10^5 Pa. We performed one at a time sensitivity analysis by focusing on the variation of one parameter and set all other parameters to remain the same as the baseline value (Table 2). The first Young's modulus parameter χ is chosen because it determines the peat stiffness, which in turn influences the mechanical deformation of the peat body. Output variables examined from the sensitivity analysis include the spatial variations of bulk density, active porosity, and hydraulic conductivity.

4 Simulation results

4.1 First group: Constant climate

In the initial stage of development, the peatland shape is relatively flat, with a low value of bulk density and a high value of active porosity and hydraulic conductivity. By 5000 years, a dome-shaped peatland is produced with the maximum thickness obtained at the centre and decreases toward the margin. The increasing thickness leads to higher loading and a more significant deformation effect on the peat pore structure, which affects the peat physical properties. The changes in peat physical properties during the development process exhibit spatial variabilities in the vertical and horizontal directions with the range value between 50 and 100 kg m^3, 0.49 and 0.8, and 5.5×10^{-6} and 1×10^{-2} m s^{-1} 50 – 100 kg m^3, 0.49 – 0.8, and 5.5×10^{-6} – 1×10^{-2} m s^{-1} for bulk density, active porosity, and hydraulic conductivity, respectively (Fig. 5).

355 **Figure 5: The profiles of (a and b) bulk density, (c and d) active porosity, and (e and f) hydraulic conductivity with spatial variability in the vertical and horizontal directions under constant climate.**

360 **Figure 6: The variations of (a) water table depth, (b) plant functional types (PFT) proportion at the centre, (c) PFT proportion at the margin, and (d) plant weight over 5000 years under constant climate. The centre is defined at the central vertical axis, while the margin is located at a horizontal distance of ~~500 m~~ 500 m from the centre.**

Over 5000 years of development, water table depth decreases, resulting in the wetter condition of the peatland (Fig. 6). This

condition occurs because the loading from peat accumulation increases as the peatland grows, which provides internal feedback

365 mechanisms on the water balance through the deformation of peat pore space. The difference in the final simulation year

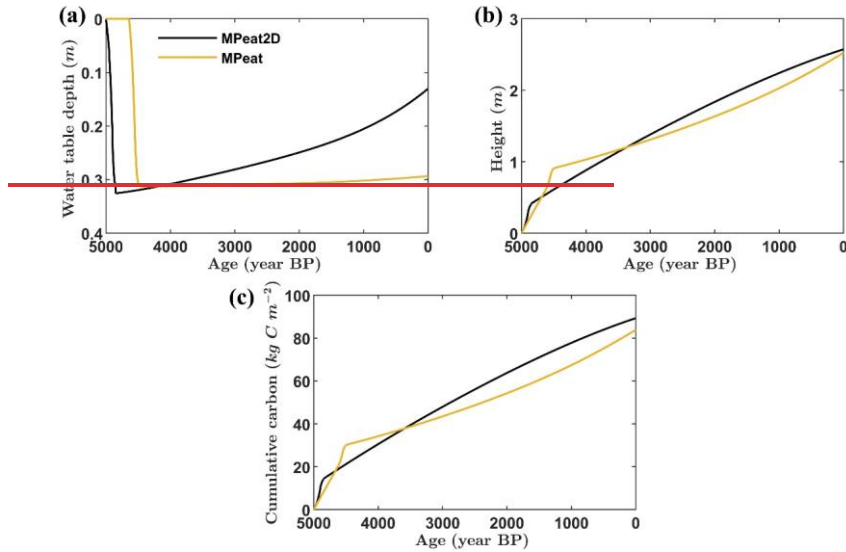
between the water table depth at the centre (0.13 m) and at the margin (0.20 m), which is separated by a horizontal distance

of 500 m, leads to the variation in vegetation composition and plant weight. The proportion of shrub is lower at the centre

compared to the margin, with the value of about 1% and 17%, respectively. In contrast, the sedge and *Sphagnum* proportions

reduce from around 45% and 54% at the centre to 35% and 48% at the margin, respectively. The variations in the vegetation

370 composition affect the distribution of plant weight, with the centre (19 kg m^{-2}) providing a lower value of loading than the

margin (22 kg m^{-2}).

375   The comparison between MPeat2D and MPeat is conducted based on the simulation at the centre of the peatland. Under constant climate, the emergence of the unsaturated zone, represented by the non-zero values of water table depth, is faster in the MPeat2D than in the MPeat, with a difference of about 360 years (Fig. 7a). Moreover, the water table depth obtained from MPeat2D (0.13 m) is lower than MPeat (0.3 m) in the final simulation year. Although MPeat2D and MPeat estimate similar peatland height with values of about 2.57 m and 2.52 m (Fig. 7b), respectively, the cumulative carbon obtained from

380   MPeat2D (89 kg C m^{-2}) is higher compared to the MPeat (84 kg C m^{-2}) over 5000 years (Fig. 7c).

4.2 Second group: Non-constant climate

Under a non-constant climate, the profiles of peat physical properties are similar to those in the constant climate case. The value of bulk density increases while active porosity and hydraulic conductivity decrease from the centre toward the margin (Fig. 78). The main difference is that the range values of bulk density (50 − 104 kg m^3), active porosity (0.47 − 0.8), and

385   hydraulic conductivity ($3.7 \times 10^{-6} - 1 \times 10^{-2}$ m s^{-1}) are higher in the second group after 5000 years. This condition indicates a more significant effect of mechanical deformation on the peat pore space due to the changing climate.

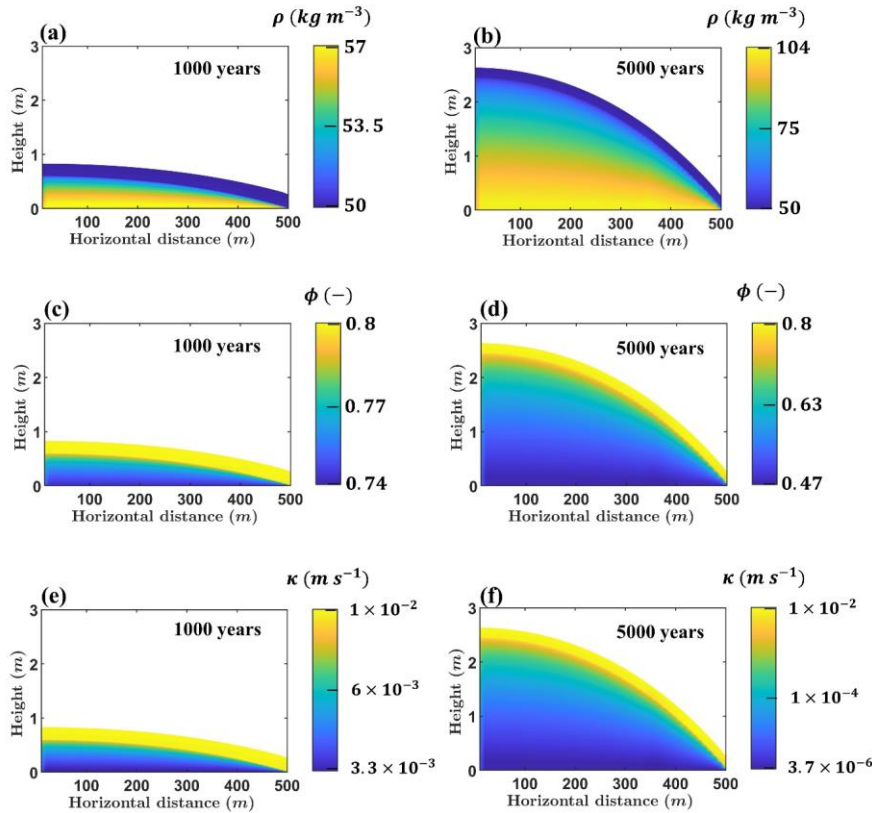



Figure 78: The profiles of (a and b) bulk density, (c and d) active porosity, and (e and f) hydraulic conductivity with spatial variability in the vertical and horizontal directions under non-constant climate.

390   After the unsaturated zone is developed, around 150 years since peatland initiation, water table depth experiences fluctuations and exhibits lateral variability. The margin, which is located at a horizontal distance of 500 m from the centre, experiences drier conditions indicated by a higher water table depth compared to the centre (Fig. 89). Furthermore, the spatial variability of water table depth results in lateral changes in PFT proportions and plant weight. For example, around the year 37501250 years BP, the water table depth is about 0.07 m at the centre, while at the margin, the water table is located about 0.22 m below

395   the surface. Consequently, the shrub proportion increases from 0% at the centre to 21% at the margin, while sedge and

Sphagnum decrease from 48% and 52% to 32% and 47% from the centre to the margin, respectively. This condition produces a spatial variation in plant weight between the centre and the margin with values of about 17 kg m^{-2} and 22 kg m^{-2}.

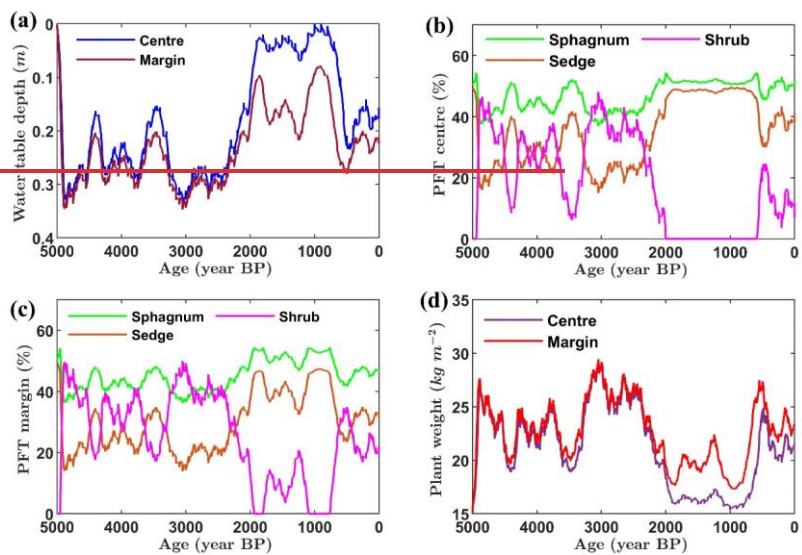
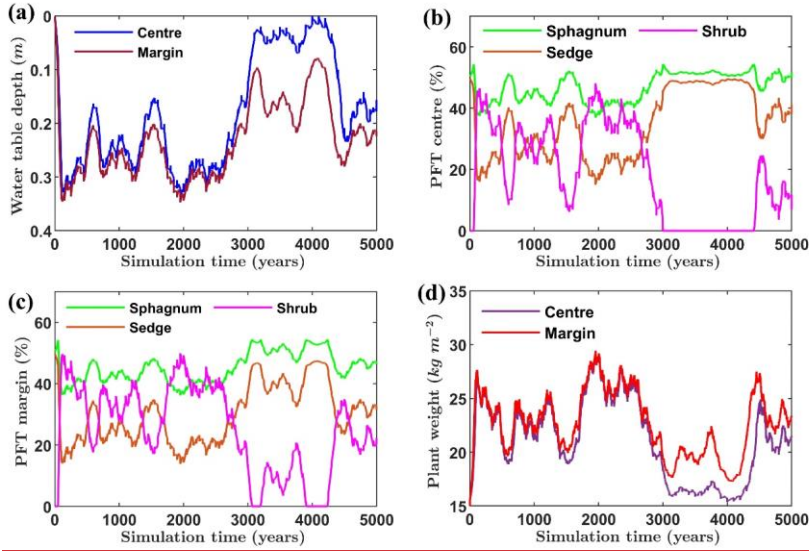



Figure 89: The variations of (a) water table depth, (b) plant functional types (PFT) proportion at the centre, (c) PFT proportion at the margin, and (d) plant weight over 5000 years under non-constant climate. The centre is defined at the central vertical axis, while the margin is located at a horizontal distance of ~~500 m~~ 500 m from the centre.

4.3 Comparison between MPeat2D with MPeat and DigiBog

The comparison between MPeat2D and MPeat is conducted based on the simulation at the centre of the peatland. Under constant climate, the emergence of the unsaturated zone, represented by the non-zero values of water table depth, is faster in the MPeat2D than in the MPeat, with a difference of about 360 years (Fig. 97a). Moreover, the water table depth obtained from MPeat2D (0.13 m) is lower than MPeat (0.3 m) in the final simulation year. Although MPeat2D and MPeat estimate similar peatland height with values of about 2.57 m and 2.52 m (Fig. 97b), respectively, the cumulative carbon obtained from MPeat2D (89 kg C m^{-2}) is higher compared to the MPeat (84 kg C m^{-2}) over 5000 years (Fig. 97c).

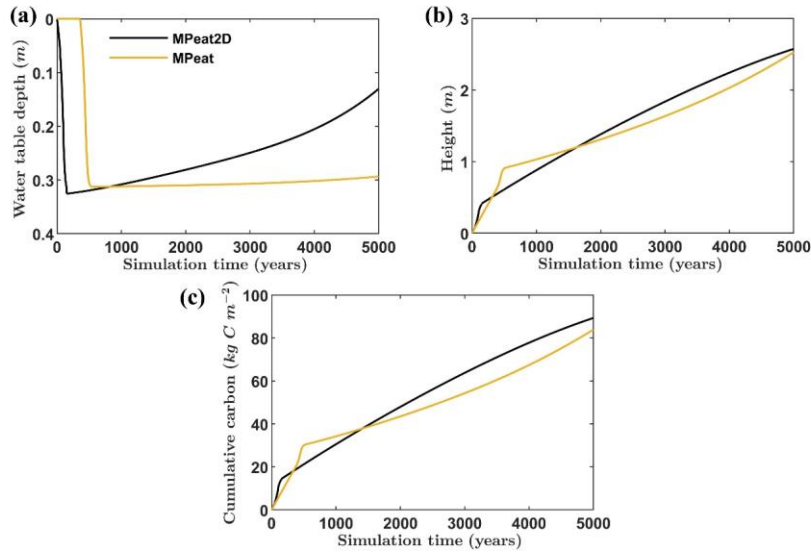



Figure 9: The comparison between MPeat2D and MPeat at the centre for (a) water table depth, (b) peatland height, and (c) cumulative carbon over 5000 years under constant climate.

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The comparisons between MPeat2D and MPeat for water table depth, peatland height, and cumulative carbon at the centre area under non-constant climate are shown in Fig. 10. The appearance of the unsaturated zone is around 400 years earlier in the MPeat2D than MPeat based on the non-zero values of the water table depth since peatland initiation. After the unsaturated zone is developed in both models, MPeat2D predicts a lower water table depth compared to the MPeat with the range value of 420 $0 - 0.34$ m and $0.16 - 0.36$ m, respectively. Peatland height and cumulative carbon obtained from MPeat2D around 2.61 m and 92 kg C m^{-2} are more significant than the MPeat estimated values of about 2.39 m and 76 kg C m^{-2}, after 5000 years.

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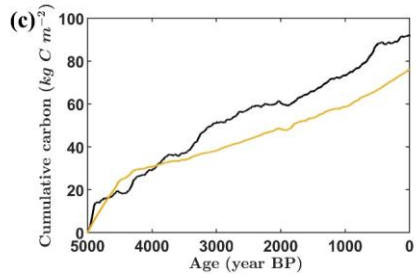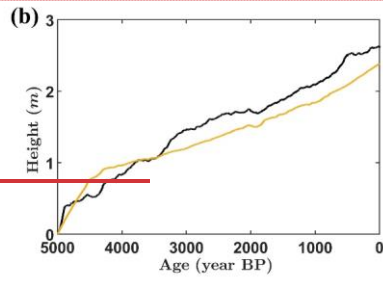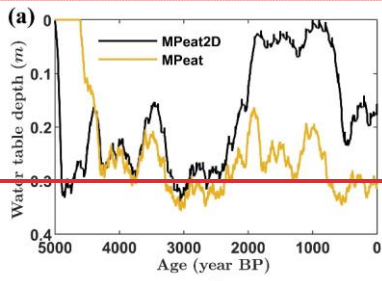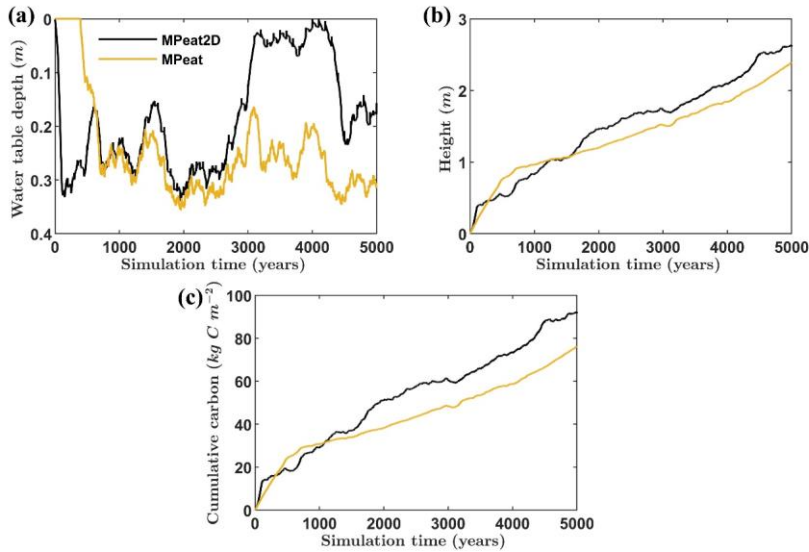
Figure 10: The comparison between MPeat2D and MPeat at the centre for (a) water table depth, (b) peatland height, and (c) cumulative carbon over 5000 years under a non-constant climate.

The comparison between MPeat2D and DigiBog is run only under a constant climate due to the limitations of the chosen DigiBog version (Morris et al., 2012; Baird et al., 2012). Over 5000 years, the peatland height at the centre obtained from

430 MPeat2D is higher compared to DigiBog, with a difference of about 0.6 m (Fig. 11a). Furthermore, both models produce peatland shapes that experience the formation of a cliff at the margin. The height of the cliffs obtained from MPeat2D and DigiBog are about 0.27 m and 1.15 m, respectively. The spatial variations of water table depth between the centre and the margin are more significant in the MPeat2D compared to DigiBog (Fig. 11b). In the final simulation year, MPeat2D simulates water table depth with values of about 0.13 m at the centre and 0.2 m at the margin, while DigiBog produces water table

435 depth of around 0.43 m and 0.44 m at the centre and margin, respectively.

Figure 11: The comparison between MPeat2D and DigiBog Bog 2 (Morris et al., 2012) for (a) peatland shape and (b) water table depth over 5000 years. Both models assume that the peatland develops above the flat and impermeable substrate with constant climate.

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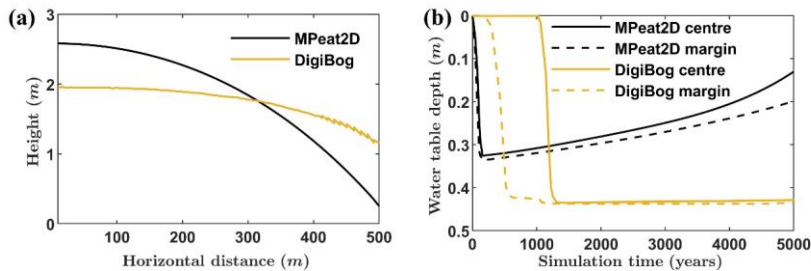
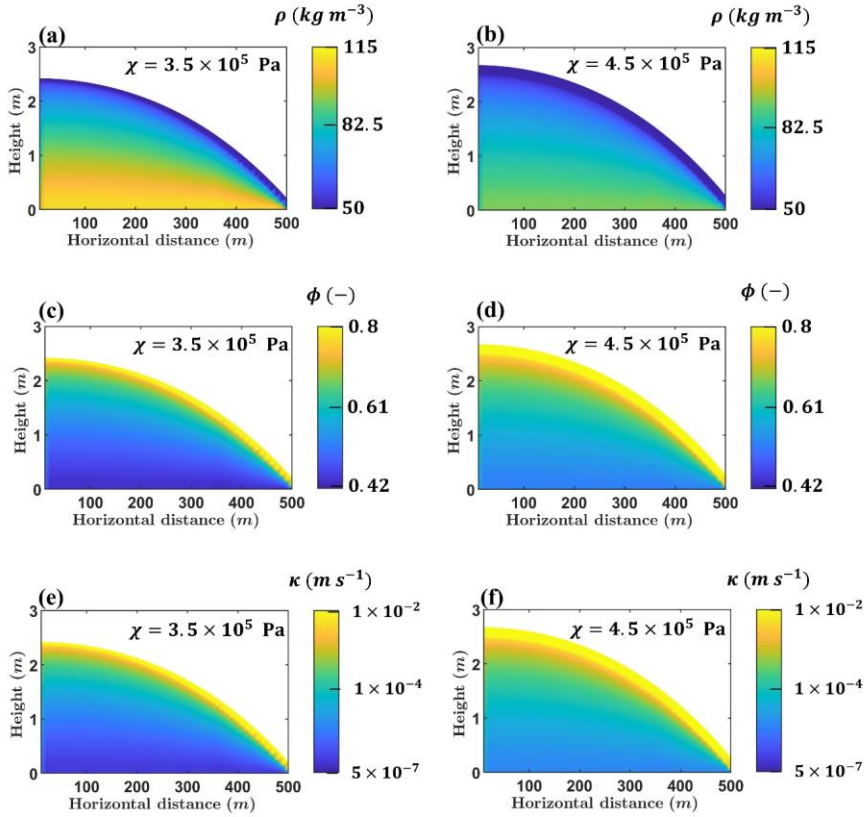

4.4 Sensitivity analysis

We changed the first peat Young's modulus parameter χ, which is an essential variable in the MPeat2D because it determines the peat stiffness and the compaction effect on the peat pore structure. Under constant climate (Fig. 12), reducing the first peat Young's modulus parameter χ to 3.5×10^5 Pa led to a higher value of bulk density (50 – 111 kg m^3) and lower values of
445 active porosity (0.44 – 0.8) and hydraulic conductivity ($1.2 \times 10^{-6} - 1 \times 10^{-2}$ m s^{-1}). The more significant effect of compaction due to a lower first peat Young's modulus parameter χ results in a decreasing peatland height at the centre by about 6% compared to the baseline value after 5000 years. Contrastingly, increasing the first peat Young's modulus parameter χ to 4.5×10^5 Pa produced a lower bulk density (50 – 94 kg m^3) and higher active porosity (0.52 – 0.8) and hydraulic conductivity ($1.6 \times 10^{-5} - 1 \times 10^{-2}$ m s^{-1}). These conditions increased the peatland height at the centre by about 4%
450 compared to the baseline value in the final simulation year.

Under non-constant climate (Fig. 13), the influence of parameter χ on the peat physical properties and thickness is similar to that observed in the constant climate scenario. Reducing χ to 3.5×10^5 Pa resulted in a higher bulk density (50 – 114 kg m^3) and lower active porosity (0.42 – 0.8) and hydraulic conductivity ($6.9 \times 10^{-7} - 1 \times 10^{-2}$ m s^{-1}). As a consequence, the peatland height at the centre was reduced by about 5% compared to the baseline value after 5000 years. In contrast, increasing
455 χ to 4.5×10^5 Pa led to a lower bulk density (50 – 96 kg m^3) and higher active porosity (0.51 – 0.8) and hydraulic conductivity ($1.2 \times 10^{-5} - 1 \times 10^{-2}$ m s^{-1}), which in turn produced a more significant peatland thickness at the centre by about 4% compared to the baseline value over 5000 years of simulations.

460   Figure 12: The sensitivity analysis of MPeat2D by changing the first Young's modulus parameter χ with the output variables are (a and b) bulk density, (c and d) active porosity, and (e and f) hydraulic conductivity under constant climate over 5000 years. In the base run χ is equal to 4×10^5 Pa.

5 Discussion

The most important result from MPeat2D is the ability to model the influence of spatial variability on long-term peatland behaviour. The addition of the second dimension provides significant impacts on the analysis of peat physical properties because it allows the bulk density, active porosity, and hydraulic conductivity to change in the horizontal and vertical directions. We found that the bulk density increases systematically from the centre to the margin, while the active porosity and

hydraulic conductivity experience an opposite pattern with decreasing values from the peatland interior to the edges (Figs. 5 and 78). The horizontal variability of the peat physical properties is not only caused by occurs because the peatland experiences different effects of decomposition (Morris et al., 2012) but also by different effects of compaction between the margin and the centre. The steeper hydraulic gradient at the margin promotes water release and reduces the position of the water table (Figs. 6a and 89a) (Reeve et al., 2006; Lewis et al., 2012; Kværner and Snilsberg, 2011; Regan et al., 2019), which results in higher loading from plant weight (Figs. 6d and 89d) and effective stress. In contrast, peatland topography at the centre is mainly flat, leading to the shallow water table position that limits the deformation of the peat pore space.

At smaller scales of a few meters, another possible factor affecting the horizontal variance of peat physical properties is the peatland microform. The measurement from Whittington and Price (2006) indicated that bulk density and hydraulic conductivity differ substantially in the lateral direction over distances of a few metres between hummocks, lawns, and hollows. Moreover, Baird et al. (2016) showed that the difference in the hydraulic conductivity between contiguous microforms could vary by more than an order of magnitude. The variation in the water table position and plant functional types between in the peatland microforms (Eppinga et al., 2008; Malhotra et al., 2016; Moore et al., 2019), which significantly affect the loading, effective stress, and compaction on the peat pore space, might become a reasonable explanation for this behaviour. However, Baird et al. (2016) found that the change in hydraulic conductivity is less evident at a deeper location between adjacent hummocks and hollows, which suggests that the lateral variability of hydraulic conductivity at the small scale between the microhabitat types beyond the uppermost peat is less clear. is equivocal.

The changes of peat physical properties in the vertical direction, from the top surface to the bottom layer, obtained from MPeat2D show an increasing value of bulk density and a decreasing value of active porosity and hydraulic conductivity (Clymo, 1984; Hoag and Price, 1995; Hoag and Price, 1997; Quinton et al., 2008; Quinton et al., 2000; Fraser et al., 2001). The rapid changes occur at the transition between the unsaturated and saturated zones, indicating significant compaction due to the substantial increase of effective stress (Mahdiyasa et al., 2023; Mahdiyasa et al., 2022). The fluctuations of peat physical properties become gradual in the saturated zone because pore water pressure reduces the effective stress and limits the deformation of the peat solid skeleton. Price (2003) found the decreasing value of effective stress below the water table that leads to smaller changes in peat volume, which supports our simulation results.

The inclusion of spatial heterogeneity provides crucial feedback on peat thickness and carbon stock, as shown by the comparison between MPeat2D and MPeat (Figs. 97 and 10). MPeat2D simulates spatial variations in the peat physical properties and produces a non-uniform hydraulic gradient, including a lower hydraulic conductivity at the margin and nearly flat topography at the centre, which supports the water accumulation. In contrast, as a 1D model, MPeat assumes constant peat physical properties in the lateral direction and a uniform hydraulic gradient, resulting in the omission of peatland processes that affect the water balance. Consequently, MPeat2D simulates a shallower water table position than MPeat, leading to the shorter residence time of organic matter in the unsaturated zone and providing positive feedback on the peat and carbon accumulation (Evans et al., 2021; Huang et al., 2021; Ma et al., 2022). The differences between MPeat2D and MPeat are more

505 pronounced under a non-constant climate (Fig. 10), indicating the potential importance of spatial variability to understand the influence of climate change on the peatland carbon balance and resilience.

Our simulation results are in agreement with Lapen et al. (2005), who found that lateral variations of hydraulic conductivity encourage water accumulation and produce a more significant peat thickness. However, Lapen et al. (2005) based their finding on a sensitivity analysis of a steady-state groundwater model, finding is constructed based on the sensitivity analysis of the

510 groundwater flow model at steady state conditions, which omits the complex feedback from the peatland. Conversely, MPeat2D provides a comprehensive approach incorporating mechanical, ecological, and hydrological feedback to highlight the influence of spatial variations of physical properties and water table position on the peat and carbon accumulation during development process.

5.1 Comparison with field measurements

515 We compare the simulation results from MPeat2D under a non-constant climate that provides a more realistic condition with field observation for peat physical properties, peat thickness, and carbon accumulation. The comparison of peat physical properties is conducted in the horizontal and vertical directions due to the spatial heterogeneity of bulk density, active porosity, and hydraulic conductivity. In the horizontal direction, we use the data from Lewis et al. (2012), who measured the lateral variabilities of hydraulic conductivity and bulk density at a depth of 30 to 40 cm from a blanket peatland in Ireland as a

520 comparison. Although the peatland type from Lewis et al. (2012) is different from our simulations, the main reason for the comparison is to demonstrate the ability of the model to produce reasonable outputs of the spatial variability on peat physical properties. Lewis et al. (2012) found that the average values of hydraulic conductivity at the margin and the centre are around 10^{-6} and 10^{-4} m s^{-1}, respectively. After 5000 years of development, MPeat2D produces hydraulic conductivity (Fig. 78f) with a similar value at the margin (6.4×10^{-6} m s^{-1}) but higher at the centre (1.3×10^{-3} m s^{-1}) compared to the Lewis et

525 al. (2012) observations. Moreover, the bulk density values obtained from Lewis et al. (2012) are around 55 and 110 kg m^{-3}, while our simulation (Fig. 78b) provides values of about 59 and 101 kg m^{-3} at the centre and margin, respectively. In the vertical direction, the changes in bulk density simulated from MPeat2D (Fig. 78b) are in the range of 50 − 104 kg m^3, consistent with the reported measurements of bulk density about 30 − 120 kg m^3 (Lunt et al., 2019; Loisel et al., 2014; Clymo, 1984). Furthermore, the simulation results of active porosity (Fig. 78d) and hydraulic conductivity (Fig. 78f) fluctuate between

530 0.47 − 0.8 and 3.7×10^{-6} − 1×10^{-2} m s^{-1}, which are in accord with the field observations of active porosity and hydraulic conductivity about 0.1 − 0.8 and 7×10^{-9} − 1.6×10^{-2} m s^{-1}, respectively (Quinton et al., 2008; Quinton et al., 2000; Clymo, 2004; Fraser et al., 2001; Hoag and Price, 1997; Hoag and Price, 1995). Therefore, in general, MPeat2D can model the spatial variability of peat physical properties in the horizontal and vertical directions with reasonable outputs. The discrepancies between simulation results and the field measurement mainly related to the site specific characteristics, including

535 peat stiffness, PFT composition, and substrate topography that result in the variations of compaction effect (Mahdiyasa et al., 2023; Mahdiyasa et al., 2022; Whittington et al., 2007; Malmer et al., 1994).

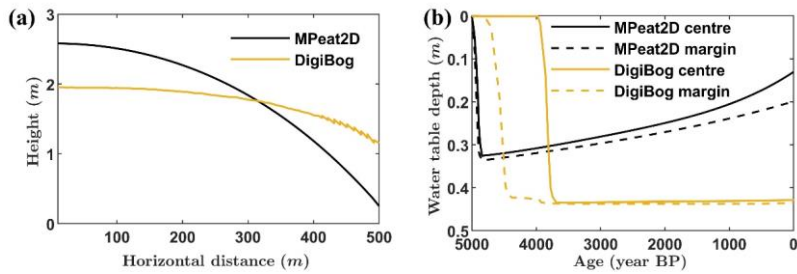
The peat thickness and carbon accumulation rate ~~obtained~~ from MPeat2D, which are calculated based on the total amount of peat and carbon with the total simulation time, appear to be realistic. MPeat2D produces an average growth rate of about 0.52 mm yr^{-1}, which leads to a height of 2.61 m after 5000 years (Fig. 10b). Charman (2002) found that the average growth
540 rates of the blanket and raised peatland are about 0.65 and 1 mm yr^{-1}, respectively, based on the relation between peatland carbon accumulation and age-depth curves. Aaby and Tauber (1975) analysed the correlation between the rate of peat accumulation and the degree of humification that produced the growth rate of raised peatland in the range of 0.16 − 0.80 mm yr^{-1} with an average value of 0.44 mm yr^{-1}. Aaby and Tauber (1975) suggested that the relationship between the degree of humification and the growth rate is affected significantly by mechanical compaction. A more decomposed peat
545 experiences a higher compaction effect due to the reduction in Young's modulus and strength (Mahdiyasa et al., 2023; Mahdiyasa et al., 2022), which results in a lower peat thickness. Furthermore, the average value of the net rate of carbon accumulation obtained from MPeat2D is about 0.0183 kg C m^{-2} yr^{-1} (Fig. 10c), which is in agreement with the reported measurements of northern peatlands during the Holocene with an average value around 0.0186 kg C m^{-2} yr^{-1} (Yu et al., 2010; Yu et al., 2009).

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Figure 11: The comparison between MPeat2D and DigiBog Bog 2 (Morris et al., 2012) for (a) peatland shape and (b) water table depth over 5000 years. Both models assume that the peatland develops above the flat and impermeable substrate with constant climate.

5.2 Comparison with the other two-dimensional peatland development model

555 We emphasise the critical function of mechanical-ecohydrological feedback to simulate peatland development in 2D by comparing MPeat2D with the other ecohydrological model DigiBog (Baird et al., 2012; Morris et al., 2012). Using the same assumption of the flat and impermeable substrate with constant climate, both models produce dome shapes of the peatland over 5000 years (Fig. 11a). However, the inclusion of mechanical-ecohydrological feedback on MPeat2D provides a plausible profile of bulk density (Fig. 5b) and active porosity (Fig. 5d) that are assumed to be a constant by DigiBog. Consequently, in
560 the early stage of development, the value of bulk density from MPeat2D is lower than DigiBog, producing a more rapid increase in peat thickness and a faster appearance of the unsaturated zone (Fig. 11b). As peatland grows, ~~The~~ the changes in peat physical properties and the discrepancy in the hydraulic gradient obtained from MPeat2D lead to the spatial variation of

water table depth, which is in line with the field observations (Reeve et al., 2006; Lewis et al., 2012; Kværner and Snilsberg, 2011; Regan et al., 2019). Furthermore, the water table depth decreases as the peatland develops in the MPeat2D, resulting in wetter conditions of the peatland due to a more significant effect of compaction that supports the water accumulation. (Fig. 11b). Contrastingly, DigiBog produces a relatively uniform hydraulic gradient, leading to the constant water table depth between the centre and the margin during the simulation period. This condition limits the capabilities of DigiBog to analyse the lateral variation in peat production, decomposition, and PFT proportion because these peatland characteristics depend on the water table depth (Clymo, 1984; Belyea and Clymo, 2001; Moore et al., 2002; Kokkonen et al., 2019; Laine et al., 2021). The inclusion of mechanical-ecohydrological feedback also produces a more plausible shape of the peatland in 2D. Although MPeat2D suffers from the appearance of a cliff at the margin as DigiBog (Fig. 11a), the influence of mechanical compaction on the MPeat2D results in a lower cliff height than DigiBog, with values of about 0.27 m compared to 1.15 m, respectively. The peat cliff at the margin does not appear in the natural condition except due to extraction or erosion (Tuukkanen et al., 2017; Tarvainen et al., 2022). Furthermore, the continuum concept (Irgens, 2008; Jog, 2015) employed by MPeat2D produces continuous deformation of peat pore space, resulting in the smoother profile of peatland shape, especially near the margin, compared to than DigiBog that uses linked vertical column (Fig. 11a). The comparison of the predicted peatland shape from MPeat2D with the Groundwater Mound Hypothesis (GMH) (Ingram, 1982), indicates that MPeat2D produces a lower hydraulic gradient at the margin compared to the hemi-ellipse shape from GMH. The hemi-ellipse shape is obtained by assuming constant hydraulic conductivity throughout the peatland area, which is not true because the field observation from Baird et al. (2008) and Lewis et al. (2012) showed that hydraulic conductivity change in the vertical and horizontal directions. Armstrong (1995) modified GMH by proposing non-uniform hydraulic conductivity that exponentially decreases with depth, resulting in a lower hydraulic gradient at the margin and a more significant thickness at the centre, which agrees with MPeat2D.

However, MPeat2D assumes a uniform distribution of peat throughout the fixed horizontal domain in the initial stages of development, which prevents MPeat2D from modelling the lateral expansion. In contrast, DigiBog can capture the lateral growth of the peatland from the margin toward the centre .

5.3 Limitations and future development

MPeat2D assumes a uniform distribution of peat throughout the fixed horizontal domain in the initial stages of development, which results in the omission of the lateral expansion process as the peatland grows. The lateral expansion Lateral expansion is crucial to model the paludification process that influences peatland behaviour because the transition process from forest to peatland involves changes in vegetation, nutrient availability, and peat physical properties (Charman, 2002; Anderson et al., 2003; Rydin and Jeglum, 2006). Peatland lateral expansion requires an evolving domain that results in moving boundary problems (Tezduyar, 2001; Gawlik and Lew, 2015). Simplifying assumptions may be necessary to involve the moving boundary conditions into MPeat2D, including providing the rate of lateral expansion that determines the boundary motion and

595 the changing domain. Moreover, to improve the numerical stability of the model, a smaller grid size might be required, particularly around the boundaries, due to significant differences in the internal stresses.

The assumption of a flat substrate employed by MPeat2D could be improved by introducing a more general landscape condition consisting of upland, sloping area, and lowland based on the theoretical landscape model proposed by Winter (2001). The landscape variations, together with the feedback from mechanical, ecological, and hydrological processes, affect the

600 stresses on the peat body that control the occurrence of failure conditions on the peatland. The peatland failure involving mass movement (Dykes and Selkirk-Bell, 2010; Dykes, 2022; Dykes, 2008) influences the estimation of carbon accumulation on the peatland because it might result in the formation of water channels that facilitate the drainage and oxidation processes (Warburton et al., 2003; Evans and Warburton, 2007). Potentially, this phenomenon could determine the maximum limit to peatland carbon accumulation in a landscape (Large et al., 2021).

605 The entrapped gas bubbles that are neglected by the current version of MPeat2D might have a significant influence on the peatland mechanics and behaviour. The presence of gas bubbles influences hydraulic conductivity (Baird and Waldron, 2003; Beckwith and Baird, 2001; Reynolds et al., 1992) and pore pressure (Kellner et al., 2004), which results in variations of effective stress. Consequently, the mechanical deformation of peat pore space, including the shrinking or swelling, is also affected by the presence of gas bubbles. The simulation from Reeve et al. (2013) suggested that a higher gas content results in

610 a more significant peatland surface deformation. We could expand the poroelasticity formulation in the MPeat2D to accommodate the gas bubbles by introducing another fluid below the water table, for example, a water and gas mixture (Kurzeja and Steeb, 2022). This modification requires generalisation in Biot's theory of consolidation to model multiphase fluid saturation.

The current version of MPeat2D is focused on modelling raised ombrotrophic peatland, which grows in temperate climates.

615 However, it should be possible to develop MPeat2D to model the other peatland types, for example, the tropical peatland. Modifications of some processes are required before applying MPeat2D to analyse the peatland in tropical areas, including the variation in the rate of peat production, peat physical properties characteristics, and loading behaviour. MPeat2D uses the empirical relationship between peat production and water table depth, which is formulated based on the data from Ellergower Moss, Scotland (Belyea and Clymo, 2001). The rate of peat production in the tropical peatland should be different from the

620 northern temperate peatland due to the variations in the vegetation composition. The hydraulic conductivity of tropical peatlands is relatively high compared to the northern temperate peatland (Baird et al., 2017), which might lead to different hydrological processes. which affects the water table position . Moreover, the loading from trees and the influence of roots for maintaining mechanical stability are significant processes in tropical peatlands, which requires an additional formulation in the MPeat2D. mechanical submodel. For example, the weight of trees with a root system could be modelled through the

625 data of above-ground and below-ground biomass. In this case, the loading is applied not only at the top surface but also at the specific depth of the peatland, depending on the root characteristics.

Finally, the development of MPeat2D into a three-dimensional (3D) model provides a more comprehensive analysis of the peatland carbon accumulation process and phenomena that require explicit spatial interactions in 3D. The comparison between

MPeat2D and MPeat indicates the crucial function of adding a second dimension to estimate peatland carbon accumulation. MPeat2D produces greater cumulative carbon, particularly under non-constant climate, due to the lateral variability of water table depth and peat physical properties incorporated by the 2D model. Based on this preliminary result, it might be possible that a 3D model of peatland development might result in a more significant carbon accumulation than the 1D or 2D models because of the more complex feedback mechanisms involved by a higher dimensional model. The 3D model is also required to understand the patterning phenomena on the peatland surface, which is highly directional and affected by spatial characteristics. The analysis of surface patterning is typically developed based on ecohydrological feedback, which encompasses the interactions between water table position, vegetation communities, nutrient availability, and peat hydraulic properties (Eppinga et al., 2009; Eppinga et al., 2008; Morris et al., 2013; Béguin et al., 2019). However, as a porous medium with relatively low shear and tensile strength (Long, 2005; Boylan et al., 2008; O'kelly, 2017; Dykes, 2008), mechanical instability also determines the process of surface patterning on the peatland. The simulation from Briggs et al. (2007) indicates that the peatland surface might experience wrinkles due to the changing pattern between tensile and compressive stresses. Moreover, the peatland surface patterns could appear as a consequence of the tensile or compressive failure condition (Dykes, 2008), which dominantly occurs under a low slope angle (Dykes and Selkirk-Bell, 2010). Therefore, a fully coupled mechanical, ecological, and hydrological model of peatland growth in three dimensions might be suitable for analysing the appearance and impact of surface patterning on the peatland water flow and carbon balance.

6 Conclusion

MPeat2D is a two-dimensional peatland growth model that incorporates mechanical-ecohydrological feedback and the influence of spatial variability on peatland behaviour. This model is developed based on the poroelasticity and continuum concept, resulting in the plausible outputs of peat physical properties, water table position, and vegetation composition. MPeat2D produces a higher bulk density and lower active porosity and hydraulic conductivity at the margin compared to the centre due to the different effects of compaction, which are in accord with field observations. Furthermore, lateral variability of water table depth because of the changes in the hydraulic gradient leads to different vegetation compositions between the margin and the centre. The comparison between MPeat2D and the other peatland growth models, MPeat and DigiBog, indicates the critical function of mechanical, ecological, and hydrological processes together with the feedback from spatial heterogeneity on the peatland shape, carbon stock and resilience.

Code availability

The codes that support the findings of this study are openly available in zenodo at https://doi.org/10.5281/zenodo.10050891 (Mahdiyasa, 2023)

Author contribution

AWM and DJL conceptualised and designed the research. AWM developed the model, performed the simulations, and
660 prepared the initial manuscript. DJL, MI, and BPM provided advice on the model interpretation and contributed to the editing
and reviewing of the manuscript. BPM provided financial support and computing resources for the simulations.

Competing interests

The authors declare that they have no conflict of interest.

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