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Interactive comment on "Modelling Holocene peatland dynamics with an individual-based dynamic vegetation model" *by* Nitin Chaudhary et al.

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We appreciate the time and effort spent by the reviewers in reviewing this manuscript. We have addressed all the issues indicated in the review reports and believe that the revised version will meet the journal's publication requirements.

Substantive comments

Model choice and model scale

The authors note the following:

"Model formulations of peat accumulation and decay have been proposed and demon-

strated at the site scale (Frolking et al., 2010) but have not yet, to our knowledge, been implemented within the framework of a DGVM, or applied at larger spatial scales than a single study site or landscape."

The authors are right, but they then go on to apply their landscape-scale model (or land surface scheme) to individual sites, so we do not get to see what the LPJ-GUESS model does at larger scales in comparison to a series of smaller site models. The authors also provide a very limited review of other peatland models. At least two other models have been developed – MILLENNIA (Heinemeyer et al., 2010) and DigiBog (e.g., Morris et al. (2012) and Morris et al. (2015)) – and it might be useful to acknowledge what these models are capable of doing and their limitations.

Response: Our model can be employed at the site-scale and, where climate forcing is available at a sufficient resolution, at the regional scale. We focused on site-scale runs in this study because we wanted to describe the model processes and their evaluation using data from well-studies sites such as Stordalen and Mer Bleue. However, in work that was completed in the time since this paper was submitted, we have run the model for 180 sites evenly spread across the pan-Arctic and shown that the model can produce reasonable predictions of past and present carbon accumulation rates at regional scale. See our companion paper in discussion - Biogeosciences Discuss., doi:10.5194/bg-2017-34, 2017.

We have now expanded our acknowledgements of the work done by other groups and referred to them in relevant places. See lines: 35-45 in the revised manuscript (RM). We compared the functionality and scope of a representative set of current peatland models in Table S1 in the RM (there are many other models apart from the one mentioned in the Table S1) but this list we think is not suitable for the paper. Could be included in the appendix though.

Revised text- Dynamic global vegetation models (DGVMs) are used to study past, present and future vegetation patterns from regional to global scales, together with associated biogeochemical cycles and climate feedbacks, in particular through the carbon cycle (Smith et al., 2001; Friedlingstein et al., 2006; Sitch et al., 2008; Strandberg et al., 2014; Zhang et al., 2014). Only a few DGVMs include representations of the unique vegetation, biophysical and biogeochemical characteristics of peatland ecosystems (Wania et al., 2009a, b; Kleinen et al., 2012; Tang et al., 2015). Model formulations of multiple peat layer accumulation and decay have been proposed and demonstrated at the site scale (Frolking et al., 2010; Heinemeyer et al., 2010) but have not yet, to our knowledge, been implemented within the framework of a DGVM. However, peatland processes are included in some other types of model frameworks (Morris et al., 2012; Alexandrov et al., 2016; Wu et al., 2016) and been shown to perform reasonably for peatland sites. Large area simulations of regional peatland dynamics have been performed by (Kleinen et al., 2012; Schuldt et al., 2013; Stocker et al., 2014; Alexandrov et al., 2016) (see Table S1 in the RM).

Table S1 in the RM shows comparison of functionality and scope of a representative set of current peatland models.

The authors note that vegetation in their modelled domain can develop into patches and that each patch is represented by a different soil column. The authors seem to suggest that patches can emerge over time, but, if that is so, how can a different soil column be assigned a priori to each patch? The authors also suggest that water can flow between patches, which makes sense, but do not indicate how such flows are simulated (see point 3 below).

Response: We are sorry of this is a little unclear. The number of patches in our model is fixed at the outset. Each patch has its own soil column (composed of mineral and, eventually, peat layers) and dynamic vegetation properties. Vegetation within the patches competes for water and sunlight but there is no competition or communication between patches except for the distribution of water. Our model randomly distributes the carbon in the start of the simulation over the static mineral soil layers leading to an initially heterogeneous surface (different patch heights). As they accumulate C, these individual

patches develop their own hydrologies and water holding capacities leading to different patch water heights. At the end of each day of the simulation, we take the mean of water table position (WTP) across all patches, and this is referred to as mean landscape WTP in the manuscript. The water flow from higher patches to lower patches is based on mean landscape WTP. For instance, hollows have lower peat C mass leading to lower water holding capacity overall and a lower water height relative to hummocks. We add or remove the amount of water required to match the mean landscape WTP in each patch, in each time step (see below for a more detailed description).

Model complexity and process and parameter redundancy

LPJ-GUESS is a complicated model – it does many things. In choosing what processes to represent in a model it is important to consider process and parameter redundancy. For example, it may seem intuitively correct to include all obvious plant functional types, but the inclusion of some may add little to the predictive power of the model. For example, how does the model behave if litter production is confined to, for example, a single shrub PFT; do the model's results change substantially? I wonder too whether the litter production functions in the model could be replaced with a simpler function and the model results remain essentially the same? I am not suggesting the authors change the model and re-run it. It would, however, be useful to see brief consideration of why the model has been set up as it has been. Currently, the model set up is described rather than justified. An important paper on this topic is that by Crout et al. (2009) who show, for example, that a well-established and popular wetland CH4 model is over-complicated and can achieve the same predictive success in much simpler form. Models are often more complicated that they need to be.

Crout NMJ, Tarsitano D, Wood AT. 2009. Is my model too complex? Evaluating model formulation using model reduction. Environmental Modelling and Software 24: 1–7, doi: 10.1016/j.envsoft.2008.06.004.

Response: This is a very good point. In fact, we were forced to make decisions to balance complexity and utility while developing our model. For example, we initially chose four PFTs (mosses, two dwarf shrubs and graminoids) and found that though the model was performing fairly well for the Stordalen site, it performed less than satisfactorily when we applied the model to temperate sites which have higher plant diversity than the Stordalen subarctic mire. Further investigation revealed the litter carbon mass deposited by the four PFTs was not sufficient (less than the reported values) leading to shallow peat heights in temperate regions. Therefore, we decided to include high summergreen shrubs (HSS) in the model, which is one of the more important PFTs in temperate peatland ecosystems (Moore et al., 2002). HSS establishes when the growing degree days (GDD) is higher than 1000 degree-days, thereby limiting HSS establishment in colder regions. However, adding high evergreen shrubs (HSE) did not substantially improve the predictive power of the model so we excluded it from the set up.

A further example is the treatment of soil temperature in the model. There are thousands of peat layers in the later stages of our simulations, and one approach to calculating layer temperatures for use in the decomposition equation would be to use a finite-difference numerical scheme considering all these layers in each step. It is questionable if such detail is warranted however, and it would be difficult to evaluate such a profile, so we opted for a scheme in which we aggregated the peat layers to a smaller number of layers for use in the numerical scheme, with the exact number increasing from 3 to 7 as the peat depth increases. This method was sufficient to model the active layer depth seasonally and annually.

Hydrological components of the model

I found the explanation of the hydrological part of the model difficult to follow. In particular, it was unclear how the model predicts the soil moisture content of the peat above the water table. The authors note that rates of peat decomposition depend on peat wetness and suggest that the highest rates of decay occur when the peat is at field capacity, but they do not say how they modelled soil moisture content (as opposed to

water-table position). Equation 7 is a balance equation that shows the different inflows into, and outflows from, the model. However, I could not find any discussion of how water inputs are allocated separately between the unsaturated and saturated zones.

Response: We use a simple bucket scheme when adding water (rain or snowmelt) from the current WTP to the top of the peat column formed by individual peat layers giving a new WTP in each time step. In our model peat layers above the WTP are thus assumed to be completely unsaturated. We simulate water and ice in each peat layer of each individual patch and convert them into water and ice content by dividing the amount of ice and water with total water holding capacity. If layer is totally frozen (100% ice), then it cannot hold additional water. In partially frozen soil, the sum of the fractions of water and ice is limited to water holding capacity of that layer. The soil water content determines the peat decomposition rate in individual layers.

The authors are also unclear on how lateral flows of water occur in the model. On lines 254-256 they note:

“We equalize the WTP of individual patches according to the mean WTP of the landscape. The higher patches loses water if the WTP is above the mean WTP of the landscape while the lower patches receive water.”

This description is too general and it is not clear numerically how water is moved across the landscape. I assume the model has lateral boundary conditions but such conditions are not mentioned in the paper. These can have a profound effect on how the model functions hydrologically so should be discussed and justified.

Response: We calculate the landscape WTP (as discussed above) and add and remove the amount of water from each patch required to match the landscape WTP. See below the representation how it is done.

MWTP= $\sum PWTP\_i/n$

where MWTP is the mean WTP across all the patches, PWTPi is the water table position in individual patches (i) and n is the total number of patches. The water to be added to or removed from each patch with respect to mean WTP (MWTP) in each patch, i.e. lateral flow (LF) is given by:

DWTPi = PWTP_i - MWTP

LFi = DWTP . Φa

where DWTPi is the difference in the patch (i) and MWTP and LFi is the total water to be added or removed with respect to MWTP in each patch (i). If the WTP is below the surface then the total water is calculated by the difference in WTP (water heights) multiplied by average porosity (Φa). When the WTP is above the surface then Φa is not included in the calculation. This exchange of water between patches is implemented after the daily water balance calculation.

There seems to be some confusion too in how different processes are reported. For example, 'R' is defined as surface runoff in Equation 7 but later (in Equation 9) is described as a function of base runoff which seems to be some type of subsurface flow.

Response: R in Eq. 7 is the total runoff – base runoff plus and surface runoff. We have corrected it in the text. See lines: 201-203 in the RM. We have made the changes and termed the base flow as BR.

Revised text: where W is the total water input, P is the precipitation, ET is the evapotranspiration rate, R is the total runoff, DR for the vertical drainage and LF (see section 2.1.7 below) is the lateral flow within the landscape depending upon the relative position of the patch.

I recommend section 2.1.4 is re-written to make it clearer and that it is accompanied by a new diagram which shows all of the components of the hydrological budget as represented in the model (the current Figure 1 is not sufficient for this purpose).

Response: We have re-written section 2.1.4 and 2.1.4 (see lines: 191-236 and 263-289

in the RM)

4. Representation of Stordalen and of soil ice

The authors compare their simulation of the Stordalen mire to a reconstruction by Kokfelt et al. (2010), a paper which I have not read. I think it would be useful if the authors indicated in more detail how Kokfelt et al. estimated past peat thicknesses of the mire. More fundamentally, I am not clear on the appropriateness of considering peat thickness from one location at a site. My understanding is that Stordalen is a palsa mire in which case it will comprise elevated palsas – large ombrotrophic hummocks – formed by the growth of ice lenses, and intervening minerotrophic areas that form after wastage and collapse of the ice lenses. The authors note on line 543 that their model cannot simulate peat subsidence due to permafrost thaw. What is not clear is whether it can also simulate the palsa cycles that would have occurred prior to the recent warming of the climate in the region. As far as I can tell the model is not capable of simulating ice lenses.

Response: We have included a short description of how Kokfelt et al. 2010 estimated past peat thickness of the Stordalen mire. They used radioisotope dating at several depths and a Bayesian modeling technique to reconstruct the thickness of the mire. They have also used peat cores from nearby lakes to reconstruct the past climate influence on vegetation dynamics, hydrological changes and nutrient flow within the catchment. We discussed this in lines: 313-315 in the RM.

Response: We agree that the ideal case is to compare the model with multiple peat cores from the same site this is not feasible in this case because this data is not available for the Stordalen site. Though the model has peatland and permafrost functionality, it doesn't yet simulate ice lenses, palsas and palsa expansion and contraction cycles. In the future modifications, we may include these features.

Revised Text:

Based on radioisotope dating of peatland and lake sequences supplemented with Bayesian modelling, Kokfelt et al. (2010) inferred that the peat initiation started ca. 4700 calendar years before present (cal. BP) in the northern part and ca. 6000 cal. BP in the southern part.

Figure 4 shows the 'observed' peat thickness (the reconstructed peat thickness) at different times during Stordalen's development and the modelled thickness. The authors provide a 95% CI around the 'observed' values but say the CI was inferred from the model runs. Did the model actually produce multiple peat thicknesses for different patches, in which case why don't the authors show the spread of outputs from the model?

Response: Yes, the 95% confidence interval is calculated from the individual peat depths simulated for each of the modelled patches. The model simulated 10 different peat thickness trajectories, one for each patch (see Fig. 4 in the RM). We originally thought that showing the spread would not add much to the figure so we only included 95% confidence interval. However, we have now updated the Figure and its caption to remove this source of uncertainty.

Finally, a more minor issue, but one that is important to address, is that it is not always clear what units are used in different parts of the model. They are given in some places but not others – I recommend that whenever a parameter or variable is first defined its units are given.

Response: We have now gone through the paper and made the required changes to include the units whenever a parameter or variable is first introduced. See lines: 150-153, 156-158, 166-168, 219, 222, 231 and 234 and Table 2 in the RM.

General Comments

However, current DGVMs lack functionality for the representation of peatlands, an important store of carbon at high latitudes

Comment: And also in parts of the tropics.

Response: We have revised the sentence (see lines: 10-13 in the RM).

Revised text: Dynamic global vegetation models (DGVMs) are designed for the study of past, present and future vegetation patterns together with associated biogeochemical cycles and climate feedbacks. However, most DGVMs do not yet have detailed representations of permafrost and non-permafrost peatlands, which are an important store of carbon particularly at high latitudes.

Our approach employs a dynamic multi-layer soil with representation of freeze-thaw processes and litter inputs from a dynamically-varying mixture of the main peatland plant functional types; mosses, dwarf shrubs and graminoids.

Comment: I recommend a colon here (see line: 16 in the RM).

Response: We have revised the sentence.

Revised text: Our approach employs a dynamic multi-layer soil with representation of freeze-thaw processes and litter inputs from a dynamically-varying mixture of the main peatland plant functional types: mosses, shrubs and graminoids.

We found that the Stordalen mire may be expected to sequester more carbon in the first half of the 21st century due to milder and wetter climate conditions, a longer growing season, and CO2 fertilization effect, turning into a carbon source after mid-century because of higher decomposition rates in response to warming soils.

Comment: "and *a* CO2" (add 'a')

Response: We have revised the sentence (see line 23 in the RM).

Revised text: We found that the Stordalen mire may be expected to sequester more carbon in the first half of the 21st century due to milder and wetter climate conditions, a longer growing season, and the CO2 fertilization effect, turning into a carbon source after mid-century because of higher decomposition rates in response to warming soils.

Peatlands are a conspicuous feature of northern latitude landscapes (Yu et al., 2010), of key importance for regional and global carbon balance and potential responses to global change.

Comment: A bit vague. Change of what? I assume climate is meant. I suggest rewording to be more specific.

Response: Yes, we forgot to add "climate". We have now revised the sentence (see line: 26-27 in the RM).

Revised text: Peatlands are a conspicuous feature of northern latitude landscapes (Yu et al., 2010), of key importance for regional and global carbon balance and potential responses to global climate change.

In the past 5-10 thousand years they have sequestered approximately 200-550 Pg C across an area of approximately 3.5 million km2 (Gorham, 1991; Turunen et al., 2002; Yu, 2012).

Comment: Give as a number rather than a mix of numbers and words? The higher end is more likely.

Response: We have revised the sentence (lines: 27-28 in the RM)

Revised text: In the past 10,000 years (10 kyr) they have sequestered 550 $\pm$100 PgC across an area of approximately 3.5 million km2 (Gorham, 1991; Turunen et al., 2002; Yu, 2012).

Peatlands are also considered one of the major natural sources of methane, contributing significantly to the greenhouse effect (IPCC, 2013; Lai, 2009; Whiting and Chanton, 1993)

Comment: Considered or actually are one of the main sources?

Response: We have revised the sentence (see lines: 29-30 in the RM).

Revised text: Peatlands are one of the major natural sources of methane, contributing significantly to the greenhouse effect (Whiting and Chanton, 1993; Lai, 2009; IPCC, 2013).

The majority of northern peatland areas coincide with low altitude permafrost (Wania et al., 2009a). Comment: Really? The majority?

Response: We have revised the sentence (see lines: 30-31 in the RM).

Revised sentence: Around 19% (3556 $\times$ 103 km2) of the soil area of the northern peatlands coincides with low altitude permafrost (Tarnocai et al., 2009; Wania et al., 2009a).

There is a scientific consensus that the climate is likely to warm in the coming century, and that the warming will be amplified in northern latitudes, relative to the global mean trend (IPCC, 2013).

Comment: The present century? In which case the climate has already warmed and is predicted to continue doing so.

Response: Agreed. We have revised the sentence (see lines: 46-47 in the RM).

Revised text: Climate warming is amplified in northern latitudes, relative to the global mean trend, due to associated carbon-climate feedbacks (IPCC, 2013).

Uniquely among existing large-scale (regional-global) models, we thus account for feedbacks associated with hydrology, peat properties and vegetation dynamics, providing a basis for understanding how these feedbacks affect peat growth on the relevant centennial-millennial time-scales and in different climatic situations.

Comment: Okay, but you actually apply your model at the site scale, so your implementation is not really different from an implementation of the Holocene Peat Model for example. Response: We have explained this part above.

Five PFTs characteristic of peatlands – mosses (M), graminoids (Gr), deciduous and evergreen low shrubs (LSS and LSE) and deciduous high shrubs (HSS) – are included in the present study.

Comment: Why were five chosen? Why not three PFTs, or 12?

Response: We have addressed this point in an early response to a question by the reviewer.

A one-dimensional soil column is represented for each patch (defined below), divided vertically into four distinct layers: a snow layer of variable thickness, a litter/peat layer of variable thickness, a mineral soil column with a fixed depth of 2 m (with further sublayers of thickness 0.1 m), and finally a "padding" column of m depth (with thicker sublayers) allowing to simulate accurate arctic soil thermal dynamics (Wania et al., 2009a). The insulation effects of snow, phase changes in soil water, precipitation and snowmelt input and air temperature forcing are important determinants of daily soil temperature dynamics at different depths.

Comment: Can the physical properties (e.g., porosity, hydraulic conductivity) of this layer vary with depth?

Response: Porosity is a function of bulk density, and influenced by total mass remaining in each peat layer. If the layers are highly decomposed their bulk density increases and porosity will decline. We do not consider the hydraulic conductivity explicitly in this study, but the drainage is affected by the permeability of peat layers and the saturation limit of the mineral soil underneath.

Fresh litter debris decomposes through surface forcing until the last day of the year.

Comment: It's not clear what this means.

Response: When the litter (leaves and stems, where appropriate) is dropped on the ground surface it doesn't become a part of peat column (formed of multiple layers – see above) instantaneously. This litter then decomposes at rates depending on the surface conditions in that year, i.e. surface temperature and moisture, becoming the

top layer in the peat layer of the soil column the following year. So, in our framework, we decompose the litter mass present on the peat surface for the first year before it transforms into a peat layer. However, for dead roots, we add them directly to the peat layers where they belong (see lines: 106-110 in the RM).

Revised text: Fresh litter debris decomposes on the surface through exposure to surface temperature and moisture conditions until the last day of the year. The decomposed litter carbon is assumed to be released as respiration directly to the atmosphere while any remaining litter mass is treated as a new individual peat layer from the first day of the following year, which then underlies the newly accumulating litter mass.

This layer can be composed of up to 17 carbon components (g C m-2), namely leaf, root, stem and seeds from shrubs, mosses and graminoids (see Table 1) and the model keeps a track of these layer components as they decompose through time.

Comment: That's a lot of components. Does the model need to be this complicated or could (should) it be more parsimonious? Is it over-parameterised?

Response: We believe that this distinction is important because each litter component plays an important part in peat formation and the quantity and quality of litter is also different for each PFT component. For example, stem wood decomposes at a much slower rate than other components of shrubs, while root turnover directly enter subsurface peat layers where they belong.

Total peat depth is derived from the dynamic bulk density values calculated for individual peat layers.

Comment: I'm confused. How many peat layers are there? Just two - acrotelm and catotelm - or one for each year of the model simulation?

Response: We appreciate this ambiguity now, spotted by both reviewers. It's the latter – one for each year of the simulation. For Stordalen, 4739 + 100 peat layers were simulated, i.e. one peat layer for each of the 4739 years after inception until year 2000, followed by a 100-year projection from 2001 to 2100. For Mer Bleue, it was 8400 + 100 layers. We cannot show that many layers in a figure so we simplified the representation in Fig. 1 in the RM (see lines: 91-98 in the RM).

Revised text: A one-dimensional soil column is represented for each patch (defined below), divided vertically into four distinct layers: a snow layer of variable thickness, one dynamic litter/peat layer of variable thickness corresponding to each simulation year (e.g. 4739 + 100 layers by the end of the simulations, described in Section 2.4 below, for Stordalen), a mineral soil column with a fixed depth of 2 m consisting of two sublayers: an upper mineral soil sublayer (0.5 m) and a lower mineral soil sublayer (1.5 m), and finally a "padding" column of 48 m depth (with 10 sublayers) allowing the simulation of accurate soil thermal dynamics (Wania et al., 2009a). The insulation effects of snow, phase changes in soil water, precipitation and snowmelt input and air temperature forcing are important determinants of daily soil temperature dynamics at different depths.

Comment: Why is this term given thus and not as single number? Response: Yes, we have revised the equation (see Eq. 4 in the RM).

The acrotelm is the top layer in which water table fluctuates leading to both aerated and anoxic conditions.

In our implementation, new peat layers are added on top of these mineral soil layers. To overcome computational constraints for millennial simulations we aggregate the properties of the individual annual peat layers into thicker sublayers for the peat temperature calculations, beginning with three sublayers of equal depth and adding a new sublayer to the top of previous sublayers after every 0.5 m of peat accumulation.

Comment: Some recent papers suggest the distinction between acrotelm and catotlem is not helpful. See, e.g., Morris et al. (2011) Ecohydrology 4, 1-11.

Comment: Okay; so there are multiple peat layers. This could have been made clearer

above.

Response: We have explained this above (see lines: 91-98 in the RM).

DR for the drainage

Comment: Should this be defined here as vertical drainage? Response: We have revised it to vertical drainage (see line 202 in the RM).

Revised text: where W is the total water input, P is the precipitation, ET is the evapotranspiration rate, R is the total runoff, DR for the vertical drainage and LF (see section 2.1.7 below) is the lateral flow within the landscape depending upon the relative position of the patch.

R=BR

Comment: Why the italics here and not elsewhere?

Response: We have removed the italics. Thanks.

Loss of the water through drainage/percolation depends on the permeability of peat layers and the saturation limit of the mineral soil underneath.

Comment: Only vertical drainage seems to be simulated. In many (most) ombrotrophic peatlands, drainage is predominately a lateral process - the peatland drains to its margins. Is lateral drainage accounted for in the model? If so, what relationship is used? What are the dimensions/units of permeability? Do the authors mean intrinsic permeability or hydraulic conductivity?

Response: We have not included an explicit description of the lateral drainage but our runoff function, R, implicitly takes into account the lateral drainage, and it is also dealt with through our lateral distribution of water among patches. We mean intrinsic permeability (0-1), which is calculated based on peat bulk density (kg m-3 ; see Eq. 11 in the RM).

become highly compressed under accumulating peat mass and humified by anoxic decomposition (Clymo, 1991).

Comment: But you note earlier that dry bulk density often does not show depth dependency in the 'catotelm'.

Response: Simulating bulk density is a challenge. In some peatlands, it may increases with depth due to compaction (Clymo, 1991) but other studies have shown no net increase in the bulk density with depth in some other locations (Baird et al., 2016). In our study, the simulated bulk density is a function of the total mass remaining and in the peat profile it varies between 40-102 kg m-3 for Stordalen. Ryden et al. (1980) given a range of 45-230 kg m-3 (see page 41 and Table 5 and 6 in their paper) and our values are well within this range. We also find bulk density doesn't decline with depth in our profile. Since the lower layers were frozen, they didn't decompose significantly and their bulk densities remain higher relative to other partially frozen or unfrozen layers. The value referred to by the reviewer is the mean value of the entire simulated peat profile and it was lower than 50 kg m-3 since the majority of peat layers are not highly compacted as a result limited decomposition due to permafrost or high water contents (see lines: 429-438 in the RM)

Revised text: When the peat layers had decomposed sufficiently and lost more than 70% of their original mass (Mo), their bulk density increased markedly. The observed monthly and annual WTP for the semi-wet patches and mean annual ALD were very near to the simulated values (see Figs. 8, 9 and A5). The simulated bulk density varies between 40-102 kg m-3 and the mean annual bulk density of the full peat profile was initially around 40 kg m-3, increasing to 50 kg m-3 as the peat layers grew older. Some studies (Clymo, 1991; Novak et al., 2008) noted a decline in bulk density with depth due to compaction. However, the simulated peat column does not exhibit such a decline with depth, instead being highly variable down the profile as found in other studies (Tomlinson, 2005; Baird et al., 2016). Freezing of the lower layers inhibited decomposition, with the result that bulk densities remained higher relative to other

partially frozen or unfrozen layers. The pore space and permeability are linked to the compaction of peat layers.

The amount of water draining from the peat column to the mineral soil is calculated by integrating permeability across all the peat layers (i)

Comment: Not clear what is meant by integration here. If simulating vertical drainage, then perhaps it would make sense to use a harmonic mean.

Response: We have revised the sentence (see lines: 228-229 in the RM).

Revised text: The amount of water draining from the peat column to the mineral soil is calculated by integrating permeability across all the peat layers (i).

Change of porosity (Φ) due to compaction is captured by a relationship to bulk density:

Comment: I assume this should be 'drainable porosity' which is not the same as total porosity. How is the moisture content of the peat above the water table simulated?

Response: Yes, it is a drainable porosity. We have not calculated moisture content above the water table – see the response to the reviewer's earlier comment.

Shrubs are vulnerable to waterlogged and anoxic conditions (Malmer et al., 2005) and establish only when annual WTP deeper than -25 cm below the surface.

Comment: Better to say 'relative to'?. A negative value below the surface means something above the surface. A negative depth means a positive value (something above the surface). This sentence would be simpler if you just say it was 25 cm below the surface.

Response: We agree, and have revised the text (see lines 254-255 in the RM).

Revised text: Shrubs are vulnerable to waterlogged and anoxic conditions (Malmer et al., 2005) and establish only when annual WTP is deeper than 25 cm relative to the surface.

The model is initialised with a random surface represented by uneven heights of individual patches (10 in the simulations performed here).

Comment: Okay, but do non-random patterns subsequently form in the model?

Response: Yes, we find that when we start the model with a flat surface we get heterogeneous patch/peat heights and vegetation composition after several years (see Fig. 1 in this document).

Water is redistributed from the higher elevated sites to low depressions through lateral flow (see Eq. 7).

Comment: But equation 7 is a water-balance equation. It does not indicate how LF is calculated

Response: We have added the lateral flow equations in section 2.1.7 (see our reply to an earlier comment above and section 2.1.7 in the RM).

We equalize the WTP of individual patches according to the mean WTP of the landscape. The higher patches loses water if the WTP is above the mean WTP of the landscape while the lower patches receive water.

Comment: Okay, but how does this equalisation process work?

Response: We have revised the sections 2.1.5 and 2.1.7 (see our reply to an earlier comment above)

Permafrost underlying elevated areas have been degraded as a result of climate warming in recent decades, with an increase in wet depressions modifying the overall carbon sink capacity of the mire (Christensen et al., 2004; Johansson et al., 2006; Malmer et al., 2005).

Comments: Replace with 'has'. For more recent work see Swindles et al. (2015) Scientific Reports 5, 17951.

Response: We have revised the text and added the reference (see lines: 307 in the RM).

Revised text: Permafrost underlying elevated areas has been degraded as a result of climate warming in recent decades, with an increase in wet depressions modifying the overall carbon sink capacity of the mire (Christensen et al., 2004; Malmer et al., 2005; Johansson et al., 2006; Swindles et al., 2015).

To evaluate the generality of the model for regional (e.g. pan-Arctic) applications, we validated its performance against observations and measurements at Mer Bleue (45.40° N, 75.50° W, elevation 65 m a.s.l.), a raised temperate ombrotrophic bog located around 10 km east of Ottawa, Ontario (Fig. 3). Comment: Mer Bleue is a long way from the Arctic - as you note, it is a temperate mire. Response: We have revised the sentence and removed the word pan-Arctic (see lines: 319-321 in the RM).

Revised text: To evaluate the generality of the model for regional applications, we compared its predictions to observations and measurements at Mer Bleue (45.40° N, 75.50° W, elevation 65 m a.s.l.), a raised temperate ombrotrophic bog located around 10 km east of Ottawa, Ontario (Fig. 3).

This bog is mostly covered with Sphagnum mosses (S. capillifolium, S. magellanicum) and also dominated by a mixture of evergreen (Chamaedaphne calyculata, Ledum groenlandicum, Kalmia angustifolia) and deciduous shrubs (Vaccinium myrtilloides).

Comment: This is an out of date name. It is now Rhododendron groenlandicum (Oeder) Kron. Response: Thanks, we have renamed it (see line: 325 in the RM).

Revised text: The bog surface is characterized by hummock and hollow topography. This bog is mostly covered with Sphagnum mosses (S. capillifolium, S. magellanicum) and also dominated by a mixture of evergreen (Chamaedaphne calyculata, Rhododendron groenlandicum, Kalmia angustifolia) and deciduous shrubs (Vaccinium myrtilloides).

In the standard (STD) experiment, a total of 94.96 kg C m-2 of peat was accumulated over 4700 years, leading to a cumulative peat depth profile of 2.11 m predicted for the present day Comment: Just one depth? Would not multiple depths have been predicted, one for each vegetation patch? See my referee's report.

Response: We have given a range in Table 4 and included a new figure showing different peat trajectories (Fig. 4 in the RM). This is the range 1.9 - 2.2 m (see lines: 406-408 in the RM).

Revised text: In the standard (STD) experiment, a total of 94.6 kg C m-2 (91.4-98.9 kg C m-2) of peat was accumulated over 4700 years, leading to a cumulative peat depth profile of 2.1 m (1.9-2.2 m) predicted for the present day (Fig. 4), comparable to the observed peat depth of 2.06 m reported by Kokfelt et al. (2010).

The model initially had an uneven surface where the majority of the patches were suitable for moss growth because of the shallow peat depth and an annual WTP near the surface (Figs. 5e and 6a). Comment: Did this unevenness persist? The site is a palsa mire; did the model simulate cycles of palsa mound development and decay?

Response: The uneven surface persists (see Fig. 2 in this document) though heterogeneity increased and then decreased later to stabilize over time but we didn't notice palsa mound development because the ice expansion processes is not included in the model (an intended future modification).

We used these basal dates to start our model simulations. In the STD experiment, the simulated cumulative peat depth profile for the last 4700 years is consistent with the observed peat accumulation pattern (Kokfelt et al., 2010). The average increase in peat depth was simulated to be 2.11 m, which can be compared with the observed increase in peat depth of 2.06 m (Fig. 4). The simulated trajectory of the cumulative peat depth is also comparable to the observed data. In VLD ex Comments: Some repetition here of what is said in the previous section (see lines: 501-504 in the RM). Response: Thanks, we have now removed that part and revised the sentence. Revised

text: We used these basal dates to start our model simulations. In the STD experiment, the simulated cumulative peat depth profile for the last 4700 years is consistent with the observed peat accumulation pattern (Kokfelt et al., 2010). In VLD experiment, the average increase in peat depth was simulated to be 4.2 m, which can be compared to 5 m of observed peat depth (Frolking et al., 2010).

Mosses emerged as the dominant PFT at the beginning of the simulation, while 300-400 years after peat inception shrubs started establishing in the higher elevated patches as a result of a lowering of WTP (Figs. 5e and 6a).

Comments: What about palsa formation and collapse? Is this not an area where such processes occur. These processes don't seem to be represented in the model. Response: You are right these processes are not represented in the model and will be included in the future modifications.

NPP in the first half of the 21st century, resulting in accelerated peat accumulation, but that the increase in decomposition outpaces the increase in NPP by around 2040, resulting in the loss of a substantial amount of carbon by the end of the 21st century (Fig 9). Comment: Okay, but peatlands have formed extensively in the temperate and boreal zones and many of these peatlands have a substantial bryophyte component in their flora. So, why will warmed Arctic and sub-Arctic peatlands lose carbon? Is it not possible that new peatlands will also develop? Perhaps much depends on local hydrological conditions.

Response: Yes, this is a very good point, so we have revised the sentence (see lines: 608-614 in the RM). We have found the similar finding in our companion paper

Companion paper (lines 21-30)- A majority of modelled peatland sites in Scandinavia, Europe, Russia and Central and eastern Canada change from carbon sinks through the Holocene to potential carbon sources in the coming century. In contrast, the carbon sink capacity of modelled sites in Siberia, Far East Russia, Alaska and western and northern Canada was predicted to increase in the coming century. The greatest changes were evident in eastern Siberia, northwest Canada and in Alaska, where peat production, from being hampered by permafrost and low productivity due the cold climate in these regions in the past, was simulated to increase greatly due to warming, wetter climate and greater CO2 levels by the year 2100. In contrast, our model predicts that sites that are expected to experience reduced precipitation rates and are currently permafrost free will lose more carbon in the future.

Revised Text: Higher temperatures will result in earlier snowmelt and a longer growing season (Euskirchen et al., 2006), promoting plant productivity. Our results for both a strong warming (RCP8.5) and low warming (RCP2.6) scenario indicate that the limited increase in decomposition due to soil warming will be more than compensated by the increase in NPP in the first half of the 21st century, resulting in accelerated peat accumulation. Decomposition was, however, simulated to increase after 2040 due to permafrost thawing and high temperature, resulting in the loss of comparatively higher amount of carbon by the end of the 21st century (Fig. 12).

Figure 1-

Comment: Surface runoff in this figure seems to include subsurface flow in the peat layers. Also, AWTP needs formal definition - the reader should not have to guess its meaning.

Response: We have now revised this figure (see Fig. 4 in the RM) and included those components.

Figure 4-

Comment: The light red shaded area shows the 95% confidence interval (CI) inferred from the simulation data. It would be useful to explain somewhere how the CIs were calculated.

Response: Here is the calculation. We have included this information in footnotes (see line: 674 in the RM) CI = $\mu \pm$ Z.95 SE

where μ is the mean peat depth across all the patches, SE is the standard error of the mean and Z.95 is the confidence coefficient from the means of a normal distribution required to contain 0.95 of the area.

Fig. 9 The changes in peat thickness under the 'all' scenario are actually quite small.

Response: Yes, the change in peat thickness under the all scenario is small we have revised this in the text (see lines: 22-24 and 608-614 in the RM).

Revised Text: We found that the Stordalen mire may be expected to sequester more carbon in the first half of the 21st century due to milder and wetter climate conditions, a longer growing season, and the CO2 fertilization effect, turning into a carbon source after mid-century because of higher decomposition rates in response to warming soils.

Higher temperatures will result in earlier snowmelt and a longer growing season (Euskirchen et al., 2006), promoting plant productivity. Our results for both a strong warming (RCP8.5) and low warming (RCP2.6) scenario indicate that the limited increase in decomposition due to soil warming will be more than compensated by the increase in NPP in the first half of the 21st century, resulting in accelerated peat accumulation. Decomposition was, however, simulated to increase after 2040 due to permafrost thawing and high temperature, resulting in the loss of comparatively higher amount of carbon by the end of the 21st century (Fig. 12).

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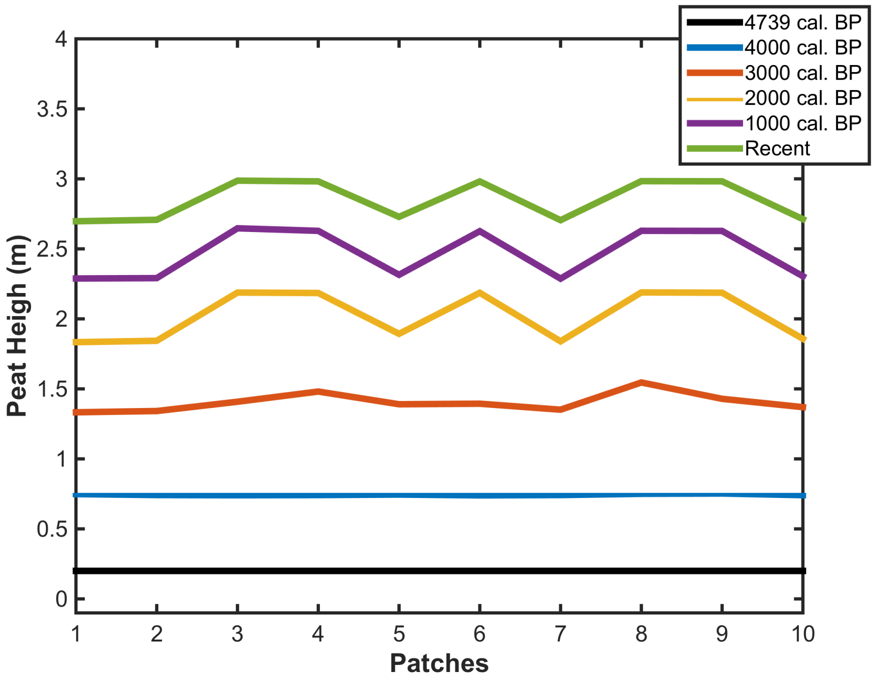

Fig. 1. Peat surface dynamics over time starting from the flat surface

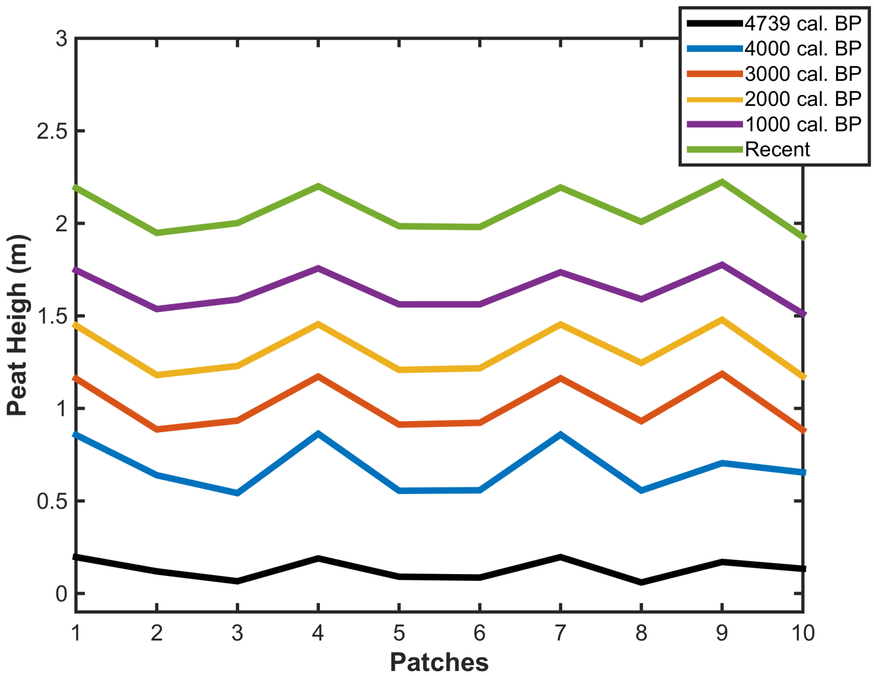

Fig. 2. Peat surface dynamics over time starting from the random surface in STD experiment