Response: 1st Reviewer

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Title: Modelling Holocene peatland dynamics with an individual-based dynamic vegetation model

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We appreciate the time and effort spent by the editor and 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.

General comments:

Looking at figure 8, it is apparent that the modelled peat depth vs. the observed peat depth is not great. This I can understand, the climate of the holocene when these peatlands were forming is not likely to be well captured with climate and conditions as they were able to produce. My main issue is the NEE estimates from the model are also not corresponding well to observations. In this instance the conditions at the sites are well known and reasonable climate should be possible. The problem with the NEE values being off significantly is that it is difficult then to trust when the model predicts the peat depth at sites should grow significantly or shrink since the NEE is how that is controlled in essence.

I also feel that many of the model outputs are not compared to observations when they should be. For e.g., the active layer depth is only compared at one of the 10 sites simulated. Do any of the other sites have information about ALD? Do any have ALD timeseries for comparision? What about the PFT distribution. The PFT distribution is shown in Table 5 but is just a presence or absence. Is there any more quantitative values that can be used to compare the model to obs here? Given the productivity differences between PFTs, it could be instructive for interpretation of model-obs differences. For the WTP, could there be some comparisons not just of some mean annual value but of the timeseries? Is the water table correct at the different times of the year? In general, much of the model performance is sort of dumped into tables, since this is the first paper describing this peatland version of LPJ-GUESS I believe more effort has to be put into demonstrating that the model doesn't get things 'sort of ok' for the wrong reasons.

Response: We agree with the reviewer's point that we need to give a better demonstration of the skill of our model. We have therefore clarified and improved these aspects of the paper, and here we provide a summary of our changes.

Net Ecosystem Exchange (NEE)

We ran the model with the observed dataset for the Stordalen site from the year 2001-2012 and our model predicts reasonable NEE values for the Stordalen site (see Fig. 11 in the revised manuscript (RM)). NEE outputs for the other three sites are almost within the range of observed NEE values (see Table 5 in the RM), albeit with some differences. Fajemyr and Degerö Stormyr are disturbed (i.e. subject to anthropogenic influence), which we have haven't accounted for in the model but relatively less influenced sites (Stordalen and Siikaneva) showed close match with the observed values. Furthermore, water borne carbon fluxes are not included in the model and that is also one of the potential causes of this discrepancy.

Peatlands are heterogeneous ecosystems and the carbon fluxes vary spatially and temporally within the landscape. Ecosystem scale NEE can be obtained using eddy flux towers, but previous studies have highlighted that peatland short-term NEE fluxes show a lot of variability and may not be indicative of long-term peatland behavior (Lafleur et al., 2003; Aslan-Sungur et al., 2016). We believe that it is equally important for models to capture the long-term carbon accumulation rate (LARCA). We find our LARCA values are quite close to the Fajemyr and Siikaneva sites and in our companion paper (Biogeosciences Discuss., doi:10.5194/bg-2017-34, 2017) we have demonstrated that the model was able to capture the right LARCA values in almost all the major peatland regions across the Arctic.

Active Layer Depth (ALD)

We have compared the simulated annual ALD with the observed values (1990-2011) for the Stordalen site (see Fig. 9 in the RM) and even analysed the hummocks and hollow ALD separately. We found that the magnitude, variability and trend of the simulated annual ALD are close to the observed values (see Fig. 9 in the RM). ALD is shallow in drier, elevated areas while deeper in wetter hollows, a phenomenon observed in many permafrost peatland sites (Johansson et al., 2013). The ALD trends over the observed period are also similar. Observed ALD trends are 69.2 cm/year, whereas the modelled ALD trend is 68.2 cm/year over the same period.

Furthermore, in our companion paper we produced a permafrost extent map (see Fig. 5 on the page 28 in the companion paper) that captures the main features of the permafrost distribution map developed by Tarnocai et al. 2009 (see their Fig. 1 on page 3), highlighting the robustness of the model in predicting the existence of permafrost in other areas besides the sites discussed in this paper.

Water Table Position (WTP) and PFT distribution

We have compared the observed annual and monthly WTP for a semi-wet patch in Stordalen to the simulated result with our model's semi-wet patches for the period 2003-12. The results were quite consistent with observed values (see Figs. 8 and A5 in the RM).

For majority of Stordalen peatland history, different species of mosses occupied the mire. The model predicted correctly the dominance of wet PFT during 4000-3000 cal. BP (see Fig. 6a in the RM). However, there was a certain period between 700-1700 cal. BP when graminoids were again the dominant PFT, but we could not reproduce that period due to the climate forcing used here, as explained in the text. See lines: 527-533.

We have given further responses to each of the reviewer's comments on WTP, plant distribution, bulk density and ALD below.

- **line 10: Change 'current' to 'many' in the start of the second sentence. Other models do indeed have peatlands, e.g.**

Response: We agree with the reviewer on this but many current models do not have a multiple peat layer representation with permafrost functionality and we wanted to highlight such functionality in current dynamic global vegetation models (DGVM), not in other models. Only Kleinen et al. (2012) and Stocker et al. (2014) have introduced initial representations of peat formation in a DGVM framework but both of them lack permafrost functionality. The papers by Wu et al. (2016) and Alexandrov et al. (2016), however, describe quite recent model developments but both were published last year when this study was being submitted, so we couldn't refer them. Also, these two models are not DGVMs (see Table S1 on page 45 (line: 793) in the RM- there are many other models apart from the one mentioned in this table). In Table S1, comparison of the functionality and scope of a representative set of current peatland models have been mentioned. So, although we think current is a more appropriate word than many, we have modified the earlier sentence and clarified the above points for the readers.

Revised text (lines: 11-13 in the RM) **-** 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.

- **l. 30: Do you really mean Wania et al here? That was a modelling study... If you are talking about the mask used for the peatland regions that was Tarnocai, not Wania. Cite the true reference please.**

Response: We have now modified the sentence and added that reference (see lines: 30-31 in the RM).

Revised text: Around 19% (3556 × 103 km^2) of the soil area of the northern peatlands coincides with low altitude permafrost (Tarnocai et al., 2009; Wania et al., 2009a).

- **l. 38: Could add some of the refs I gave above to this list.**

Response: We have added a reference to Stocker et al. (2014) (see lines: 37-39 in the RM). Here we are referring specifically to DGVMs.

Revised text: 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).

- **l. 40: See the Stocker ref along with Alexandrov to see if this statement is correct still.**

Response: Many models described in these references did not have multiple annual layer representations of peat accumulation and decomposition so we haven't included them in this sentence (see Table S1 in the RM (line: 793)). However, we have reformulated the sentence for more clarity (see lines: 35-45 in the RM) and added a separate sentence to acknowledge the work done by other modelling groups.

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).

- **l. 43: 'northern high latitudes, ... , could' - suggest adding some commas.**

Response: Thank you, we have done this (see lines: 47-49 in the RM)

Revised text: Current climate models predict that the northern high latitudes, where most of the peatlands and permafrost areas are present, could experience warming of more than 5°C by 2100 (Hinzman et al., 2005; Christensen et al., 2007; IPCC, 2013).

- **l. 70: By soil resources, you mean water right? nutrients are not simulated in this version, correct?**

Response: Yes, by soil resources we mean water, not nutrients, and we have clarified this in the text (see lines: 76-79 in the RM)

Revised text: Vegetation structure and dynamics follow an individual- and patch-based representation in which plant population demography and community structure evolve as an emergent outcome of competition for light, space and soil water among simulated plant individuals, each belonging to one of a defined set of plant functional types (PFTs) with different functional and morphological characteristics (see below).

- **l. 80: So how many soil layers? This description in this paragraph is different than the figure. Please make them more congruent. I am still not sure how many layer were truly simulated.**

Response: 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 can't show that many layers in a figure so we simplified the representation in schematic representation of the model (see Fig. 1 in the RM and lines: 91-98).

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.

- **l. 95 : based on what studies?**

Response: We added the references after the second sentence but now we have moved it a little further in the text for clarity (see lines: 104-105 in the RM)

Revised text:

Woody litter mass from shrubs decomposes relatively slowly because it is made up of hard cellulose and lignin (Aerts et al., 1999; Moore et al., 2007).

- **l.97: I don't understand the 'fresh litter debris decomposes through surface forcing until the last day of the year'. Surface forcing?**

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.

- **l 117 : Please put the values of all these constants in the text and not just the table. It was confusing until I found the table since the table is not really mentioned until much later.**

Response: We have included constant values at all the appropriate places and also referred earlier to Table 2 in the revised manuscript. See lines: 150-153, 156-158, 166-168, 219, 222, 231 and 234 and Table 2 in the RM.

- **l 117: How does K relate to K_o or K_i?**

Response: We use K in general terms to refer to an overall decomposition rate of the entire peat column.

k_i, however, is the decomposition rate of an individual peat layer (*i*) (see Eq. 2 and 3 in the RM) and k_o is the *initial* decomposition rate. This distinction was introduced by Clymo (1984) and is also used in the Frolking et al. (2010) and some other publications on peatland modelling. We explain these variables just below the equations where they were first defined and there we also referred to these papers (see lines: 129-140 and 144 in the RM)

- **Eqns 4 and 5 - would be nice if these were plotted, easier than trying to imagine in the head...**

Response: We agree with the reviewer. We have now included them as a new figure (Fig. A1 in the RM; see lines: 152, 158 and 728 in the RM)

In Fig. A1, we presented assumed decomposition dependency on (a) soil temperature and (b) soil water content.

- **All eqns - be consistent between 1.0 and 1 etc. in the equations.**

Response: Agreed. We have changed all equations to use 1 consistently

- **Eqn 6 - units?**

Response: kg m^{-3} (Included in the text see lines: 166-167 in the RM)

- **l. 153 - value of the min and max bulk densities? Calculated somewhere?**

Response: Minimum bulk density – 40 kg m^{-3} and maximum bulk density - 120 kg m^{-3}

They are prescribed values and inspired by the work of Frolking et al. (2010) (see their Fig. 3 and Table 2 on page 6) where they used a similar range of 30-120 kg m^{-3}. Heinemeyer et al. (2010) prescribed a range of 50-100 kg m^{-3} (see their section 2.3.5 on page 214). Similar ranges can be found in the majority of peatlands (see the explanation below).

- **pg 7 - choose one: cm or mm and please stick to whichever is chosen.**

Response: Agreed. We have changed it to cm throughout.

- **Eqn 8 - Did I miss how F was found?**

Response: We gave the reference in the beginning but now we have placed it right next to F (see line: 216 in the RM). F is the fraction of the modelled area subject to evaporation (i.e. bare soil fraction) calculated by LPJ-GUESS, and explained in Gerten et al. (2004) – see Eq. 9 on Page 254 in their paper.

Revised text: Evaporation can only occur when the snowpack is thinner than 1 cm and is calculated following the approach of Gerten et al. (2004), as in the standard version of LPJ-GUESS:

$$\mathrm{ET} = 1.32\,.\,\mathrm{E}\,.\,\mathrm{W}_c^2\,.\,\mathrm{F}$$

where E is the climate-dependent equilibrium evapotranspiration (cm), W_c is the water content on the top 10 cm of the peat soil and F is the fraction of modelled area subject to evaporation, i.e. not covered by vegetation (Gerten et al., 2004).

- **Eqn 12: Are you sure this is a change of porosity? This looks more like a fraction of original porosity. Change to me implies something like flux.**

Response: Porosity, the volume of empty spaces over the total volume, varies between 0-1. In our implementation, porosity is a function of bulk density and it decreases from (1-40/800 = 0.95) to (1-120/800 = 0.85) as bulk density increases. Frolking et al. (2010) used a similar function (see their Eq. 18 on page 7) and we have given a reference to it. Ryden et al. (1980) found a similar observed range of 0.97-0.88 in depressed patches and 0.93-0.87 in elevated areas in Stordalen (see their Tables 2 and 3 on page 37-39).

- **L 227: So moss can get water from 50 cm mineral + peat depth until peat => 50 cm? This seems strange and would greatly advantage moss for quite a while. Is there any indication that moss can access water almost 1 m down? I find this difficult to believe.**

Response: In our representation, moss can only take up water from the top 50 cm of the soil. It can take up water from the top 50 cm of the mineral soil during the spin up phase, after which it starts taking up the water from the peat soil (but again only the top 50 cm). We have clarified this in the text. See lines: 243-249 in the RM.

Revised text: In the beginning of the peat accumulation process, plant roots are present both in peat and upper and lower mineral soil layers but their mineral soil root distribution declines linearly as peat grows (see Fig. 2) and the corresponding mineral layer reduction is used to access water from the peat layers. Mosses are assumed only to take up water from the top 50 cm of the mineral soil in the beginning but once the peat depth exceeds 50 cm they only take water from the peat layers (top 50 cm of the peat layer). Other PFTs can continue to take up water both from the mineral and peat soils until peat depth reaches 2 m, and from only from the peat soil thereafter.

- **l. 253: How are the heights done? Is this peat height or actual elevation?**

Response: It is the cumulative peat height minus the initial elevation.

- **l. 316: Sure it conserves the IAV - but it also then pegs the IAV as the same for the whole simulation instead of perhaps changing through time.**

Response: We agree with the reviewer on this point but it is a common technique used for reconstruction of palaeo climate forcing when there are no proxy based climate data available from which one could infer a change in IAV. We have clarified the text to explain the effects of not capturing the IAV, see lines: 507-515 and 527-533.

Revised text: Studies of the influence of GCM-generated climate uncertainty (i.e. variations in climate output fields among GCMs) on carbon cycle model prediction, underline the high prediction error that can arise, for example in present-day biospheric carbon pools and fluxes (Ahlström et al., 2013; Anav et al., 2013; Ahlström, 2016). Potential bias and errors in the predicted climate may be expected to be even higher in palaeoclimate simulations, not least due to the absence of instrumental observations for validating the models. Furthermore, in this study additional bias could arise due to the interpolation procedure used to transform GCM output fields into monthly anomalies, required to force our model. These were generated by linearly interpolating between the climate model output, which is only available at 1000-year intervals. As such, the applied anomalies do not capture decadal or centennial climate variability that can contribute to climate-forced variable peat accumulation rates and vegetation dynamics on these timescales (Miller et al., 2008).

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. Graminoids were not productive during the entire simulation period apart from the period 4-3kyr cal. BP (Kokfelt et al., 2010). The model predicted correctly the dominance of graminoids, characteristic of wet conditions, during 4-3kyr cal. BP. However, a period of graminoid dominance between 700-1700 cal. BP was not accurately captured. One explanation can be the absence of decadal and centennial climate variability in the adopted climate forcing data, resulting in an "averaging out" of moisture status over time that elminates wet episodes needed for graminoids to be sufficiently competitive.

- **l. 318: No, it is really reanalysis or interpolated climate. There are no 'observed' gridded products available.**

Response: Yang et al. (2012) developed an observed climate time series (50 m resolution) from 1913-2006 for the Stordalen catchment. We used the first 30 years (1913-1942) mean (μ) and standard deviation (σ) and drew randomly generated climate data assuming a normal distribution. The randomly generated climate data is then applied to the relative anomalies derived from the gridcell nearest to the location of the site from millennium time-slice experiments using the UK Hadley Centre's Unified Model. Explained in detail between lines – 350-362.

Existing Text:

The high spatial resolution (50 m), modern observed climate dataset was developed by Yang et al. (2012) for the Stordalen site. In this dataset, the observations from the nearest weather stations and local observations were included to take into account the effects of the Torneträsk lake close to the Stordalen catchment. The monthly precipitation data (1913-2000) for Stordalen at 50 m resolution were downscaled from 10 min resolution using CRU TS 1.2 data (Mitchell and Jones, 2005), a technique quite common for cold regions (Hanna et al., 2005). The precipitation data was also corrected by including the influences of topography and also by using historical measurements of precipitation from the Abisko research station record. Finally, monthly values of Holocene temperature were interpolated to daily values, monthly precipitation totals were distributed randomly among the number (minimum 10) of rainy days per month from the climate dataset and the monthly CRU values of cloudiness for the first 30 years from the year 1901-1930 were repeated for the entire simulation period. We added random variability to the daily climate values by drawing random values from a normal distribution with monthly mean (μ) and standard deviation (σ) of the monthly observed climate were used for Stordalen from the period of 1913-1942 and for Mer Bleue, 30 years of monthly CRU values from the period of 1901-1930 were used.

l. 341: Can you please expand more on why you needed to keep the mineral and peat layers saturated during initialization. This to me would imply that your model was out of equilibrium at the start of your runs and thus the transient behaviour would be influenced by the model initial conditions. This is a bit worrying. Once you released the saturated conditions the model could then over-react to dry conditions as mentioned.

Response: We adopted this model initialisation strategy partially to avoid any sudden collapses of the peat column in very dry conditions because young, shallow peat can become drier or wetter within a very short time span and continuous dry periods would increase temperature dependent decomposition rates and reduce the accumulation rate markedly. Furthermore, peatlands develop due to the complex processes of terrestrialisation or plaudification that are not fully captured by our model in its current form. We agree that keeping the patches wet enough during the initialization phase is a limitation of our model, but it is one that corresponds to allowing peat growth in locally, low-lying saturated ecosystems in each gridcell.

- **l. 349 : This comment about adjusting to the local WTP really drives my request for comparing timeseries of WTP since it is then apparent that we cannot put too much stock in the mean WTP values matching reasonably.**

Response: We forced the model with observed climate from 2001-2012 and found modelled annual and monthly WTP for semi-wet patches are quite close to the observed annual WTP from the year 2003 to 2012 (see Figs. 8 and A5 in the RM and lines: 538-548 in the RM).

Revised text: The modelled annual and monthly WTP from 2003-2012 in semi-wet patches and modelled annual ALD 1990-2012 is in good agreement with the observed values for the Stordalen region (Figs. 8, 9 and A5) supporting the ability of model to capture hydrological dynamics that further drive peatland dynamics. For the additional evaluation sites, modelled dominant vegetation cover, LARCA and WTP were in good agreement with the observed values for the three selected sites at which this information was available. Under the present climate, Stordalen was simulated to be a small sink for atmospheric CO_2, in agreement with observed NEE (see Fig 11). NEE interannual range is likewise close to observations for the other Scandinavian sites (Table 5). However it is uncertain whether recent annual observations of NEE necessarily reflect the long-term peatland carbon balance, in view of high variability on multiple timescales. For example, Fajemyr has switched between source (14.3-21.4 g C m^{-2} yr^{-1} in 2005-2006; 23.6 g C m^{-2} yr^{-1} in 2008) and sink (-29.4 g C m^{-2} yr^{-1} in 2007; -28.9 g C m^{-2} yr^{-1} in 2009) conditions in recent years, and this variability has been attributed to disturbances and intermittent drought conditions (Lund et al., 2012).

In Fig. 8 (RM) (a) the total sum of precipitation (in cm) and **(b)** a comparison between observed and simulated mean annual WTP for semi-wet patches in Stordalen for the period 2003-2012 was presented

In Fig. A5 in the RM a comparison between observed and simulated monthly mean WTP (JJA) for semi-wet patches in Stordalen for the period 2003-2012 have been shown.

- **l. 400: 'lower than 50 kg m-3' - higher meant? l. 416: Any obs to compare with here?**

Response: Simulating bulk density is a challenge. In some peatlands, it may increases with depth due to compaction (Clymo, 1991; Novak et al., 2008) but other studies have shown no net increase in the bulk density with depth in some other locations (Tomlinson, 2005; 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 and it is highly variable down the 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:

429:440 in the RM).

Revised text: When the peat layers had decomposed sufficiently and lost more than 70% of their original mass (M_o), 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. Therefore, when the peat bulk density increased, pore space declined from 0.95 to 0.93 reducing the total permeability of peat layers that in turn reduced the amount of percolated water from the peat layers to the mineral soil.

l. 421: Are there any vegetation reconstructions available for these sites? Pollen cores that can help determine if the model successional sequence is reasonable?

Response: For majority of its peatland history, different species of mosses occupied the Stordalen mire. The model predicted correctly the dominance of wet PFT during 4000-3000 cal. BP. However, there was a certain period between 700-1700 cal. BP when graminoids were again the dominant PFT, but we could not reproduce that period due to the climate forcing used here, as explained in the text. See lines: 527-533 in the RM.

Revised text: 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. Graminoids were not productive during the entire simulation period apart from the period 4-3kyr cal. BP (Kokfelt et al., 2010). The model predicted correctly the dominance of graminoids, characteristic of wet conditions, during 4-3kyr cal. BP. However, a period of graminoid dominance between 700-1700 cal. BP was not accurately captured. One explanation can be the absence of decadal and centennial climate variability in the adopted climate forcing data, resulting in an “averaging out” of moisture status over time that elminates wet episodes needed for graminoids to be sufficiently competitive.

Fig 1: why are the mosses all different colours? Can this diagram be simplified - like only a couple grass instead of that dark mat? Should permafrost maybe be ’frozen soil’ or maybe distinguish seasonally frozen soil from perenially frozen? Why is the permafrost bubble circular? Would the model really have a different

bottom permafrost depth between its tiles in the same gridcell? I can understand a different top depth but not really a bottom.

Response: Our moss colours are different because they depict different stages of the moss growth cycle. However, for simplicity we have changed it to single colour. Graminoids numbers are also reduced. We have changed the text from permafrost to frozen soil and removed the circularity (see Fig. 1 in the RM). In principle, our model can have different ALD values in each patch based on the soil temperature and soil water content in that patch. Wet patches can have greater ALD than dry patches (see Fig. 9 in the RM).

Fig 2: Perhaps choose a different acronym than UM since that is also used in the MS to talk about a model.

Response: We have changed it to UMS (Upper mineral soil). See Fig. 2 in the RM.

Revised caption:

Fig. 2 in the RM - Root fractions in the upper (UMS) and lower mineral soil (LMS) layers as a function of peat depth (m). The broken lines represent root fractions in UMS and solid lines indicate fractions in the LMS.

- **Fig. 6 I find the acronym choice non-sensible. Why does the final S of deciduous shrubs be S and not a D? Not a big deal but it makes it harder to quickly remember what the acronym stands for.**

Response: We used HSS in the paper since it is the acronym for High Summergreen Shrubs and LSS for Low Summergreen Shrubs (see Table 1 in the RM). These are the most common acronyms used in LPJ-GUESS publications (Wolf et al., 2008; Miller and Smith, 2012). We have revised the figure (see Fig. 6 in the RM).

Fig 7: No description of the X and Z in the caption. What do Top, Middle, and Bottom really correspond to? This gets back to my earlier comment that I don't understand how your soil layers were divided.

Response: We have now explained X and Z in the caption. There are 4739 peat layers and they were aggregated in to number of sublayers for the soil temperature calculation. We start with three sublayers of equal depth and add a new sublayer for every half a meter peat depth increment. We adopted this scheme for soil temperature because over the time these individual layers become so thin and numerous that they slow down the numerical soil temperature calculations. In total, seven sublayers formed at the Stordalen site and in figure the three sublayers are shown as top (average of layers 6+7), middle (average of layers 3+4+5) and bottom (average of layers 1+2). See lines: 172-181 in the RM.

Revised text: To simulate permafrost, peat layer decomposition and cycles of freezing and thawing, the soil temperature at different depths must be calculated correctly. In the Arctic version of LPJ-GUESS as described by Miller and Smith (2012), mineral soil layers (i.e. below the peat layers added in this study) are subdivided into 20 sublayers of 10 cm thickness to calculate soil temperature at different depths. 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. This resulted, for example, in seven aggegate sublayers for the Stordalen simulations described in Section 2.4. The result is a soil column with a dynamic number of peat sublayers, 20 mineral soil layers and multiple “padding” layers to a depth of 48 m. A single layer of snow is included, as in existing versions of the model.

Revised Caption:

Fig. 7. (**a)** Total simulated peat ice fraction (10-year moving average) over 4700 years at Stordalen. Peat layers corresponding to annual litter cohorts were aggregated to top (top 1 m), middle (middle 1 m) and bottom (lower 1.5 m) for display. **(b)** Total simulated ice fraction for 1900-2100 following the RCP8.5 scenario (see Fig. A6 for the RCP2.6 scenario results), **(c)** Total simulated mean September active layer depth for the last 4700 years and **(d)** for 1900-2100 at Stordalen following the RCP8.5 scenario (FTPC8.5) and RCP2.6 scenario (FTPC2.6).

- **Fig 8: As I said in the general comments, this figure does not give much confidence when combined with the NEE results.**

Response: As mentioned earlier, NEE outputs for the other three sites are almost within the range of observed NEE values (see Table 5 in the RM), albeit with some differences. The recent short-term NEE values are not the right criteria to judge whether the model is doing the right job or not because they vary a lot spatially as well as temporally and since the peatland landscape is such a heterogeneous site, the NEE values vary between each points. Though, large-scale fluxes can be obtained from eddy flux tower but they also showed high variability (Lafleur et al., 2003; Aslan-Sungur et al., 2016). In this study, some sites (Fajemyr and Degero Stormyr) are relatively disturbed sites with high N deposition which might have influenced their NEE fluxes (Lund et al., 2007). The other factor of large uncertainty in NEE in Fajemyr is non-inclusion of trees. Also, water borne carbon fluxes (DOC) and CH_4 are not yet considered in our model (but are under development; e.g. Tang et al., 2015b). Inclusion of these factors would minimize the uncertainty. This is the reason we didn’t do any future predictions for these sites. However, comparatively less disturbed sites showed reasonable simulated NEE values (see Fig.11 in the RM). We believe, the right evaluation for the peat carbon balance can be extracted from long-term carbon accumulation values (LARCA) and we find a close match between modelled and observed LARCA values. In our companion paper, we have found the model is able to capture the right LARCA value across many regions. See lines: 540-548 in the RM.

In **Fig. 11** of the RM, we presented (a) annual simulated NEE (kg C m^{-2} yr^{-1}) for Stordalen and (b) relationship between observed and modeled annual NEE (kg C m^{-2} yr^{-1}) for three Scandinavian peatland ecosystems (Table 5; observed NEE data from (Aurela et al., 2007; Lund et al., 2007; Sagerfors et al., 2008; Aslan-Sungur et al., 2016)). EC = eddy covariance (flux tower) data; CH = chamber flux measurements.

Revised text: For the additional evaluation sites, modelled dominant vegetation cover, LARCA and WTP were in good agreement with the observed values for the three selected sites at which this information was available. Under the present climate, Stordalen was simulated to be a small sink for atmospheric CO_2, in agreement with observed NEE (see Fig 11). NEE interannual range is likewise close to observations for the other Scandinavian sites (Table 5). However it is uncertain whether recent annual observations of NEE necessarily reflect the long-term peatland carbon balance, in view of high variability on multiple timescales. For example, Fajemyr has switched between source (14.3-21.4 g C m^{-2} yr^{-1} in 2005-2006; 23.6 g C m^{-2} yr^{-1} in 2008) and sink (-29.4 g C m^{-2} yr^{-1} in 2007; -28.9 g C m^{-2} yr^{-1} in 2009) conditions in recent years, and this variability has been attributed to disturbances and intermittent drought conditions (Lund et al., 2012).

Also, **see Table 5 in RM** where observed dominant vegetation cover, long-term apparent rate of carbon accumulation (LARCA), short-term net ecosystem exchange (NEE), and annual water table position (WTP) compared with mean modelled values (1990-2000) for the 3 grid points in Scandinavian region were included

- **Fig A1 - perhaps add total water (liquid and frozen) so we can see if the total content was changing and it wasn't just changing phase.**

Response: We have added a new panel showing the total water and ice in cm (see Fig. A4 in the RM). In the figure, total water is the melted water and total ice is the frozen water.

- **Table 2: density is needing the o as an subscript. Also please bring these all into the main text, it is annoying to have to search out the table when one is reading the text (and it is often not mentioned that one needs to search for a table...)**

Response: We have added a subscript to the density parameter. We have also included all the parameter values in the text and we also now refer to Table 2 in RM when a new constant is first mentioned See lines: 150-153, 156-158, 166-168, 219, 222, 231 and 234 and Table 2 in the RM.

- **Table 5: WTP units? Please put in proportions of the veg so we can tell if the proportions modelled are in any way correct rather than just presence/absence.**

Response: The WTP unit is cm and we have included in the text (see Table 5 in the RM). However, we unfortunately couldn't find total vegetation proportion data for these sites.

Response: 2nd Reviewer

Substantive comments

1. ***Model choice and model scale***

The authors note the following:

"Model formulations of peat accumulation and decay have been proposed and demonstrated 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).

2. ***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 CH_4 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.

3. ***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.

$$\mathrm{MWTP} = \sum \mathrm{PWTP_i} / \mathrm{n}$$

where MWTP is the mean WTP across all the patches, $\mathrm{PWTP_i}$ 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:

$$\mathrm{DWTP_i} = \mathrm{PWTP_i} - \mathrm{MWTP}$$

$LF_i = DWTP \cdot \Phi_a$

where $DWTP_i$ is the difference in the patch (i) and MWTP and LF_i 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 (Φ_a). When the WTP is above the surface then Φ_a 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).**

Revised sections 2.1.4 and 2.1.7:

2.1.4 Hydrology

Precipitation is the major source of water input in the majority of peatlands. In our model, precipitation is treated as rain or snow depending upon the daily surface air temperature. When temperature falls below the freezing point (0°C assumed), water is stored as a snow above the peat layers. Snow melts when the air temperature rises above the freezing point and is also influenced by the amount of precipitation on that day (Choudhury et al., 1998). We assume that the peatland can hold water up to +20 cm above the peat surface. Water is removed from the peat layers through evapotranspiration, drainage, surface and base runoff. A traditional water bucket scheme is adopted to simulate peatland hydrology (Gerten et al., 2004):

$$W = P - ET - R - DR \pm LF \tag{7}$$

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. We add 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 remain 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 a 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 the respective layer. WTP is updated daily based on existing WTP, W, the total drainage porosity and permeability of the peat layers. WTP is expressed in cm in this paper, with a value of 0 indicating a water table at the peat surface.

Evaporation can only occur when the snowpack is thinner than 1 cm and is calculated following the approach of Gerten et al. (2004), as in the standard version of LPJ-GUESS:

$$ET = 1.32 \,.\, E \,.\, W_c^2 \,.\, F \tag{8}$$

where E is the climate-dependent equilibrium evapotranspiration (cm), W_c is the water content on the top 10 cm of the peat soil and F is the fraction of modelled area subject to evaporation, i.e. not covered by vegetation (Gerten et al., 2004).

Runoff is an exponential function of WTP (Wania et al., 2009a):

$$R = BR + \begin{cases} e^{0.01}\ \mathrm{WTP}, & \mathrm{WTP} > \mathrm{TH} \\ 0, & \mathrm{WTP} \leq \mathrm{TH} \end{cases} \tag{9}$$

where TH is the WTP threshold, set to -30 cm (Table 2) and BR is the base runoff proportional to the total peat depth (D) is estimated as:

$$BR = u\,D \tag{10}$$

where u is a parameter (see Table 2) which determines rate of increase in the base runoff with increase in the peat depth (D), set to 0.45 (Frolking et al., 2010). Loss of the water through drainage/percolation depends on the permeability of peat layers and the saturation limit of the mineral soil underneath. Percolation ceases if the mineral layers are saturated with water, incoming rainfall or snowmelt leading instead to an increase in WTP. Peat layer density is assumed to increase due to compression when highly decomposed by anoxic decomposition (Frolking et al., 2010). This results in declining permeability, affecting the flow of water from the peat layers to the mineral soil. The permeability of each peat layer (i) is calculated as a function of peat layer bulk density (Eq. 11) (Frolking et al., 2010). The amount of water draining from the peat column to the mineral soil is calculated by integrating permeability across all the peat layers (i).

$$\kappa_i = 10\ e^{-0.058\rho_i} \tag{11}$$

where κ_i is the permeability (0-1) and ρ_i is the bulk density of peat layer (i). Change of porosity (Φ) due to compaction is captured by a relationship to bulk density:

$$\Phi_i = 1 - \frac{\rho_i}{\rho_o} \tag{12}$$

where ρ_o is the particle bulk density of the organic matter (800 kg m^{-3}; see Table 2). Finally, water infiltrating from the peat to the mineral soil layers is treated as the input to the standard LPJ-GUESS hydrology scheme described in Smith et al. (2001) and Gerten et al. (2004).

2.1.7 Microtopographical structure

Many studies have highlighted the importance of surface micro-formations in peatland dynamics (Weltzin et al., 2001; Nungesser, 2003; Belyea and Malmer, 2004; Belyea and Baird, 2006; Sullivan et al., 2008; Pouliot et al., 2011). The patterned surface creates a distinctive environment with contrasting plant cover, nutrient status, productivity and decomposition rates in adjacent microsites. Such spatial heterogeneity is typically ignored in peatland modelling studies, but can be critically important for peatland development and carbon balance. In our approach, multiple vegetation patches are simulated to account for such spatial heterogeneity. The model is initialised with a random surface represented by uneven heights of individual patches (10 in the simulations performed here). Water is redistributed from the higher elevated sites to low depressions through lateral flow (LF) (see Eq. 7). We equalize the WTP of individual patches to match the mean WTP of the landscape on a daily time step. Patches lose water if their WTP is above the mean WTP of the landscape while the lower patches receive water (see Eqs. 13-15). This in turn affects the PFT composition, productivity and decomposition rate in each patch, and peat accumulation over time. We calculate the landscape WTP and add and remove the amount of water from each patch required to match the landscape WTP.

$$\mathrm{MWTP} = \sum \mathrm{PWTP_i}\ /\mathrm{n} \tag{13}$$

where MWTP is the mean WTP across all the patches, $\mathrm{PWTP_i}$ 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:

$$DWTP_i = PWTP_i - MWTP \quad (14)$$
$$LF_i = DWTP_i \cdot \Phi_a \quad (15)$$

where $DWTP_i$ is the difference in the patch (i) and MWTP and LF_i 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 (Φ_a). When the WTP is above the surface then Φ_a is not included in the calculation. This exchange of water between patches is implemented after the daily water balance calculation (Eq 7).

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 CO_2 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 CO_2 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 re-wording 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 km^2 (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 ±100 PgC across an area of approximately 3.5 million km^2 (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 × 103 km^2) 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.

$$W_m = \begin{cases} 1 - (1 - 0.025)\left(\dfrac{\theta - \theta_{opt}}{1.0 - \theta_{opt}}\right)^{\alpha}, & \theta > \theta_{opt} \\ 1 - \left(\dfrac{\theta_{opt} - \theta}{\theta_{opt}}\right)^{\alpha}, & \theta > 0.01 \text{ and } \theta \leq \theta_{opt} \\ \beta, & \theta \leq 0.01 \text{ and WTP} < -40 \end{cases}$$

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).

Revised equation:

$$W_m = \begin{cases} 1 - 0.975\left(\dfrac{\theta - \theta_{opt}}{1.0 - \theta_{opt}}\right)^{\alpha}, & \theta > \theta_{opt} \\ 1 - \left(\dfrac{\theta_{opt} - \theta}{\theta_{opt}}\right)^{\alpha}, & \theta > 0.01 \text{ and } \theta \leq \theta_{opt} \\ \beta, & \theta \leq 0.01 \text{ and WTP} < -40 \end{cases}$$

- **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 (M_o), 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).

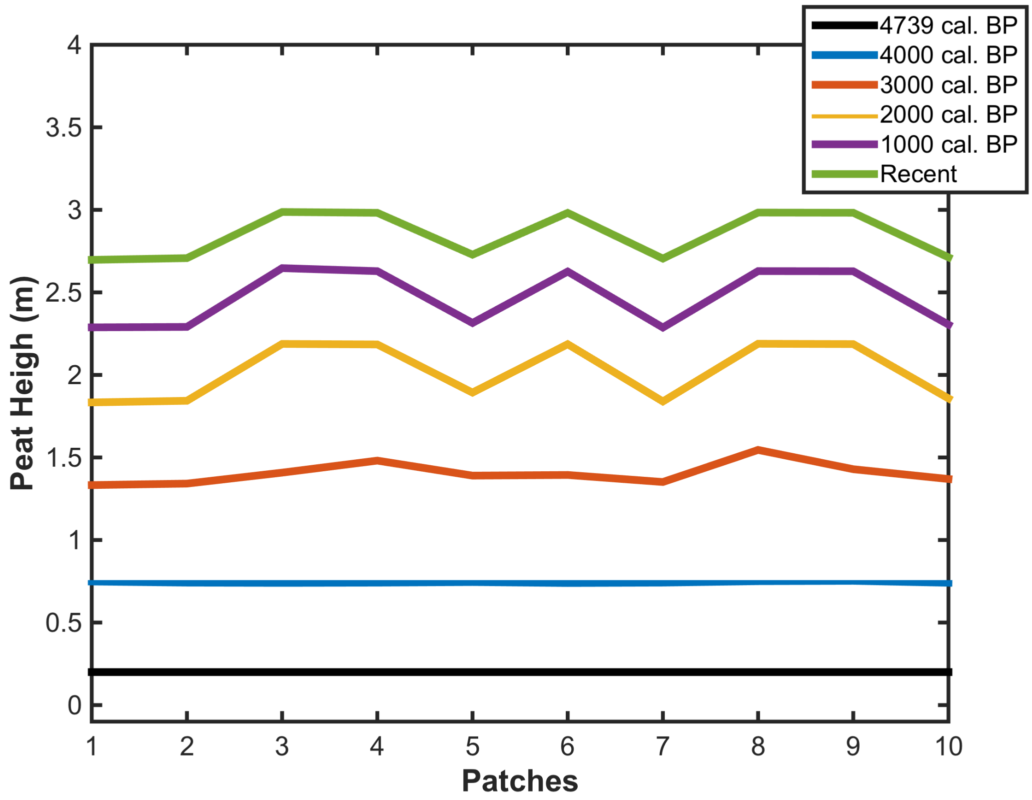

Fig. 1 Peat surface dynamics over time starting from the flat surface

- **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).

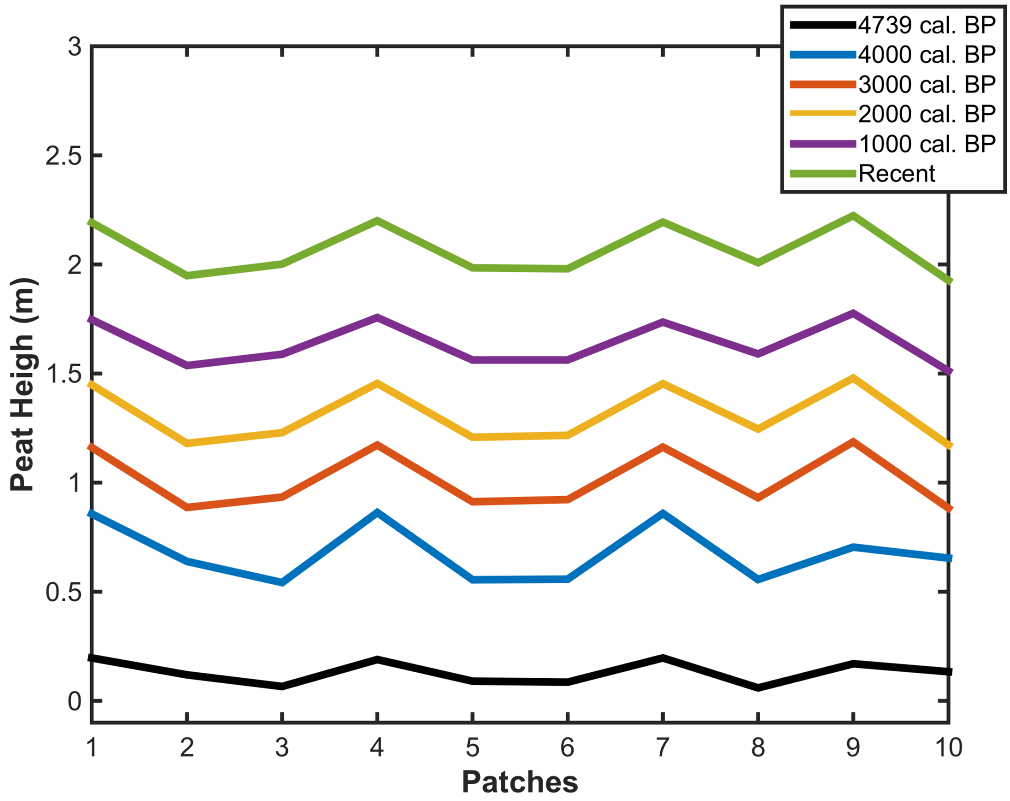

Fig. 2 Pxeat surface dynamics over time starting from the random surface in STD experiment

- **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 CO_2 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 CO_2 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).

References:

Aerts, R., Verhoeven, J. T. A., and Whigham, D. F.: Plant-mediated controls on nutrient cycling in temperate fens and bogs, Journal, 80, 2170-2181,doi: 10.1890/0012-9658(1999)080[2170:pmconc]2.0.co;2, 1999.

Ahlström, A., Schurgers, G. & Smith, B. : The large influence of climate model bias on terrestrial carbon cycle simulations, Environmental Research Letters, in press., 2016.2016.

Ahlström, A., Smith, B., Lindström, J., Rummukainen, M., and Uvo, C. B.: GCM characteristics explain the majority of uncertainty in projected 21st century terrestrial ecosystem carbon balance, Biogeosciences, 10, 1517-1528,doi: 10.5194/bg-10-1517-2013, 2013.

Alexandrov, G. A., Brovkin, V. A., and Kleinen, T.: The influence of climate on peatland extent in Western Siberia since the Last Glacial Maximum, Sci Rep, 6,doi: ARTN 24784
10.1038/srep24784, 2016.

Anav, A., Friedlingstein, P., Kidston, M., Bopp, L., Ciais, P., Cox, P., Jones, C., Jung, M., Myneni, R., and Zhu, Z.: Evaluating the Land and Ocean Components of the Global Carbon Cycle in the CMIP5 Earth System Models, J. Clim., 26, 6801-6843,doi: 10.1175/Jcli-D-12-00417.1, 2013.

Aslan-Sungur, G., Lee, X. H., Evrendilek, F., and Karakaya, N.: Large interannual variability in net ecosystem carbon dioxide exchange of a disturbed temperate peatland, Science of the Total Environment, 554, 192-202,doi: 10.1016/j.scitotenv.2016.02.153, 2016.

Aurela, M., Riutta, T., Laurila, T., Tuovinen, J. P., Vesala, T., Tuittila, E. S., Rinne, J., Haapanala, S., and Laine, J.: CO2 exchange of a sedge fen in southern Finland - The impact of a drought period, Tellus Ser. B-Chem. Phys. Meteorol., 59, 826-837,doi: 10.1111/j.1600-0889.2007.00309.x, 2007.

Baird, A. J., Milner, A. M., Blundell, A., Swindles, G. T., and Morris, P. J.: Microform-scale variations in peatland permeability and their ecohydrological implications, Journal of Ecology, 104, 531-544,doi: 10.1111/1365-2745.12530, 2016.

Belyea, L. R. and Baird, A. J.: Beyond "The limits to peat bog growth": Cross-scale feedback in peatland development, Ecol. Monogr., 76, 299-322,doi: 10.1890/0012-9615(2006)076[0299:btltpb]2.0.co;2, 2006.

Belyea, L. R. and Malmer, N.: Carbon sequestration in peatland: patterns and mechanisms of response to climate change, Global Change Biology, 10, 1043-1052,doi: 10.1111/j.1529-8817.2003.00783.x, 2004.

Choudhury, B. J., DiGirolamo, N. E., Susskind, J., Darnell, W. L., Gupta, S. K., and Asrar, G.: A biophysical process-based estimate of global land surface evaporation using satellite and ancillary data - II. Regional and global patterns of seasonal and annual variations, Journal of Hydrology, 205, 186-204,doi: 10.1016/s0022-1694(97)00149-2, 1998.

Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, Sarr, A., and Whetton, P.: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2007.2007.

Christensen, T. R., Johansson, T. R., Akerman, H. J., Mastepanov, M., Malmer, N., Friborg, T., Crill, P., and Svensson, B. H.: Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, Geophysical Research Letters, 31,doi: L04501 10.1029/2003gl018680, 2004.

Clymo, R. S.: The limits to peat bog growth, Philos. Trans. R. Soc. Lond. Ser. B-Biol. Sci., 303, 605-654,doi: 10.1098/rstb.1984.0002, 1984.

Clymo, R. S.: Peat growth, Quaternary Landscapes. Eds Shane LCK, Cushing EJ. Minneapolis, University of Minnesota Press., 1991. 76-1121991.

Euskirchen, E. S., McGuire, A. D., Kicklighter, D. W., Zhuang, Q., Clein, J. S., Dargaville, R. J., Dye, D. G., Kimball, J. S., McDonald, K. C., Melillo, J. M., Romanovsky, V. E., and Smith, N. V.: Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems, Global Change Biology, 12, 731-750,doi: 10.1111/j.1365-2486.2006.01113.x, 2006.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K. G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate-carbon cycle feedback analysis: Results from the (CMIP)-M-4 model intercomparison, J. Clim., 19, 3337-3353,doi: 10.1175/jcli3800.1, 2006.

Frolking, S., Roulet, N. T., Tuittila, E., Bubier, J. L., Quillet, A., Talbot, J., and Richard, P. J. H.: A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation, 1 Article, Earth System Dynamics, 1-21 pp., 2010.

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., and Sitch, S.: Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model, Journal of Hydrology, 286, 249-270,doi: 10.1016/j.jhydrol.2003.09.029, 2004.

Hanna, E., Huybrechts, P., Janssens, I., Cappelen, J., Steffen, K., and Stephens, A.: Runoff and mass balance of the Greenland ice sheet: 1958-2003, Journal of Geophysical Research-Atmospheres, 110, 16,doi: 10.1029/2004jd005641, 2005.

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

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., Griffith, B., Hollister, R. D., Hope, A., Huntington, H. P., Jensen, A. M., Jia, G. J., Jorgenson, T., Kane, D. L., Klein, D. R., Kofinas, G., Lynch, A. H., Lloyd, A. H., McGuire, A. D., Nelson, F. E., Oechel, W. C., Osterkamp, T. E., Racine, C. H., Romanovsky, V. E., Stone, R. S., Stow, D. A., Sturm, M., Tweedie, C. E., Vourlitis, G. L., Walker, M. D., Walker, D. A., Webber, P. J., Welker, J. M., Winker, K., and Yoshikawa, K.: Evidence and implications of recent climate change in northern Alaska and other arctic regions, Clim. Change, 72, 251-298,doi: 10.1007/s10584-005-5352-2, 2005.

IPCC: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013. NY, USA2013.

Johansson, M., Callaghan, T. V., Bosio, J., Akerman, H. J., Jackowicz-Korczynski, M., and Christensen, T. R.: Rapid responses of permafrost and vegetation to experimentally increased snow cover in sub-arctic Sweden, Environmental Research Letters, 8,doi: 10.1088/1748-9326/8/3/035025, 2013.

Johansson, T., Malmer, N., Crill, P. M., Friborg, T., Akerman, J. H., Mastepanov, M., and Christensen, T. R.: Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing, Global Change Biology, 12, 2352-2369,doi: 10.1111/j.1365-2486.2006.01267.x, 2006.

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

Kokfelt, U., Reuss, N., Struyf, E., Sonesson, M., Rundgren, M., Skog, G., Rosen, P., and Hammarlund, D.: Wetland development, permafrost history and nutrient cycling inferred from late Holocene peat and lake sediment records in subarctic Sweden, J. Paleolimn., 44, 327-342,doi: 10.1007/s10933-010-9406-8, 2010.

Lafleur, P. M., Roulet, N. T., Bubier, J. L., Frolking, S., and Moore, T. R.: Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog, Glob. Biogeochem. Cycle, 17,doi: 10.1029/2002gb001983, 2003.

Lai, D. Y. F.: Methane Dynamics in Northern Peatlands: A Review, Pedosphere, 19, 409-4212009.

Lund, M., Christensen, T. R., Lindroth, A., and Schubert, P.: Effects of drought conditions on the carbon dioxide dynamics in a temperate peatland, Environmental Research Letters, 7,doi: Artn 045704
10.1088/1748-9326/7/4/045704, 2012.

Lund, M., Lindroth, A., Christensen, T. R., and Strom, L.: Annual CO2 balance of a temperate bog, Tellus Ser. B-Chem. Phys. Meteorol., 59, 804-811,doi: 10.1111/j.1600-0889.2007.00303.x, 2007.

Malmer, N., Johansson, T., Olsrud, M., and Christensen, T. R.: Vegetation, climatic changes and net carbon sequestration in a North-Scandinavian subarctic mire over 30 years, Global Change Biology, 11, 1895-1909,doi: 10.1111/j.1365-2486.2005.01042.x, 2005.

Miller, P. A. and Smith, B.: Modelling Tundra Vegetation Response to Recent Arctic Warming, Ambio, 41, 281-291,doi: 10.1007/s13280-012-0306-1, 2012.

Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693-712,doi: 10.1002/joc.1181, 2005.

Moore, T. R., Bubier, J. L., and Bledzki, L.: Litter decomposition in temperate peatland ecosystems: The effect of substrate and site, Ecosystems, 10, 949-963,doi: 10.1007/s10021-007-9064-5, 2007.

Moore, T. R., Bubier, J. L., Frolking, S. E., Lafleur, P. M., and Roulet, N. T.: Plant biomass and production and CO2 exchange in an ombrotrophic bog, Journal of Ecology, 90, 25-36,doi: 10.1046/j.0022-0477.2001.00633.x, 2002.

Morris, P. J., Baird, A. J., and Belyea, L. R.: The DigiBog peatland development model 2: ecohydrological simulations in 2D, Ecohydrology, 5, 256-268,doi: 10.1002/eco.229, 2012.

Morris, P. J., Baird, A. J., Young, D. M., and Swindles, G. T.: Untangling climate signals from autogenic changes in long-term peatland development, Geophysical Research Letters, 42, 10788-10797,doi: 10.1002/2015gl066824, 2015.

Morris, P. J., Belyea, L. R., and Baird, A. J.: Ecohydrological feedbacks in peatland development: a theoretical modelling study, Journal of Ecology, 99, 1190-1201,doi: 10.1111/j.1365-2745.2011.01842.x, 2011.

Novak, M., Brizova, E., Adamova, M., Erbanova, L., and Bottrell, S. H.: Accumulation of organic carbon over the past 150 years in five freshwater peatlands in western and central Europe, Science of the Total Environment, 390, 425-436,doi: 10.1016/j.scitotenv.2007.10.011, 2008.

Nungesser, M. K.: Modelling microtopography in boreal peatlands: hummocks and hollows, Ecological Modelling, 165, 175-207,doi: 10.1016/s0304-3800(03)00067-x, 2003.

Pouliot, R., Rochefort, L., Karofeld, E., and Mercier, C.: Initiation of Sphagnum moss hummocks in bogs and the presence of vascular plants: Is there a link?, Acta Oecol.-Int. J. Ecol., 37, 346-354,doi: 10.1016/j.actao.2011.04.001, 2011.

Ryden, B. E., Fors, L., and Kostov, L.: Physical Properties of the Tundra Soil-Water System at Stordalen, Abisko, Ecological Bulletins, 1980. 27-541980.

Sagerfors, J., Lindroth, A., Grelle, A., Klemedtsson, L., Weslien, P., and Nilsson, M.: Annual CO2 exchange between a nutrient-poor, minerotrophic, boreal mire and the atmosphere, Journal of Geophysical Research-Biogeosciences, 113, 15,doi: 10.1029/2006jg000306, 2008.

Schuldt, R. J., Brovkin, V., Kleinen, T., and Winderlich, J.: Modelling Holocene carbon accumulation and methane emissions of boreal wetlands - an Earth system model approach, Biogeosciences, 10, 1659-1674,doi: 10.5194/bg-10-1659-2013, 2013.

Sitch, S., Huntingford, C., Gedney, N., Levy, P. E., Lomas, M., Piao, S. L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C. D., Prentice, I. C., and Woodward, F. I.: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs), Global Change Biology, 14, 2015-2039,doi: 10.1111/j.1365-2486.2008.01626.x, 2008.

Smith, B., Prentice, I. C., and Sykes, M. T.: Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space, Glob. Ecol. Biogeogr., 10, 621-637,doi: 10.1046/j.1466-822X.2001.t01-1-00256.x, 2001.

Stocker, B. D., Spahni, R., and Joos, F.: DYPTOP: a cost-efficient TOPMODEL implementation to simulate sub-grid spatio-temporal dynamics of global wetlands and peatlands, Geosci. Model Dev., 7, 3089-3110,doi: 10.5194/gmd-7-3089-2014, 2014.

Strandberg, G., Kjellstrom, E., Poska, A., Wagner, S., Gaillard, M. J., Trondman, A. K., Mauri, A., Davis, B. A. S., Kaplan, J. O., Birks, H. J. B., Bjune, A. E., Fyfe, R., Giesecke, T., Kalnina, L., Kangur, M., van der Knaap, W. O., Kokfelt, U., Kunes, P., Latalowa, M., Marquer, L., Mazier, F., Nielsen, A. B., Smith, B., Seppa, H., and Sugita, S.: Regional climate model simulations for Europe at 6 and 0.2 k BP: sensitivity to changes in anthropogenic deforestation, Climate of the Past, 10, 661-680,doi: 10.5194/cp-10-661-2014, 2014.

Sullivan, P. F., Arens, S. J. T., Chimner, R. A., and Welker, J. M.: Temperature and microtopography interact to control carbon cycling in a high arctic fen, Ecosystems, 11, 61-76,doi: 10.1007/s10021-007-9107-y, 2008.

Swindles, G. T., Amesbury, M. J., Turner, T. E., Carrivick, J. L., Woulds, C., Raby, C., Mullan, D., Roland, T. P., Galloway, J. M., Parry, L., Kokfelt, U., Garneau, M., Charman, D. J., and Holden, J.: Evaluating the use of testate amoebae for palaeohydrological reconstruction in permafrost peatlands, Palaeogeography Palaeoclimatology Palaeoecology, 424, 111-122,doi: 10.1016/j.palaeo.2015.02.004, 2015.

Tang, J., Miller, P. A., Crill, P. M., Olin, S., and Pilesjo, P.: Investigating the influence of two different flow routing algorithms on soil-water-vegetation interactions using the dynamic ecosystem model LPJ-GUESS, Ecohydrology, 8, 570-583,doi: 10.1002/eco.1526, 2015.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Glob. Biogeochem. Cycle, 23,doi: Artn Gb2023
10.1029/2008gb003327, 2009.

Tomlinson, R. W.: Soil carbon stocks and changes in the Republic of Ireland, Journal of Environmental Management, 76, 77-93,doi: 10.1016/j.jenvman.2005.02.001, 2005.

Wania, R., Ross, I., and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 1. Evaluation and sensitivity of physical land surface processes, Glob. Biogeochem. Cycle, 23,doi: Gb3014
10.1029/2008gb003412, 2009a.

Wania, R., Ross, I., and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 2. Evaluation and sensitivity of vegetation and carbon cycle processes, Glob. Biogeochem. Cycle, 23,doi: Gb3015
10.1029/2008gb003413, 2009b.

Weltzin, J. F., Harth, C., Bridgham, S. D., Pastor, J., and Vonderharr, M.: Production and microtopography of bog bryophytes: response to warming and water-table manipulations, Oecologia, 128, 557-565,doi: 10.1007/s004420100691, 2001.

Whiting, G. J. and Chanton, J. P.: Primary production control of methane emission from wetlands, Nature, 364, 794-795,doi: 10.1038/364794a0, 1993.

Wolf, A., Callaghan, T. V., and Larson, K.: Future changes in vegetation and ecosystem function of the Barents Region, Clim. Change, 87, 51-73,doi: 10.1007/s10584-007-9342-4, 2008.

Wu, Y. Q., Verseghy, D. L., and Melton, J. R.: Integrating peatlands into the coupled Canadian Land Surface Scheme (CLASS) v3.6 and the Canadian Terrestrial Ecosystem Model (CTEM) v2.0, Geosci. Model Dev., 9, 2639-2663,doi: 10.5194/gmd-9-2639-2016, 2016.

Yang, Z., Sykes, M. T., Hanna, E., and Callaghan, T. V.: Linking Fine-Scale Sub-Arctic Vegetation Distribution in Complex Topography with Surface-Air-Temperature Modelled at 50-m Resolution, Ambio, 41, 292-302,doi: 10.1007/s13280-012-0307-0, 2012.

Yu, Z. C., Loisel, J., Brosseau, D. P., Beilman, D. W., and Hunt, S. J.: Global peatland dynamics since the Last Glacial Maximum, Geophysical Research Letters, 37, 5,doi: 10.1029/2010gl043584, 2010.

Zhang, W., Jansson, C., Miller, P. A., Smith, B., and Samuelsson, P.: Biogeophysical feedbacks enhance the Arctic terrestrial carbon sink in regional Earth system dynamics, Biogeosciences, 11, 5503-5519,doi: 10.5194/bg-11-5503-2014, 2014.

Modelling Holocene peatland dynamics with an individual-based dynamic vegetation model

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Abstract. 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 ~~both~~ permafrost and non-permafrost peatlands, which are an important store of carbon particularly at high latitudes~~ and in parts of tropics~~. ~~However, current DGVMs lack functionality for the representation of peatlands an important store of carbon at high latitudes.~~ We demonstrate a new implementation of peatland dynamics in a customised "Arctic" version of the ~~dynamic vegetation model~~ LPJ-GUESS DGVM, simulating the long-term evolution of selected northern peatland ecosystems and assessing the effect of changing climate on peatland carbon balance. 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. The model was calibrated and tested for a sub-arctic mire in Stordalen, Sweden, and validated at a temperate bog site in Mer Bleue, Canada. A regional evaluation of simulated carbon fluxes, hydrology and vegetation dynamics encompassed additional locations spread across Scandinavia. Simulated peat accumulation was found to be generally consistent with published data and the model was able to capture reported long-term vegetation dynamics, water table position and carbon fluxes. A series of sensitivity experiments were carried out to investigate the vulnerability of high latitude peatlands to climate change. 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~~a~~ CO_2 fertilization effect, turning into a carbon source after mid-century because of higher decomposition rates in response to warming soils.

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1 Introduction

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 10,000 years (10 kyr) they have sequestered 550 ±100 PgC across an area of approximately 3.5 million km^2 (Gorham, 1991; Turunen et al., 2002; Yu, 2012). Peatlands are one of the major natural sources of methane, contributing significantly to the greenhouse effect (Whiting and Chanton, 1993; Lai, 2009; IPCC, 2013). Around 19% (3556 × 103 km^2) of the soil area of the northern peatlands coincides with low altitude permafrost (Tarnocai et al., 2009; Wania et al., 2009a). ~~In the past 5-10 thousand years they have sequestered approximately 200-550 Pg C across an area of approximately 3.5 million km^2 (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). The majority of northern peatland areas coincide with low altitude permafrost (Wania et al., 2009a).~~ Permafrost changes the peat accumulation process by altering plant productivity and decomposition, affecting the carbon sequestration rate (Robinson and Moore, 2000). Thawing of permafrost exposes the organic carbon stored in the frozen soil which then becomes available for decomposition by soil microbes (Zimov et al., 2006).

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; Stocker et al., 2014; Tang et al., 2015a). Model formulations of multiple peat layer accumulation and decay have been proposed and demonstrated at the site scale (Bauer et al., 2004; 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 ~~their~~ frameworks (Morris et al., 2012; Alexandrov et al., 2016; Wu et al., 2016) and been shown to perform reasonably for peatland sites. L~~l~~arge area ~~s~~ 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).~~Model formulations of peat accumulation and decay have been proposed and demonstrated 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.~~

Climate ~~is changing at a much faster rate, and the~~ warming is~~will be~~ amplified ~~most,~~ in northern latitudes, relative to the global mean trend, due to associated feedbacks (IPCC, 2013). ~~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).~~ Current climate models predict that the northern high latitudes, where most of the peatlands and permafrost areas are present, could experience warming of more than 5°C by 2100 (Hinzman et al., 2005; Christensen et al., 2007; IPCC, 2013)~~.~~. A warming~~The warm~~ climate may alleviate the constraints on biological activity imposed by very low temperatures, leading to higher productivity and decomposition rates. The resultant shift in the balance between plant production and decomposition will alter the carbon balance, potentially leading to enhanced carbon sequestration in some peatlands (Yu, 2012; Charman et al., 2013)~~(~~ while inducing a carbon (CO_2 and CH_4) source in others (Wieder, 2001; Ise et al., 2008; Fan et al., 2013). Permafrost peatlands may respond quite differently to non-permafrost peatlands in changing climate conditions. Increases in soil temperature may accelerate permafrost decay (Åkerman and Johansson, 2008) and thereby modify the moisture balance of the peat soil, which could in turn alter the above ground vegetation composition and carbon balance of the permafrost peatlands (Christensen et al., 2004; Johansson et al., 2006).

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We demonstrate a new implementation of peatland dynamics in the ~~dynamic vegetation model~~ LPJ-GUESS DGVM, aiming to emulate the long-term dynamics of northern peatland ecosystems and to assess the effect of changing climate on peatland carbon balance at the regional scale and across climatic gradients. To our knowledge, our new model implementation is unique in combining a dynamic representation of vegetation composition and function, suitable for application at global to regional scale, with an explicit representation of permafrost and peat accumulation dynamics. We build on previous work by implementing a dynamic multi-layer approach (Bauer et al., 2004; Frolking et al., 2010; Heinemeyer et al., 2010)~~()~~ to peat formation and composition with existing representations of soil freezing-thawing functionality, plant physiology and peatland vegetation dynamics (Wania et al., 2009a) in a customised "Arctic" version of LPJ-GUESS (Miller and Smith, 2012). 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. We evaluate the model at a range of observational study sites across the northern high latitudes, and perform a model sensitivity analysis to explore the potential fate of peatland carbon in response to variations in temperature, atmospheric CO_2 and precipitation change in line with 21st century projections from climate models.

2 Model Overview

2.1 Ecosystem modelling platform

We employed a customised Arctic version of the Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS; Smith et al., 2001; Miller and Smith, 2012) as the ecosystem modelling platform for our study. LPJ-GUESS is a process-based model that couples an individual-based vegetation dynamics scheme to biogeochemistry of terrestrial vegetation and soils (Smith et al., 2001). Vegetation structure and dynamics follow an individual- and patch-based representation in which plant population demography and community structure evolve as an emergent outcome of competition for light, space and ~~soil resources (water)~~soil water among simulated plant individuals, each belonging to one of a defined set of plant functional types (PFTs) with different functional and morphological characteristics (see below).

In this paper, we employ a customised Arctic implementation of LPJ-GUESS that incorporates differentiated representations of hydrological, biophysical and biogeochemical processes characteristic of upland and peatland ecosystems of the tundra and taiga biomes, as well as plant functional types (PFTs) specific to Arctic ecosystems (Fig. 1) (McGuire et al., 2012; Miller and Smith, 2012). Five PFTs characteristic of peatlands – mosses (M), graminoids (Gr), low summergreen and evergreen shrubs~~deciduous and evergreen low shrubs~~ (LSS and LSE) and high summergreen shrubs ~~deciduous high shrubs~~ (HSS) – are included in the present study. These PFTs have different parameterizations of physiological processes, for instance relating to photosynthesis, leaf thickness, carbon allocation, phenology, and rooting depth. Full parameters sets for these PFTs are given in Miller and Smith (2012).

New functionality was incorporated in LPJ-GUESS in this study in order to represent the dynamics of peat formation and aggradation based on vegetation litter inputs and decomposition processes. To this end, we adapted the dynamic multi-layer approach used in Bauer et al., 2004, Heinemeyer et al., 2010 and Frolking et al., 2010 generalised for regional application. The new implementation is detailed in sections 2.1.1-2.1.7 below.

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~~a~~ dynamic litter/peat layer of variable thickness corresponding to each simulation year (e.g. ~~composed of~~ 4739 + 100 layers by the end of the simulations, described in Section 2.4 below, for ~~in the case of~~ 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), ~~with further sublayers of thickness 0.1 m),~~ and finally a "padding" column of 48 m depth (with 10 sublayers) ~~(with thicker sublayers)~~ allowing the~~o~~ simulation of~~e~~ 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.

~~New functionality was incorporated in LPJ-GUESS in this study in order to represent the dynamics of peat formation and aggradation based on vegetation litter inputs and decomposition processes. To this end, we adapted the dynamic multi-layer approach used in Bauer et al., 2004, Heinemeyer et al., 2010 and Frolking et al., 2010 Frolking et al., 2010 and Hilbert et al., 2000 generalised for regional application. The new implementation is detailed in sections 2.1.1-2.1.7 below.~~

2.1.1 Litterfall

Peat accumulation is determined by the annual addition of new layers of litter at the top of the soil column. Litter is characterized as fresh, undecomposed plant material composed of dead plant debris such as wood, leaves and fine roots. ~~Different~~ PFTs accumulate carbon in the litter pool at different rates according to their productivity, mortality and leaf turnover properties. Litter is assumed to decompose at a rate dependent on the PFT and tissue type it originates from (Table 1). Graminoid litter is assumed to decompose faster than that of shrubs and mosses. Woody litter mass from shrubs decomposes relatively slowly because it is made up of hard cellulose and lignin ~~Based on the studies, woody litter mass from shrubs decomposes relatively slowly because it is made up of hard cellulose and lignin~~(Aerts et al., 1999; Moore et al., 2007). M~~Similarly, m~~oss litter~~also~~ decomposes ~~at much~~ slowest~~r rate~~ due to its recalcitrant properties (Clymo et al., 1991; Aerts et al., 1999; Moore et al., 2007). ~~(Aerts et al., 1999; Moore et al., 2007).~~ 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~~go~~ 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.

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2.1.2 Peat accumulation and decomposition

Peat consists of partially decomposed litter mass. Accumulation occurs when net primary productivity (NPP) is higher than the decomposition rate, leading to carbon accumulation. Two functionally-distinct layers, the acrotelm and catotelm, are found in most peatland sites. The acrotelm is the top layer in which water table fluctuates leading to both aerated and anoxic conditions. Due to uneven wetness, litter decomposes aerobically as well as anaerobically in the acrotelm (Clymo, 1991; Frolking et al., 2002). This layer also plays the critical role in determining plant composition. The catotelm exists below the permanent annual water table position (WTP) and remains waterlogged throughout the year, creating anoxic conditions, which in turn attenuate the decomposition rate and promote peat accumulation. The boundary between these two layers is marked by the transition from the living plant parts to the dead plant parts and annual WTP.

Our model implicitly divides the total peat column into two parts—acrotelm and catotelm—demarcated by annual WTP, as determined by the hydrology scheme described below. Every year, a new litter layer is deposited over previously accumulated peat layers. After several years due to high carbon mineralization rates in the acrotelm layer (or upper peat layers above the annual WTP), the litter mass losses its structural integrity and transforms into peat, eventually becoming integrated into the saturated rising catotelm mass. The rate of change of total peat mass is the total peat production minus total peat loss due to decomposition (Clymo, 1984):~~:~~

$$\frac{dM}{dt} = A - K\,M \qquad (1)$$

where M (kg C m^{-2}) is the total peat mass, A is the annual peat input (kg C m^{-2} yr^{-1}), and K is the decomposition rate (yr^{-1}).

Total peat depth is derived from the dynamic bulk density values calculated for individual peat layers. The decomposition process is simulated on annual ~~a daily~~ time step based on the decomposability of the constituent litter types in each layer and the soil physical and hydraulic properties of that layer. This difference in decomposability between litter types is represented by the initial decomposition rate (k_o – see Eq. 2 and Table 1) (Aerts et al., 1999; Frolking et al., 2001; Moore et al., 2007). ~~(Aerts et al., 1999; Frolking et al., 2001).~~ The initial decomposition rates are assumed to decline over time using a simplified first order reduction equation (Clymo et al., 1998; Frolking et al., 2001):

$$k_i = k_o \left(\frac{m_t}{m_o}\right) \qquad (2)$$

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where *i* refers to a litter component in a certain peat layer, k_o is the initial decomposition rate, m_o is the initial mass and m_t is the mass remaining after some point in time (t). Peat water content and soil thermal dynamics are simulated at different depths (see below) and have a multiplicative effect on the daily decomposition rate (K) of each litter component in each layer following Lloyd and Taylor (1994) and Ise et al. (2008):

$$K_i = k_i T_m W_m \tag{3}$$

where k_i is the decomposition rate of the layer i component (see Eq. 2) and T_m and W_m are the temperature and moisture multipliers, respectively. Following Ise et al. (2008), we assume that peat decomposition is highest at field capacity and lowest during very wet conditions. However, we allowed the peat to decompose in very dry conditions when the annual WTP drops below –40~~0~~ c~~m~~m (WTP takes negative (positive) values when the water table is below (above) the peat surface) and the volumetric water content (θ) goes below 0.01 in the peat layers (Eq. 4 and Table 2).

$$W_m = \begin{cases} 1\cancel{.0} - 0.975\left(\frac{\theta-\theta_{opt}}{1.0-\theta_{opt}}\right)^{\alpha} & ,\theta > \theta_{opt} \\ 1\cancel{.0} - \left(\frac{\theta_{opt}-\theta}{\theta_{opt}}\right)^{\alpha}, & \theta > 0.01 \text{ and } \theta \le \theta_{opt} \\ \beta, & -\theta \le 0.01 \text{ and WTP} < -40\cancel{0} \end{cases} \tag{4}$$

where θ_{opt} is the field capacity (0.75) and optimum volumetric water content when W_m becomes 1~~.0~~ and α is a parameter that affects the shape of the dependency of decay on θ, set to 5~~.0~~ and β (0.064) is a minimum decomposition rate during very dry conditions when WTP goes below -40 cm (see Fig. A1)..~~,~~ The temperature multiplier is exponentially related to the peat temperature (see Eq. 5 and Table 2) (Frolking et al., 2002). Peat is assumed not to decompose under frozen conditions when the fraction of ice content is greater than zero.

$$T_m = \begin{cases} 0, & T_i < T_{min} \text{ and } I > 0 \\ \left(\frac{T_i - T_{min}}{|T_{min}|}\right)^{0.5}, & T_{min} < T_i < 0°C \\ {Q_{10}}^{T_i/10}, & T_i > 0°C \end{cases} \tag{5}$$

where T_i is the peat temperature in peat layer (i), T_{min} is the lowest temperature (-4°C) below which heterotrophic decomposition ceases, I is the ice content in each peat layer (i) and Q_{10} is the proportional increase in decomposition rate for a 10°C increase in temperature; set to 2 (Fig. A1)..~~,~~

Compaction and the loss of peat mass due to decomposition modify the structural integrity of peat layers (Clymo, 1984) potentially inducing changes in bulk density with depth. Some previous studies have found that the lower bulk density of newly accumulated peat layers increases as peat decomposes and becomes compressed due to overlying peat mass (Clymo, 1991) although bulk density often shows no net increase with depth in the catotelm (Tomlinson, 2005; Baird et al., 2016). Following Frolking et al. (2010), we assume that bulk density is a non-linear function of total mass remaining ($\mu = M_t/M_o$)

(see Eq. 6 and Table 2).

$$\rho(\mu_i) = \rho_{min} + \frac{\Delta\rho}{1+\exp(-(40(1-\mu_i)-34))} \tag{6}$$

where ρ_{min} is the minimum bulk density (40 kg m^{-3}), $\Delta\rho$ is the difference between this minimum (80 kg m^{-3}), and a maximum bulk density (120 kg m^{-3}), μ_i is the total mass remaining in peat layer *i*, M_o is the initial peat layer mass and M_t is the peat layer mass remaining after some point in time.

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2.1.3 Permafrost/Freezing-thawing cycle

Freezing and thawing of peat and mineral soil layers is an important feature in permafrost peatlands, determining plant productivity, decomposition and hydrological dynamics (Christensen et al., 2004; Johansson et al., 2006; Wania et al., 2009b). To simulate permafrost, peat layer decomposition and cycles of freezing and thawing, the soil temperature at different depths must be calculated correctly. In the Arctic version of LPJ-GUESS as described by Miller and Smith (2012), mineral soil layers (i.e. below the peat layers added in this study) are subdivided into 20 sublayers of 10 cm thickness to calculate soil temperature at different depths. 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. This resulted, for example, in seven aggegate sublayers for the Stordalen simulations described in Section 2.4. The result is a soil column with a dynamic number of peat sublayers, 20 mineral soil layers and multiple "padding" layers to a depth of 48 m. A single layer of snow is included, as in existing versions of the model. Following Wania et al. (2009a), the soil temperature profile in each layer is calculated daily by numerically solving the heat diffusion equation. Soil temperature is driven by surface air temperature which acts as the upper boundary condition. Soil temperature in each annual peat layer is then updated daily and equal to the numerical sublayer to which it belongs. The amount of water and ice present in the sublayers together with their physical composition (mineral, organic or peat fractions) determine the thermal properties (soil thermal conductivities and heat capacities) of each sublayer. Freezing and thawing of soil water (see below) is modelled using the approach in following Wania et al. (2009a). The fraction of air and water is updated daily based on the soil temperature in each sublayer while the fraction of peat and organic matter is influenced by the degree of peat layer decomposability. In the sublayers, the fraction of mineral content is based on Hillel (1998). A full description of the soil temperature and permafrost scheme in the Arctic version of LPJ-GUESS is available in Miller and Smith (2012) and references therein.

2.1.4 Hydrology

Precipitation is the major source of water input in the majority of peatlands. In our model, precipitation is treated as rain or snow depending upon the daily surface air temperature. When temperature falls below the freezing point (0°C assumed), water is stored as a snow above the peat layers. Snow melts when the air temperature rises above the freezing point and is also influenced by the amount of precipitation on that day (Choudhury et al., 1998). We assume that the peatland can hold water up to +20 cm above the peat surface. Water is removed from the peat layers through evapotranspiration, drainage, surface and base runoff. A traditional water bucket scheme is adopted to simulate peatland hydrology (Gerten et al., 2004):~~:~~

$$W = P - ET - R - DR \pm LF \tag{7}$$

where W is the total water input, P is the precipitation, ET is the evapotranspiration rate, R ~~stands~~ is ~~for~~ the ~~surface~~ 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. We add 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 remain unsaturated. Water and ice content are calculated. If a 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 the respective layer. WTP is updated daily based on existing WTP, W, the total drainage porosity and permeability of the peat layers. WTP is expressed in c~~m~~m in this paper, with a value of 0 indicating a water table at the peat surface.

Evaporation can only occur when the snowpack is thinner than 1 cm and is calculated following the approach of Gerten et al. (2004), as in the standard version of LPJ-GUESS:

$$ET = \cancel{=} 1.32\,.\,E\,.\,W_c^2\,.\,F \tag{8}$$

where E is the climate-dependent equilibrium evapotranspiration (c~~m~~m), W_c is the water content on the top 10 cm of the peat soil and F is the fraction of modelled area subject to evaporation, i.e. not covered by vegetation (Gerten et al., 2004).

Runoff is an exponential function of WTP (Wania et al., 2009a):

$$R = BR + \begin{cases} e^{0.01}\ \mathrm{WTP}, & \mathrm{WTP} > \mathrm{TH} \\ 0, & \mathrm{WTP} \leq \mathrm{TH} \end{cases} \tag{9}$$

where TH is the WTP threshold, set to -30 cm (Table 2) and BR is the base runoff proportional to the total peat depth (D) ~~and the base runoff~~ is estimated as:

$$BR = u\,D \tag{10}$$

where u is a parameter (see Table 2) which determines rate of increase in the base runoff with increase in the peat depth (D), set to 0.45 (Frolking et al., 2010). Loss of the water through drainage/percolation depends on the permeability of peat layers and the saturation limit of the mineral soil underneath. Percolation ceases if the mineral layers are saturated with water, incoming rainfall or snowmelt leading instead to an increase in WTP. Peat layer density is assumed to increase due to compression~~ed~~ when highly decomposed by anoxic decomposition (Frolking et al., 2010). ~~We make the assumption that peat layers become highly compressed under accumulating peat mass and humified by anoxic decomposition (Clymo, 1991).~~ This results in declining permeability, affecting the flow of water from the peat layers to the mineral soil. The permeability of each peat layer (i) is calculated as a function of peat layer bulk density (Eq. 11) (Frolking et al., 2010). The amount of water draining from the peat column to the mineral soil is calculated by integrating permeability across all the peat layers (i).

$$\kappa_i = \cancel{400}10\ e^{-0.058\cancel{75}\rho_i} \quad (11)$$

where κ_i is the permeability (0-1) and ρ_i is the bulk density of peat layer (i). Change of porosity (Φ) due to compaction is captured by a relationship to bulk density:

$$\Phi_i = 1 - \frac{\rho_i}{\rho_o} \quad (12)$$

where ρ_o is the particle bulk density of the organic matter (800 kg m^{-3} ~~(s~~; see Table 2). Finally, water infiltrating from the peat to the mineral soil layers is treated as the input to the standard LPJ-GUESS hydrology scheme described in Smith et al. (2001) and Gerten et al. (2004).

2.1.5 Root distribution and water uptake

In the customized Arctic version of LPJ-GUESS, the mineral soil column is 2 m deep and partitioned into two layers, an upper mineral soil layer of 0.5 m and lower mineral soil layer of 1.5 m. The fraction of roots in these two layers is prescribed for different PFTs (Table 1) and used to calculate daily water uptake. Dynamic peat layers on top of the mineral soil layers necessitated a modification to the way plants access water from both the peat layers and the underlying mineral soil. In the beginning of the peat accumulation process, plant roots are present both in peat and upper and lower mineral soil layers but their mineral soil root distribution declines linearly as peat grows (see Fig. 2) and the corresponding mineral layer reduction is used to access water from the peat layers. Mosses are assumed only to take up water from the top 50 cm of the mineral soil ~~and shallow peat surface~~ in the beginning but once the peat depth exceeds 50 cm they only take water from the peat layers (top 50 cm of the peat layer). Other PFTs can continue to take up water both from the mineral and peat soils until peat depth reaches 2 m, and from only from the peat soil thereafter.

2.1.6 Establishment and mortality

PFTs are able to establish within prescribed bioclimatic limits reflective of their distributional range (Miller and Smith, 2012) but are also limited by the position of the annual-average WTP (Table 1).~~.~~ Shrubs are vulnerable to waterlogged and anoxic conditions (Malmer et al., 2005) and establish only when annual WTP is deeper than 2~~2~~5 cm relative to ~~below~~ the surface. Mosses and graminoids, by contrast, thrive in wet conditions and establish under WTP +5 to -50 cm (mosses) and above -10 cm (graminoids). The establishment function is implemented once per annual time step, based on mean WTP for the previous 12 months. LPJ-GUESS includes a prognostic wildfire module (Thonicke et al., 2001; Smith et al., 2014). ~~(Smith et al., 2014; Thonicke et al., 2001).~~ In high-latitude peatlands, the risk of natural fire events increases in prolonged dry and warm conditions and this is simulated by the model. Fires lead to vegetation mortality but are assumed not to lead to combustion of peat carbon in our implementation.

2.1.7 Microtopographical structure

Many studies have highlighted the importance of surface micro-formations in peatland dynamics (Weltzin et al., 2001; Nungesser, 2003; Belyea and Malmer, 2004; Belyea and Baird, 2006; Sullivan et al., 2008; Pouliot et al., 2011). ~~(Belyea and Baird, 2006; Belyea and Malmer, 2004; Nungesser, 2003; Pouliot et al., 2011; Sullivan et al., 2008; Weltzin et al., 2001).~~ The patterned surface creates a distinctive environment with contrasting plant cover, nutrient status, productivity and decomposition rates in adjacent microsites. Such spatial heterogeneity is typically ignored in ~~most~~ peatland modelling studies, but can be critically important for peatland development and carbon balance. In our approach, multiple vegetation patches are simulated to account for such spatial heterogeneity. The model is initialised with a random surface represented by uneven heights of individual patches (10 in the simulations performed here). Water is redistributed from the higher elevated sites to low depressions through lateral flow (LF) (see Eq. 7). We equalize the WTP of individual patches ~~according~~ to match the mean WTP of the landscape on a daily time step. Patches lose water if their WTP is above the mean WTP of the landscape while the lower patches receive water (see Eqs. 13-15). This in turn affects the PFT composition, productivity and decomposition rate in each patch, and peat accumulation over time. We calculate the landscape WTP and add and remove the amount of water from each patch required to match the landscape WTP.

$$MWTP = \sum PWTP_i / n \qquad (13)$$

where MWTP is the mean WTP across all the patches, $PWTP_i$ 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:

$$DWTP_i = PWTP_i - MWTP \qquad (14)$$

$$LF_i = DWTP_i \cdot \Phi_a \qquad (15)$$

where $DWTP_i$ is the difference in the patch (i) and MWTP and LF_i 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 (Φ_a). When the WTP is above the surface then Φ_a is not included in the calculation. This exchange of water between patches is implemented after the daily water balance calculation (Eq 7). ~~The higher patches loses water if the WTP is above the mean WTP of the landscape while the lower patches receive water. This in turn affects the PFT composition, productivity and decomposition rate in each patch, and peat accumulation over time.~~

2.2 Study area

2.2.1 Stordalen

The model was developed based on observations and measurements at Stordalen, a subarctic mire situated 9.5 km east of the Abisko Research Station in northern Sweden (68.36° N, 19.05° E, elevation 360 m a.s.l.) (Fig. 3). Stordalen is one of the most studied mixed mire sites in the world and it has been part of the International Biological Program since 1970 (Rosswall et al., 1975; Sonesson, 1980). It is characterized by four major habitat types: (1) elevated, nutrient poor areas with hummocks and shallow depressions (ombrotrophic), (2) relatively nutrient rich wet depressions (minerotrophic), (3) pools and (4) small streams exchanging water from the catchment (Rosswall et al., 1975). Our simulations represent a mixed landscape of (1) and (2). The mire is mainly covered with mosses such as *Sphagnum fuscum* and *S. russowii*. Shrubs such as *Betula nana*, *Andromeda polifolia* and *Vaccinium uliginosum* are present in dry hummock areas where the WTP remains relatively low, while hollows are mainly dominated by tall productive graminoids, e.g. *Carex rotundata* and *Eriophorum vaginatum* (Malmer et al., 2005). The Stordalen catchment is in the discontinuous permafrost zone. The elevated areas are mainly underlain with permafrost and wet depressions are largely permafrost free and waterlogged. Permafrost underlying elevated areas has~~ve~~ 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). ~~(Christensen et al., 2004; Johansson et al., 2006; Malmer et al., 2005).~~ The annual average temperature of the Stordalen was -0.7°C for the period 1913-2003 (Christensen et al., 2004) and 0.49°C for the period 2002-2011 (Callaghan et al., 2013). The warmest month is July and coldest February. The mean annual average precipitation is low but increased from 30.4 c~~m~~m (1961-1990) to 36.2 c~~m~~m (1997-2007) (Johansson et al., 2013). Overviews of the ecology and biogeochemistry of Stordalen are provided by Sonesson (1980), Malmer et al. (2005) and Johansson et al. (2006). Ecosystem respiration in Stordalen is lower than commonly observed in other northern peatlands due to low mean temperatures, a short frost-free season and the presence of discontinuous permafrost that keeps the thawed soil cooler and restricts the decomposition rate (Lindroth et al., 2007). 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~~ of the mire as a result of terrestrialisation~~.

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2.2.2 Mer Bleue

To evaluate the generality of the model for regional ~~(e.g. pan Arctic)~~ applications, we ~~evaluatedvalidated~~compared its p~~erformance~~redictions to~~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). The peat accumulation in this area initiated ca. 8400 cal. B.P and the mean depth is around 4-5 m. The northwest arm of the bog is dome shaped with peat depths reaching 5-6 m near the central areas (Frolking et al., 2010; Roulet et al., 2007). 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~~Ledum groenlandicum~~, Kalmia angustifolia)* and deciduous shrubs (*Vaccinium myrtilloides*). A sparse cover of sedges (*Eriophorum vaginatum*) with some small trees (*Picea mariana, Larix laricina, Betula populifolia*) is also present in the peatland (Bubier et al., 2006; Moore et al., 2002). The climate of the area is cool continental with the annual average temperature being 6.0±0.8°C for the period 1970 to 2000. The warmest month is July (20.9±1.1°C) and coldest January (-10.8±2.9°C). The average monthly temperature remains above 0°C from the April until November and above 10°C between May and September. The mean annual average precipitation is 91~~0~~ c~~m~~m of which 23.5 c~~m~~m falls as a snow from December to March. The total precipitation is spread evenly across the year with a maximum of 9~~0~~ c~~m~~m in July and a minimum of 5.8 c~~m~~m in February.

2.2.3 Additional evaluation sites

To evaluate the performance of the model across high-latitude climatic gradients, simulations were performed at 8 locations across Scandinavia for which observations of peat depth and/or other variables of relevance to our study (ecosystem C fluxes, WTP, vegetation composition and cover) were available (Table 4). These sites represent different types of peatlands with distinct initialization periods (from relatively new to old sites) and climate zones (from cold temperate to subarctic sites) (Fig. 3).

2.3 Model forcing data

The model requires daily climate fields of temperature, cloudiness and precipitation as input. Holocene climate forcing series for Stordalen and Mer Bleue were constructed by the delta-change method, i.e. applying relative anomalies derived from the gridcell nearest to the location of the site from millennium time-slice experiments using the UK Hadley Centre's Unified Model (UM) (Miller et al., 2008), to the average observed monthly climate of the sites. Daily values were obtained by interpolating between monthly values for Stordalen from the year 5 kyr~~000~~ cal. BP and for Mer Bleue from the year 10 kyr~~000~~ cal. BP until the year 2000. For Stordalen we used the dataset of Yang et al. (2012) from the period 1913-1942, and for Mer Bleue we used average monthly data from the CRU TS 3.0 global gridded climate data set (Mitchell and Jones, 2005) from the period 1901 to 1930. We then linearly interpolated the values between the millennium time slices. This method conserves the interannual variability for temperature and precipitation throughout the simulation. The version of the UM used in this study was HadSM3, an atmospheric general circulation model (AGCM) coupled to a simple mixed layer ocean and sea ice model with 2.5 × 3.75° spatial resolution (Pope et al., 2000). The high spatial resolution (50 m), modern observed climate dataset was developed by Yang et al. (2012) for the Stordalen site. In this dataset, the observations from the nearest weather stations and local observations were included to take into account the effects of the Torneträsk lake close to the Stordalen catchment. The monthly precipitation data (1913-2000) for Stordalen at 50 m resolution were downscaled from 10 min resolution using CRU TS 1.2 data (Mitchell and Jones, 2005), a technique quite common for cold regions (Hanna et al., 2005). The precipitation data was also corrected by including the influences of topography and also by using historical measurements of precipitation from the Abisko research station record. Finally, monthly values of Holocene temperature were interpolated to daily values, monthly precipitation totals were distributed randomly among the number (minimum 10) of rainy days per month from the climate dataset and the monthly CRU values of cloudiness for the first 30 years from the year 1901-1930 were repeated for the entire simulation period. We added random variability to the daily climate values by drawing random values from a normal distribution with monthly mean (μ) and standard deviation (σ) of the monthly observed climate were used for Stordalen from the period of 1913-1942 and for Mer Bleue, 30 years of monthly CRU values from the period of 1901-1930 were used~~tilized~~. For the additional evaluation sites, we used the randomly generated daily climate CRU values of temperature and precipitation from the period 1901-1930. Past, annual atmospheric CO_2 concentration values from 5000 cal. BP for Stordalen and 10000 cal. BP for Mer Bleue to the year 2000 were obtained by linear interpolation between the values used as a boundary conditions in the UM time-slice simulations (Miller et al., 2008).

The CO_2 concentration values used to force the UM simulations were linearly interpolated to an annually varying value between prescribed averages for each millennium. From 1901 to 2000 observed annual CO_2 from atmospheric or ice core measurements were used (McGuire et al., 2012).

2.4 Simulation Protocol

2.4.1 Holocene hindcast experiments

The model was first initialised for 500 years from “bare ground” using the first 30 years of Holocene climate data to attain an approximate equilibrium of vegetation and carbon pools with respect to mid-Holocene climate. The mineral and peat layers were forced to remain saturated for the entire initialization period. The peat decomposition, soil temperature and water balance calculations were not started until the peat column became sufficiently thick (0.5 m). This initialisation strategy was essential in order to avoid sudden collapse of the peat in very dry conditions. After initialization, the model was forced with continuous Holocene climate from the year 4700 cal. BP until the year 1912, after which the observed climate of the

Stordalen site was used for the transient run until the year 2000. This experiment is referred to as the standard model experiment (STD). In the case of Mer Bleue, a similar procedure was adopted, but here the model was forced with continuous climate from the year 8400 cal. BP until the year 1900 and then the CRU climate was used for the transient run until the year 2000. Model parameters were identical in both cases, apart from those relating to local hydrology (u, TH – Eqs. 9 and 10) - see Table 2. This is to adjust the simulations with the local WTP. We refer to this experiment as the validation model experiment (VLD).

2.4.2 Hindcast experiment – regional climate gradient

The model was run at the eight additional evaluation sites spread across Scandinavia (Table 4; s2.2.3), comparing simulated peat accumulation to peat depth reported in the literature. Three sites were selected for additional evaluation~~;~~ of carbon fluxes, WTP and dominant vegetation cover (Fig. 3 and Table 4 and 5). These simulations used a similar set up as in STD experiment with respect to bulk density and local hydrology.

Accurate prediction of total carbon accumulation across northern and high latitude peatlands is dependent on the right inception period, initial bulk density values and the local hydrology. The model was run within the most probable period of peat inception mentioned in the literature (Table 4).

2.4.3 Climate change experiment

To investigate the sensitivity of vegetation distribution, peat formation and peatland carbon balance to climate change, future experiments using RCP2.6 and RCP8.5 (Moss et al., 2010) 21st century climate change projections were performed, extending the STD experiment, which ends in 2000, until 2100. Climate output from the Coupled Model Intercomparison Project Phase 5 (CMIP5) runs with the MRI-CGCM3 general circulation model (GCM) was used to provide future climate forcing (Yukimoto et al., 2012). Climate sensitivity of MRI-CGCM3 is 2.60 K which is rather low compared to other models in CMIP5 (Andrews et al., 2012). Atmospheric CO2 concentrations for the RCP2.6 and RCP8.5 emissions scenarios were obtained from the website of the International Institute for Applied Systems Analysis (IIASA)- http://tntcat.iiasa.ac.at/RcpDb/. Simulations were performed for the Stordalen site. Responses of the model to single factor and combined future changes in temperature, precipitation and atmospheric CO_2 were examined in separate simulations (Table 3). Model output variables examined include cumulative peat age profile, total peat accumulation, net ecosystem exchange (NEE), annual and monthly WTP, active layer depth (ALD) ~~annual WTP, active layer depth (ALD)~~ and measures of vegetation PFT composition and productivity.

3 Results

3.1 Hindcast experiment

3.1.1 Stordalen

In the standard (STD) experiment, a total of 94.~~9~~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 2.11 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 trajectory of peat accumulation since the mid-Holocene inception is also similar to the reconstruction based on radioisotope dating of the peat core sequence in combination with Bayesian modelling (Kokfelt et al., 2010) (Fig 4). Total NPP ranged from 0.06-0.18 kg C m^{-2} yr^{-1} during the simulation while the soil decay losses were between 0.05 and 0.15 kg C m^{-2} yr^{-1}. Hence, the carbon uptake by the Stordalen mire ranged between -0.03 and 0.10 kg C m^{-2} yr^{-1} (Figs. 5a, 5c and A2)~~4)~~. The long-term mean accumulation rate of the mire was 0.04~~44~~ c~~m~~m yr^{-1} or 20 g C m^{-2} yr^{-1}. Mean annual WTP drew down to -10 cm in the beginning and fluctuated between -10 to -25 cm for the entire simulation period, but decreased to a value below -25 cm in the last 100 years due to comparatively higher temperatures during this period (Fig. 5e). 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). Moss-dominated areas accumulated more carbon as they become highly recalcitrant due to saturated conditions and low initial decomposition rate (see Table 1). At around 4300 cal. BP, shrubs started to establish because of a lower annual WTP as peat depth increased (Figs. 5e, 6a and A3)~~4)~~. When the peat was shallow, plant roots were present in both the mineral and peat layers. Since the majority of lower peat and mineral layers were frozen, the water required for the plant growth was limited, which then limited the productivity of shrubs and graminoids. However, since the upper peat layers were not completely frozen the moss productivity was not limited to the same extent as they could take up the water from upper 50 cm of the peat surface (Figs. 6a and 7a). The total ice fraction was between 40 and 60% for the majority of the simulation period indicating that the peat soil was partially frozen from the beginning (Fig. A4~~1~~). The fraction of ice present in the peat soil is influenced by mean annual air temperature (MAAT) and peat thickness (section 2.1.3). Increasing MAAT can lead to a reduction in the fraction of ice present in the peatland if the peat is sufficiently shallow. However, in thicker peat profiles the influence of temperature was ~~s~~lower due to the thermal properties of the thicker peat layers. From Figure 7a, it is clear that at the end of the simulation period the lower layer (see X in Fig. 7a) was almost completely frozen but upper and middle layers were partially frozen (see Z in Fig. 7a) leading to a mean annual active layer depth (MAAD) of 0.64 m (Fig. 7c). When the peat layers had decomposed sufficiently and lost more than 70% of their original mass (M_o), 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. ~~When the peat layers had decomposed sufficiently and lost more than 70% of their original mass (M_o), their bulk density increased markedly. 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 and~~

~~became highly decomposed after 4700 years, with the deepest layers often achieving bulk densities lower than 50 kg m^{-3}.~~ The pore space and permeability are linked to the compaction of peat layers. Therefore, when the peat bulk density increased, pore space declined from 0.95 to 0.93~~7~~ reducing the total permeability of peat layers that in turn reduced the amount of percolated water from the peat layers to the mineral soil.

3.1.2 Mer Bleue

In the VLD experiment, a total of 227~~1~~.9~~2~~ kg C m^{-2} (192.6-249.1 kg C m^{-2}) peat was accumulated over the simulation period, resulting in a peat profile of around 4.~~05~~ 2 m (3.6-4.6 m) (Fig. 4), which may be compared to the observed peat depth of 5 m reported by Frolking et al. (2010). The trajectory of peat accumulation is similar to the reconstruction based on radiocarbon dates for core MB930 by Frolking et al. (2010) for the first 6 kyr ~~whereafter~~ after which it diverges (Fig 4). The likely explanation for this late-Holocene divergence is discussed in section 4.1.1. Total NPP ranged from 0.1-0.5 kg C m^{-2} yr^{-1} in the course of the simulation while the soil carbon fluxes ranged between 0.12 and 0.25 kg C m^{-2} yr^{-1}. Therefore, the simulated carbon sequestration rate was in the range -0.2 to 0.3 kg C m^{-2} yr^{-1} (Figs. 5b, 5d and A3~~4~~). NPP increased during the simulation period reaching 0.5 kg C m^{-2} by the end of the simulation. Though both shrubs and mosses were the dominant PFTs from the beginning of the simulation, mosses were replaced by graminoids during ~~the~~ certain phases of peatland history and in the last 1000 years of the simulation (Fig. 6c). The mean accumulation rate was 0.05~~48~~ ~~cm~~m yr^{-1} or 27~~6~~.1~~3~~ g C m^{-2} yr^{-1}. After the initialization period, annual WTP dropped to -50 cm and later stabilised between -30 to -60 cm (Fig. 5f). The initial average bulk density of the peat profile was around 40 kg C m^{-3}, increasing to 93.4~~8~~ kg C m^{-3} as peat grew older while the pore space declined from 0.95 to 0.89~~8~~.

3.2 Hindcast experiment – regional climate gradient

The majority of modelled peat depth values were in good agreement with published data (see Fig. 10~~8~~ a, b and Table 4). At certain locations, notably Kontolanrahka (60.78° N, 22.78° E), Fajemyr (56.27° N, 13.55° E) and Lilla Backsjömyren (62.41°N, 14.32°E) modelled peat depth was substantially different from observations reported in the literature (see Table 4 and Fig. 10~~8~~). This could be because of the unavailability of site-specific climate forcing data (simulations were forced by interpolated station data from the CRU global gridded dataset), an incorrect initial bulk density profile or failure of the model to capture the local hydrological conditions. Fajemyr is a temperate tree bog and we have not considered litter coming from trees (T) and high evergreen shrubs (HSE) in this study, providing an additional potential reason for the underestimation of simulated peat depth at this site. However, the modelled dominant vegetation cover, WTP and long-term apparent rate of carbon accumulation (LARCA)[1] were within the published ranges for all three sites with some discrepancies in short-term carbon fluxes (Table 5). Modelled dominant vegetation cover is similar to the observed cover except in Fajemyr where tree was also one of the dominant PFTs. Modelled LARCA values were also similar to observed values for the two sites (Fajemyr and Siikaneva) while no observed LARCA value was reported for Degerö Stormyr. Slightly wetter conditions were simulated than observed at Degerö and Siikaneva. NEE outputs for the three sites are comparable to the range of observed NEE values although with some differences (Fig. 11 and Table 5).~~Modelled NEE was totally different from the observed fluxes for all the three sites.~~

3.3 Climate change experiments

In the future scenario experiments, the surface air temperature increased by approximately 4.8°C and 1.5°C in the T8.5 and T2.6 experiments by 2100, respectively, relative to the year 2000. The significantly higher temperature increase in the T8.5 experiment leads to complete disappearance of permafrost from the peat soil (Fig. 7c,d). Higher soil temperatures are associated with higher decomposition rates (Eq. 5) but since the MAAT is near to the freezing point (-0.7°C) at Stordalen a slight increase in temperature in the first 50 years leads only to a marginal increase in decomposition. However, melting of ice in the peat and mineral soils in combination with a milder climate and longer growing season lead to higher plant productivity (Fig. 6b and 7b). Therefore, the increase in decomposition is compensated by higher plant productivity leading to an initial increase in the peat depth in the both T8.5 and T2.6 experiments (Fig. 12~~9~~a and b). However, after 2050 decomposition dominates as temperature further increases leading to loss of a substantial amount of carbon mass. Enhancement of plant photosynthesis due to CO_2 fertilization leads to increasing peat accumulation in both C8.5 and C2.6 experiments. Precipitation increases result in only a slight increase in peat depth in both the experiments (P8.5 and P2.6) because when the system is already saturated, any additional input of water will be removed at faster rates since evaporation and surface runoff are positively correlated to WTP (see Eqs. 8 and 9, respectively). The combined effects of all drivers in FTPC8.5 and FTPC2.6 result in higher peat accumulation initially (see Fig. 12~~9~~a and b), with reductions after 2050 as carbon mineralization rate increases as a result of higher temperature. The increase in carbon mineralization is also associated with thawing of permafrost. Before 2050 the fraction of ice is higher, restricting the decomposition rate. It is also evident from Fig. A2 that the vegetation and soil carbon fluxes are higher in both the experiments after 2050. In both the experiments (FTPC8.5 and FTPC2.6), there is a loss of carbon after 2050 which stabilizes by the end of the century due to increased NPP (Fig. 12~~9~~).

4 Discussion

[1] LARCA is calculated by dividing total cumulative carbon (peat thickness) by the corresponding time interval (basal age)

4.1 Model performance

4.1.1 Peat accumulation

Peat formation may be induced by a combination of several factors, among which climate, underlying topography, and local hydrological conditions are the important determinants (Clymo, 1992; Yu et al., 2009). In Stordalen, peat initiation started due to terrestrialisation of an open water area around ca. 4700 cal. BP in the northern part of the mire (Kokfelt et al., 2010) while in Mer Bleue, the peatland formed ca. 8400 cal. BP (Frolking et al., 2010). 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 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). The underestimation might be because the simulated annual productivity was slightly low, leading to relatively lower peat depth than observed. This discrepancy may also be traceable to the uncertainty in the climate model-generated palaeoclimate forcing of the peatland model. Studies of the influence of GCM-generated climate uncertainty (i.e. variations in climate output fields among GCMs) on carbon cycle model prediction, underline the high prediction error that can arise, for example in present-day biospheric carbon pools and fluxes (Ahlström et al., 2013; Anav et al., 2013; Ahlström, 2016).~~(Ahlström, 2016; Ahlström et al., 2013; Anav et al., 2013)~~. Potential bias and errors in the predicted climate may be expected to be even higher in palaeoclimate simulations, not least due to the absence of instrumental observations for validating the models. Furthermore, in this study a~~A~~dditional bias could arise due to the interpolation procedure used to transform GCM output fields into monthly anomalies, required to force our model. These were generated by linearly interpolating between the climate model output, which is only available at 1000-year intervals. As such, the applied anomalies do not capture decadal or centennial climate variability that can contribute to climate-forced variable peat accumulation rates and vegetation dynamics on these timescales (Miller et al., 2008). Although the majority of the sites were in good agreement with the observed peat depth values in the regional gradient experiment, several factors may have contributed to poorer agreement for certain sites. In particular, a correct parameterization of local hydrological conditions, bulk density profile, climate forcing data and the right inception period are critical in determining the modelled long-term peat dynamics (Yu et al., 2009), together with inclusion of suitable PFTs. Only the basal age was prescribed on a site-specific basis in our simulations (Table 4).

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4.1.2 Coupled vegetation and carbon dynamics

Changes in vegetation cover significantly affect the long-term carbon fluxes due to differences in PFT productivity and decay resistance properties of their litter (Malmer et al., 2005). In Stordalen, mosses and dwarf shrubs are the main peat forming plants present on hummocks and intermediate areas (Malmer and Wallen, 1996). Our results are largely in agreement with the observed changes in major PFTs during the last 4700 years of Stordalen history (Kokfelt 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. Graminoids were not productive during the entire simulation period apart from the period 4-3kyr cal. BP (Kokfelt et al., 2010). The model predicted correctly the dominance of graminoids, characteristic of wet conditions, during 4-3kyr cal. BP and a transition between the *Sedge-Drepanocladus* (around 3kyr cal. BP). A period of graminoid dominance between 700-1700 cal. BP was not accurately captured. One explanation can be the absence of decadal and centennial climate variability in the adopted climate forcing data, resulting in an "averaging out" of moisture status over time that elminates wet episodes needed for graminoids to be sufficiently competitive. In Mer Bleue, mosses form the dominant vegetation cover together with low shrubs and graminoids. Though in general the model was able to capture these dynamics fairly well, we found some discrepancies in the beginning and at the end of the simulation. In the beginning, there were no graminoids while at the end the moss-dominated areas were replaced by graminoids due to submergence of lower patches, which is not reflected in the peat core analysis (Frolking et al., 2010).

The modelled annual and monthly WTP from 2003-2012 in semi-wet patches and modelled annual ALD 1990-2012 is in good agreement with the observed values for the Stordalen region (Figs. 8, 9 and A5) supporting the ability of model to capture hydrological dynamics that further drive peatland dynamics. For the additional evaluation sites, modelled dominant vegetation cover, LARCA and WTP were in good agreement with the observed values for the three selected sites at which this information was available. Under the present climate, Stordalen was simulated to be a small sink for atmospheric CO_2, in agreement with observed NEE (see Fig 11). NEE interannual range is likewise close to observations for the other Scandinavian sites (Table 5)..However it is uncertain whether recent annual observations of NEE necessarily reflect the long-term peatland carbon balance, in view of high variability on multiple timescales. For example, Fajemyr has switched between source (14.3-21.4 g C m^{-2} yr^{-1} in 2005-2006; 23.6 g C m^{-2} yr^{-1} in 2008) and sink (-29.4 g C m^{-2} yr^{-1} in 2007; -28.9 g C m^{-2} yr^{-1} in 2009) conditions in recent years, and this variability has been attributed to disturbances and intermittent drought conditions (Lund et al., 2012).

~~For the additional evaluation sites, we found that the modelled dominant vegetation cover, LARCA and WTP were in good agreement with the observed values for the three selected sites at which this information was available. However, there were discrepancies between the observed and modelled values of short term fluxes (Table 5). The variability in NEE is quite high and also very sensitive to local climate conditions, affecting prediction of these fluxes. However it is uncertain whether recent annual observations of NEE necessarily reflect the long-term peatland carbon balance, in view of high variability on multiple timescales. For example, observation of NEE during 1998-2001 in Mer Bleue averaged 70.2 g C m^{-2} yr^{-1} which dropped to 9.1 g C m^{-2} yr^{-1} in 2001-2002 due to dry summer~~

Plant productivity simulated by our model in this study was generally quite low, as is generally observed in subarctic environments (Malmer et al., 2005). However, the NPP of mosses was comparatively higher than the dwarf shrubs because of two factors (Fig. 6a). The presence of permafrost (Fig. 7a) and an ALD near the surface (Fig. 7c) reduced the vascular plants' ability to take up water from the peat soil layers, reducing NPP and in turn affecting the total litter biomass (Fig. 5a). Mosses, however, could access water more easily because their uptake is largely above the ALD. The exposure to wind and snow drift may also contribute to reducing plant productivity (Johansson et al., 2006; Malmer et al., 2005) but these factors are not represented in the model. In the temperate conditions of Mer Bleue, plant productivity is quite high compared to subarctic conditions of Stordalen, as plant water uptake is not limited by permafrost conditions and it is also influenced by a longer growing season. In Mer Bleue, the total simulated NPP was low compared to that used as input to the modelling study by Frolking et al. (2010) but within the observed range reported by Moore et al. (2002). The lower simulated NPP in our model provides one explanation for relatively lower peat accumulation and peat depth, although agreement with the reconstructed peat accumulation trajectory is high for the first 6 kyr (Figs. 4 and 6c).

However, estimates of carbon fluxes derived from the flux tower measurements are not directly comparable with the long-term carbon fluxes derived from the peat core analyses (Belyea and Malmer, 2004; Silvola et al., 1996). LARCA for the two sites are 20 and 27~~6~~.1~~3~~ g C m^{-2} yr^{-1} respectively, which is near the reported mean for 795 peat cores from Finland (21 g C m^{-2} yr^{-1}) (Clymo et al., 1998) and 127 accumulation records from northern peatlands (22.9 g C m^{-2} yr^{-1}) (Loisel et al. 2014). The LARCA of all our evaluation sites also fall within reported ranges (see Table 4). Similarly, the mean annual simulated NEE (~~43.8~~34.1 g C m^{-2} yr^{-1}) for the last three decades (1971-2000) at~~ the~~ Stordalen ~~site~~ also falls within the recent observed range at the site of 8-45 g C m^{-2} yr^{-1} (Malmer et al., 2005; Malmer and Wallen, 1996). Christensen et al. (2012) found that the mean NEE of Stordalen~~ mire~~ during 2001-2008 was 46 g C m^{-2} yr^{-1} and for 2008-2009 it was 50 ± 17.0 g C m^{-2} yr^{-1} (Olefeldt et al., 2012; Yu, 2012). The mean NEE for 2001-2009 in our simulations was 51~~0~~.4~~7~~ g C m^{-2} yr^{-1}, which is very near to the observed values. However, as discussed above, an exact comparison cannot yet be made as the carbon fluxes from the wet and semi-wet areas are not properly represented in our model, and the water borne fluxes are also not included in the calculation.

Water borne carbon fluxes (DOC) and CH_4 are not yet considered in our model (but are under development; e.g. Tang et al., 2015b) and inclusion of both would alter the NEE values we report above and in Figs. 5c,d and 11~~ and 5d~~. Both release and uptake components of NEE are relatively low in Stordalen compared to other peatlands (Nilsson et al., 2008; Olefeldt et al., 2012). The low ecosystem respiration is associated with low autotrophic respiration (Olefeldt et al., 2012) and the presence of permafrost which keeps the thawed peat soil cool and reduces the decomposition rate in the shallow thawed soil.

Temperature increase since the 1970's at Stordalen (Christensen et al., 2012) has caused the permafrost in the peat soil to thaw, leading to a predominance of wet sites dominated by graminoids in parts of the mire, affecting its overall vegetation composition and carbon fluxes (Christensen et al., 2004; Johansson et al., 2006; Swindles et al., 2015). ~~().~~This situation was not captured by our simulation, where there is no such increase in graminoids (Fig. 6b). The increase in wet areas at

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Stordalen is however associated with peat soil subsidence during permafrost thaw and the resultant change in hydrological networks across the mire landscape (Åkerman & Johansson 2008), a complex physical process not included in our model. Another factor that contributed to the recent dynamics of the site is the influence of the underlying topography on the sub-surface flow and the addition of water through run-on from the surrounding catchment (Tang et al., 2015). Though we incorporated lateral exchange of water between the simulated patches, we ignored the effect of underlying topography that affects the water movement. In Stordalen, the southern and western parts of the mire are normally fed from higher areas centrally and to the east (Johansson et al., 2006), and recent warming has resulted in the runoff rate increasing from the elevated sites to the low lying areas that have slowly become increasingly waterlogged. Tang et al. (2015) showed the importance of including the slope and drainage area in order to distribute water within the catchment area, and demonstrated how these factors influence vegetation distribution and carbon fluxes in LPJ-GUESS.

4.2 Impact of climate change

4.2.1 Coupled vegetation and carbon dynamics

Some peatlands may sequester more carbon under warming climate conditions (Charman et al., 2013) while some may turn into carbon sources and degrade (Ise et al., 2008; Fan et al., 2013). ~~(Fan et al., 2013; Ise et al., 2008).~~ For Stordalen, our simulations suggested that the temperature (T8.5 and T2.6) is the main factor which accelerates the decomposition in the peat soil after the year 2050. However, the rate of decomposition remains stable in the first half of the 21^{st} century due to the presence of permafrost. The rise in atmospheric CO_2 concentration (C8.5 and C2.6) accelerates the plant productivity. An increase in precipitation (P8.5 and P2.6) has a very limited effect on peat growth as the mire has already been saturated and any additional input of water will be removed at a faster rate because the surface runoff and evaporation are positively correlated with WTP. The warmer and wetter future conditions, in combination with CO_2 fertilization (FTPC8.5 and FTPC2.6), would lead to increased moss productivity and a slight increase in shrub abundance (Figs. 6b and 12~~9~~). The latter trend is consistent with widespread reports of expansion of tall shrubs in the second half of the 21^{st} century in many parts of the Arctic and beyond (Loranty and Goetz, 2012; Sturm et al., 2005). 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 21^{st} 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 21^{st} century (Fig. 12). ~~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).~~

4.2.2 Permafrost and climate warming

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Temperature and precipitation are expected to increase at Stordalen in the coming decades (Saelthun and Barkved, 2003) and alongside an increase in snow depth are expected to result in rapid rates of permafrost degradation and a thicker active layer (Christensen et al., 2004; Johansson et al., 2013; Swindles et al., 2015). ~~(Christensen et al., 2004; Johansson et al., 2013).~~ Due to recent warming the ALD has already increased at Stordalen~~ mire~~ and surrounding sites over the past three decades (Åkerman and Johansson, 2008). This event has also changed the surface hydrology of the mire and in turn the vegetation distribution within the basin. ALD has increased between 0.7 and 1.3 cm per year in different parts of the mire, accelerating to an average of around 2 cm yr^{-1} in recent decades. In our results, we found that simulated MAAD was around 0.69~~7~~ m for 1972-2005, consistent with the observed MAAD of 0.58 m for the same period (Christensen et al., 2004; Johansson et al., 2006). However, it should be noted that our model does not account for the large observed impact of local variation in permafrost thaw on hydrological network and variability in wetness across the mire landscape. According to Fronzek et al. (2006), a slight increase (1 ºC) in temperature and precipitation (10% increase) could lead to widespread disappearance of permafrost throughout Scandinavia in the future. In one scenario, they found a complete disappearance of permafrost by the end of the 21st century. Our results for Stordalen are consistent with this scenario: in the FTPC8.5 experiment, permafrost completely disappears by 2050 due to climate warming (Figs. 7b and d). In the more moderate warming of the FTPC2.6 experiment, permafrost thaws but does not disappear after the year 2050, leading to the simulated MAAD of 1.75 m by 2100 (Fig. 7d).

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5 Conclusion

Our results demonstrate that the incorporation of peatland and permafrost functionality in LPJ-GUESS provides a suitable framework for assessing the combined and interactive responses of peatland vegetation, hydrology and soils to changing drivers under a range of high latitude climates. Modelled peat accumulation, vegetation composition, water table position, and carbon fluxes were found to be broadly consistent with published data for simulated localities in a range of high-latitude climates. Climate change sensitivity simulations for ~~the~~ Stordalen~~ mire~~ suggest that peat will continue to accumulate in the coming decades, culminating in mid-century (the year 2050), thereafter switching to a CO_2 source as a result of accelerating decomposition in warming peatland soil. As a complement to empirical studies, our modelling approach can provide an improved understanding of the long-term dynamics of northern peatland ecosystems at the regional scale, including the fate of peatland carbon stocks under future climate and atmospheric change. In ongoing work, the model is being extended to incorporate methane biogeochemistry and nutrient dynamics, and will be used to assess impacts of projected future changes in climate and atmospheric CO_2 on peatland vegetation and greenhouse gas exchange across the Arctic. Coupled to the atmospheric component of a regional Arctic system model, it is being used to examine the potential for peatland-mediated biogeochemical and biogeophysical feedbacks processes to amplify or dampen climate change in the Arctic and globally.

Acknowledgements

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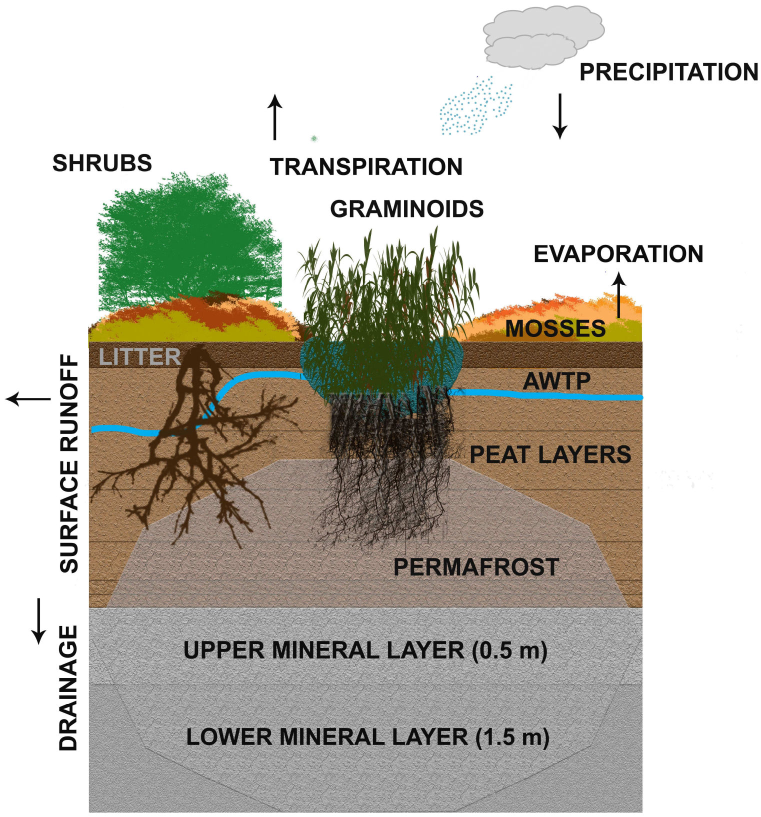
Figures:


PRECIPITATION
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GRAMINOIDS
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MOSSES
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DRAINAGE
UPPER MINERAL LAYER (0.5 m)
LOWER MINERAL LAYER (1.5 m)

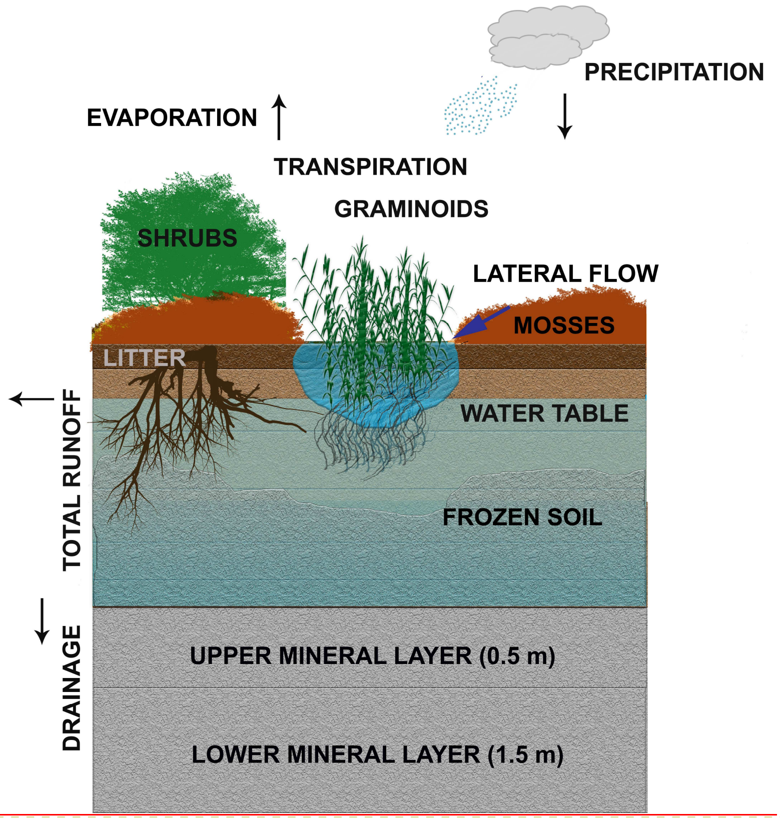

Fig. 1. Schematic representation of peatland structure and function in the implementation described in this paper. Dynamic peat layers deposit above the static mineral soil layers (0.5+1.5 m). In the shallow peat, plant roots are present in both mineral and peat layers. Once the peat becomes sufficiently thick (2 m), all roots are confined to the peat layers.

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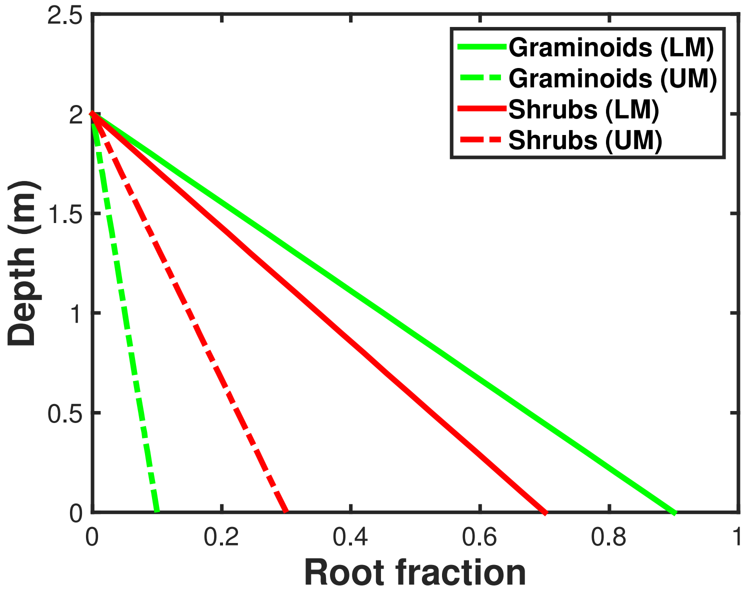

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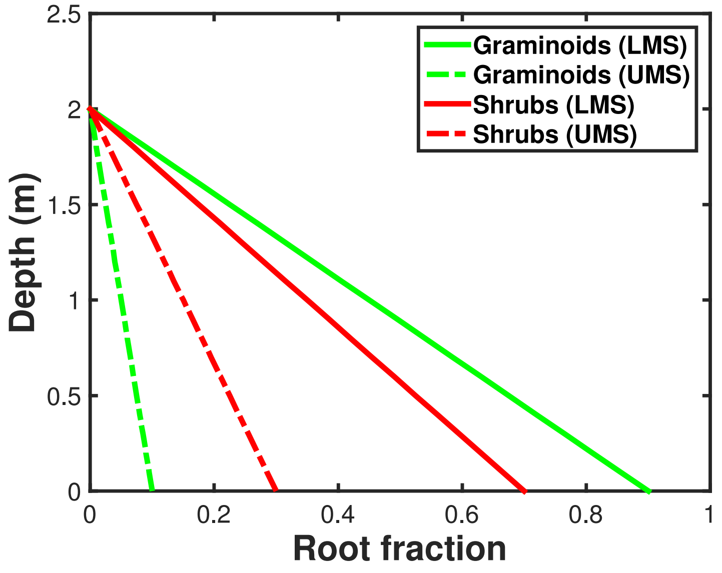

Fig. 2. Root fractions in the upper (UMS) and lower mineral soil (LMS) ~~soil~~ layers as a function of peat depth (m). The broken lines represent root fractions in UMS ~~soils~~ and solid lines indicate fractions in the LM~~soil~~S.

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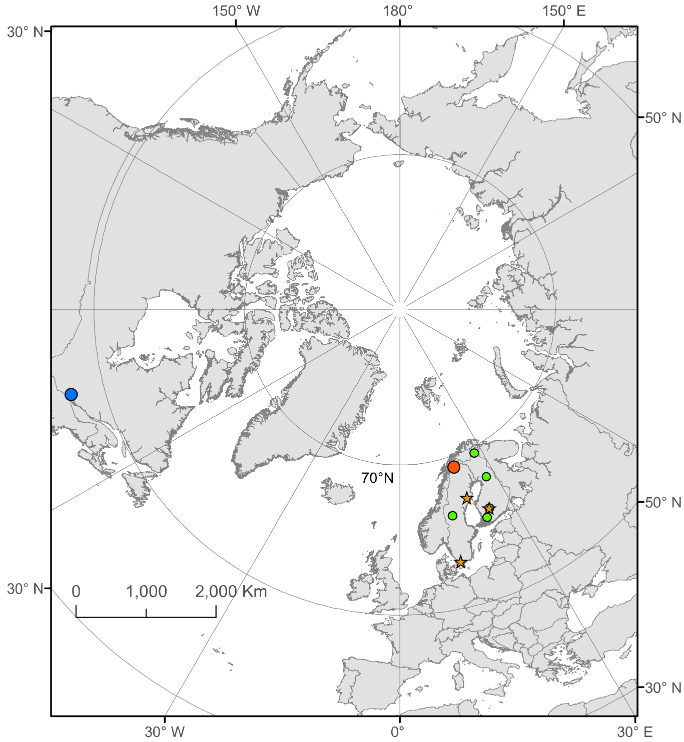

Fig. 3. Map showing the location of the evaluation site (in red), the validation site (in dark blue) and the distribution of regional gradient points across northern European (in green) used for validating the peat depth. Orange stars show the location of the three points used for the evaluation of peat depth, carbon fluxes, WTP and dominant vegetation cover.

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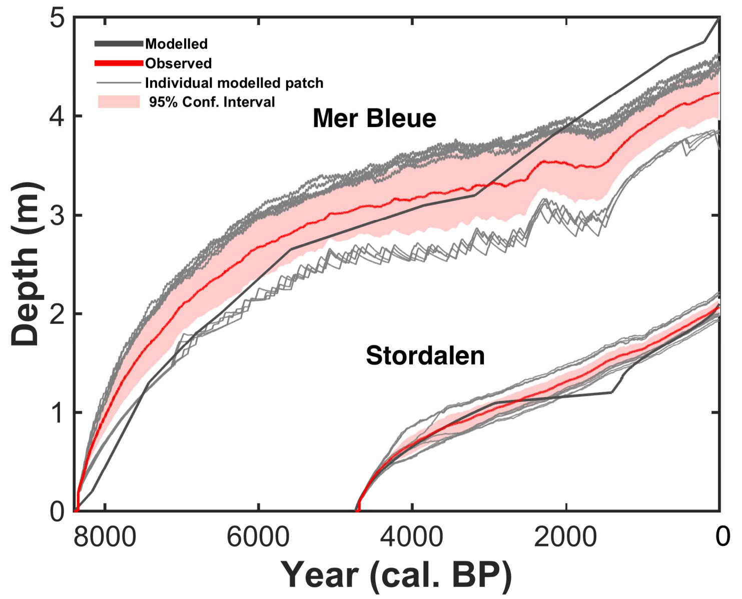

Fig. 4 Comparison of mean landscape simulated peat depth (m) with inferred ages of peat layers of different depths in peat cores from the Stordalen and Mer Bleue sites. The light red shaded area shows the 95% confidence interval (CI)[2] inferred from the ~~simulation data for the replicate~~variability among simulated patches at each site (shown in light grey lines).

~~**Fig. 4. Fig. 4.** Comparison of mean landscape simulated peat depth (m) with inferred ages of peat layers of different depths in peat cores from the Stordalen and Mer Bleue sites. The light red shaded area shows the 95% confidence interval (CI) inferred from the simulation data.~~

[2]

$CI = \mu \pm Z_{95}\, SE$

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.

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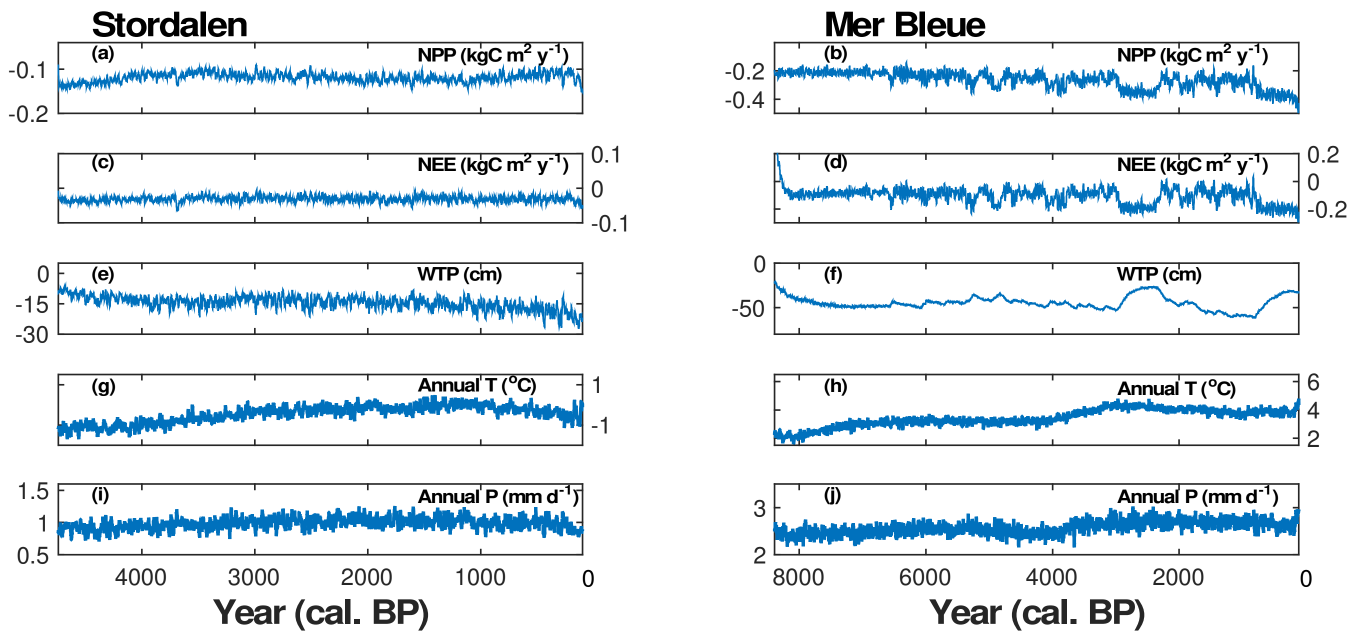


Stordalen
Mer Bleue
(a) NPP (kgC m2 y-1)
(b) NPP (kgC m2 y-1)
(c) NEE (kgC m2 y-1)
(d) NEE (kgC m2 y-1)
(e) WTP (cm)
(f) WTP (cm)
(g) Annual T (°C)
(h) Annual T (°C)
(i) Annual P (mm d-1)
(j) Annual P (mm d-1)
Year (cal. BP)
Year (cal. BP)

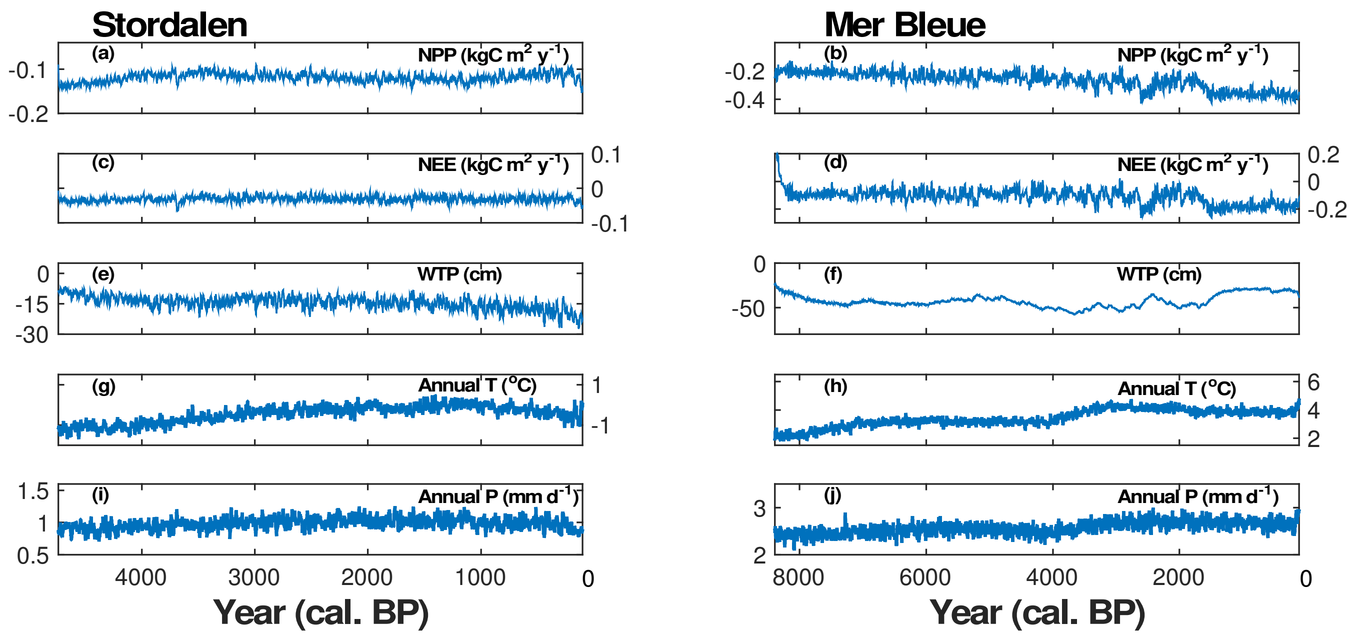


Fig. 5. Simulated annual average values (10-year moving average) of **(a, b)** net primary productivity (NPP), **(c, d)** net ecosystem exchange (NEE), **(e, f)** water table position (WTP), **(g, h)** temperature and **(i, j)** precipitation for the last 4700 years at ~~the~~ Stordalen ~~mire~~ and for the last 8400 years at Mer Bleue, respectively.

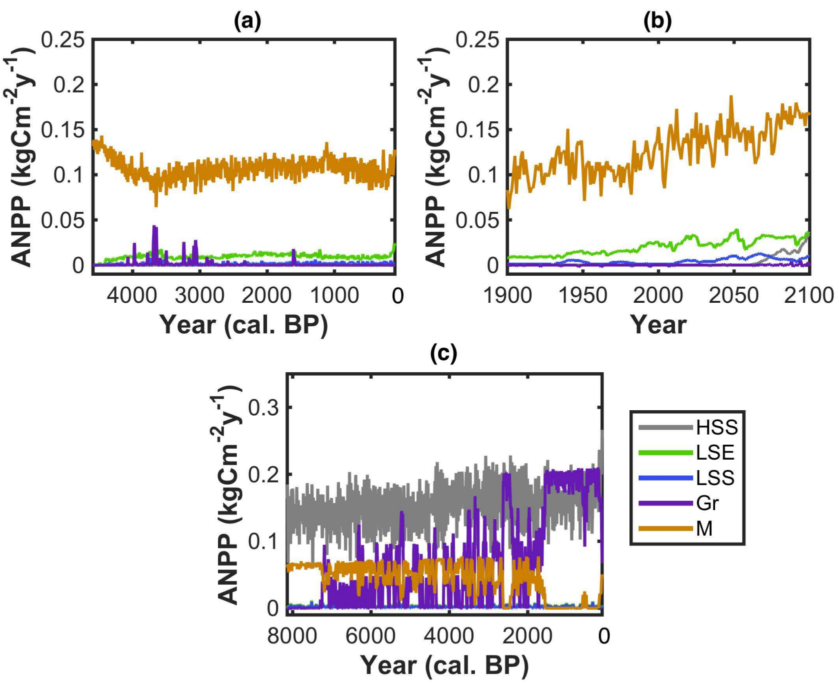
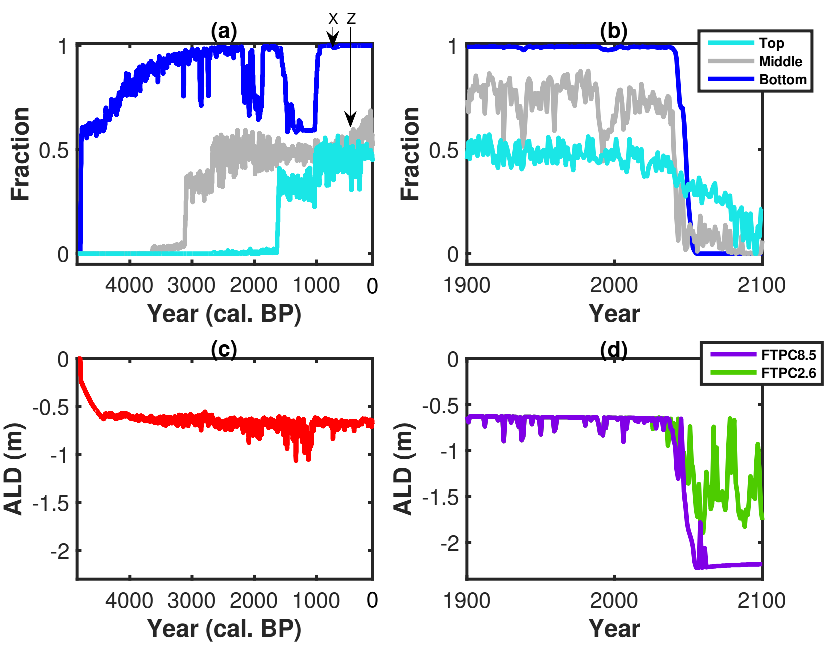


Fig. 6. Simulated annual net primary productivity (ANPP) (10-year moving average) of simulated PFTs (Table 1) **(a)** for the last 4700 years at ~~the~~ Stordalen~~ site~~, **(b)** for~~rom the year~~ 1900~~ to~~ 2100 at ~~the~~ Stordalen~~ site~~ following RCP8.5 scenario (see Fig. A3 for RCP2.6 scenario) and **(c)** for the last 8400 years at ~~the~~ Mer Bleue~~ site~~. ~~Here HSS~~ ~~Here HSS denotes high summergreen shrubs, LSE low evergreen shrubs and LSS low summergreen shrubs, Gr graminoids and M is moss.~~



~~is high deciduous shrubs, LSE is low evergreen shrubs and LSS is low deciduous shrubs, Gr means graminoids and M is moss.~~

Fig. 7. **(a)** Total simulated peat ice fraction (10-year moving average) over 4700 years at Stordalen. Peat layers corresponding to annual litter cohorts were aggregated to top (top 1 m), middle (middle 1 m) and bottom (lower 1.5 m) for display. **(b)** Total simulated ice fraction for 1900-2100 following the RCP8.5 scenario (see Fig. A3 for the RCP2.6 scenario results). **(c)**

Total simulated mean September active layer depth for the last 4700 years and **(d)** for 1900-2100 at Stordalen following the RCP8.5 scenario (FTPC8.5) and RCP2.6 scenario (FTPC2.6).

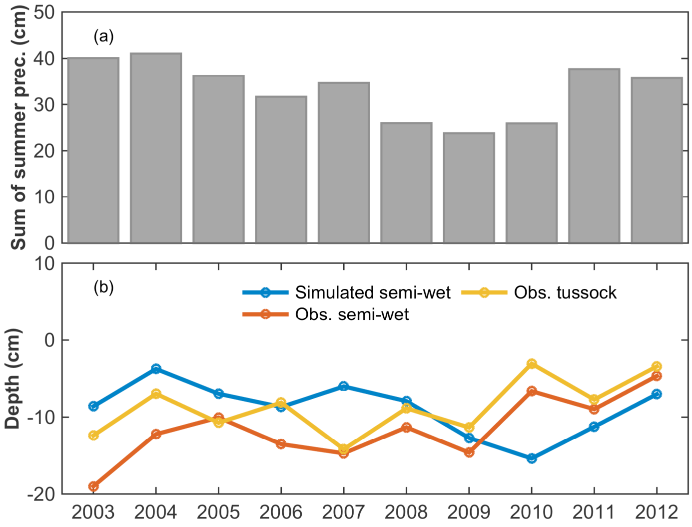


Fig. 8 **(a)** The total sum of precipitation and **(b)** comparison between observed and simulated mean annual WTP for semi-wet patches in Stordalen for 2003-2012.

~~**(a)** Total simulated ice fraction (10-year moving average) in the peat sublayers over 4700 years at Stordalen. The bottom sublayer was present from the beginning of the simulation while the middle sublayer formed once the peat depth reached to 1 m around 3200 cal. BP and the top sublayer was formed around 1200 cal. B.P. **(b)** Total simulated ice fraction from the year 1900 to 2100 using RCP8.5 scenario (see Fig. A3 for RCP2.6 scenario), **(c)** Total simulated mean active layer depth in the peat soil in September for the last 4700 years and **(d)** from the year 1900 to 2100 at Strodalen site using RCP8.5 scenario (FTPC8.5) and RCP2.6 scenario (FTPC2.6).~~

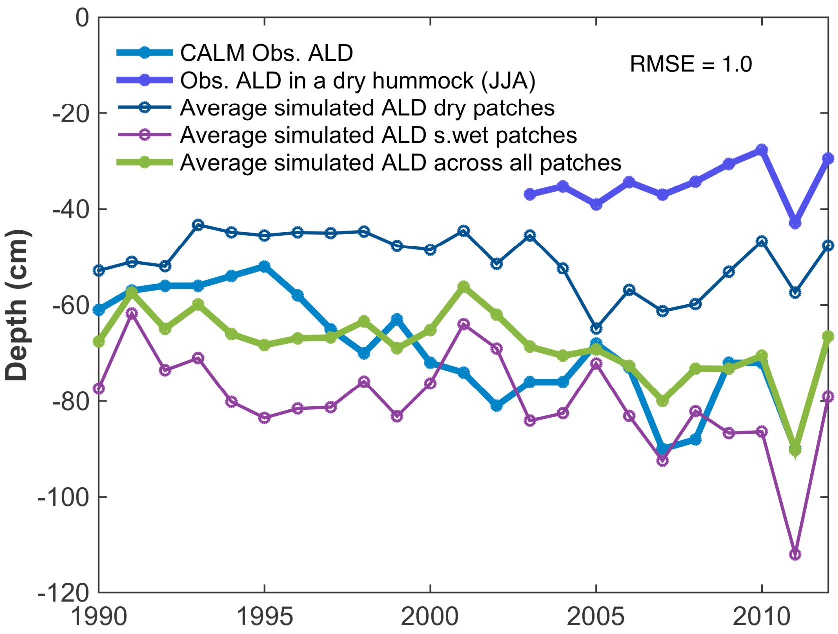


Fig. 9. Comparison between observed and simulated active layer depth for 1990-2012 and average simulated ALD in semi-wet and dry patches at Stordalen. A separate short mean (June-August) ALD observation from the Stordalen in a dry elevated hummock site.

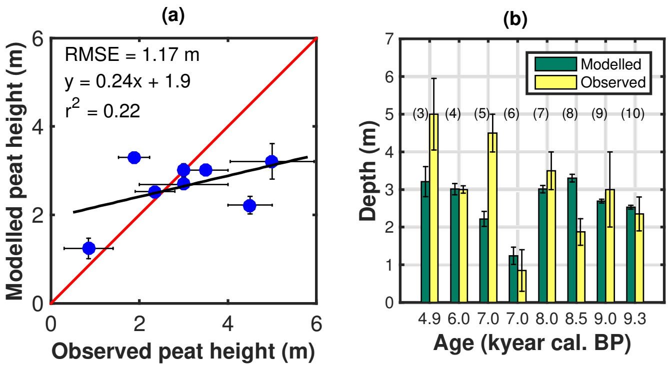


Fig. 10~~8~~. **(a)** Scatter plot with range bars and **(b)** bar graph showing the comparison between modelled and observed peat depth (m) with reported range bars (in black with yellow bars) at 8 locations (numbered from Table 4) across Scandinavia.~~ Corresponding site no. above the bars is described in Table 4.~~

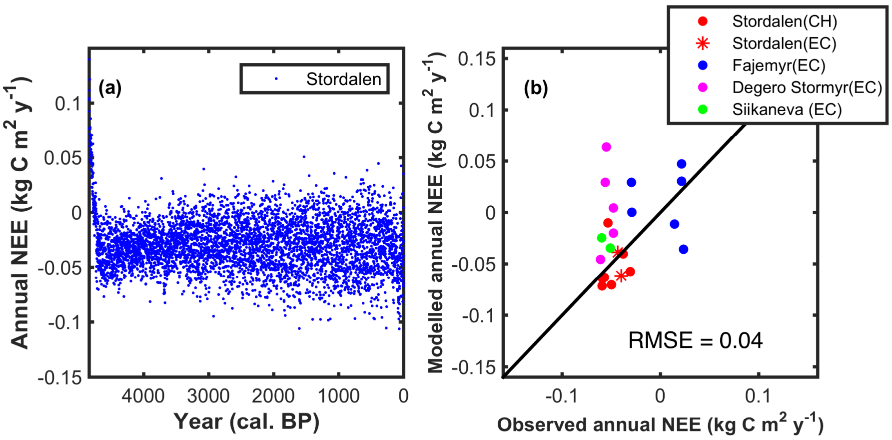


Fig. 11 (a) Annual simulated NEE (kg C m^{-2} yr^{-1}) for Stordalen and (b) relationship between observed and modeled annual NEE (kg C m^{-2} yr^{-1}) for three Scandinavian peatland ecosystems (Table 4; observed NEE data from Aurela et al., 2007; Lund et al., 2007; Sagerfors et al., 2008; Aslan-Sungur et al., 2016). EC = eddy covariance (flux tower) data; CH = chamber flux measurements.

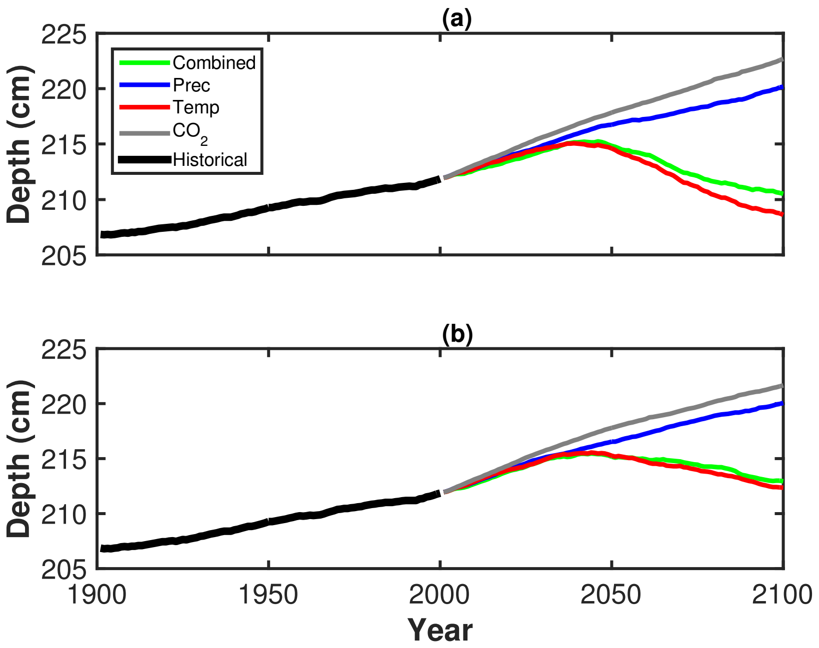


Fig. 12. Simulated peat depth (cm) in ~~the future experiments using~~ (a) RCP8.5 and (b) RCP2.6 ~~forcing~~ scenarios simulations at Stordalen. ~~mire~~

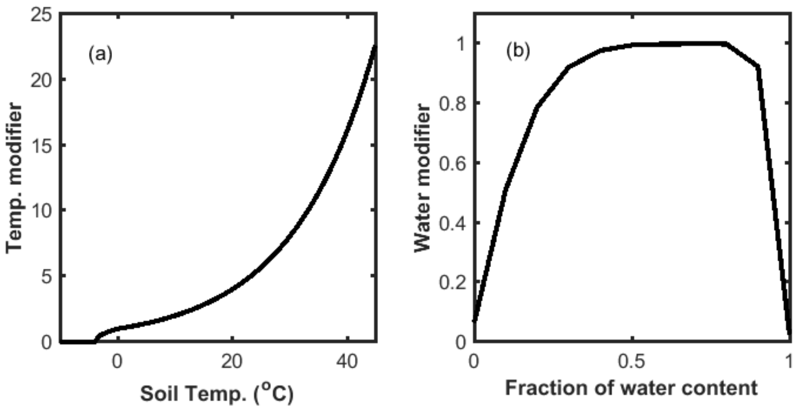


Fig. A1 Assumed decomposition dependency on (a) soil temperature and (b) soil water content.

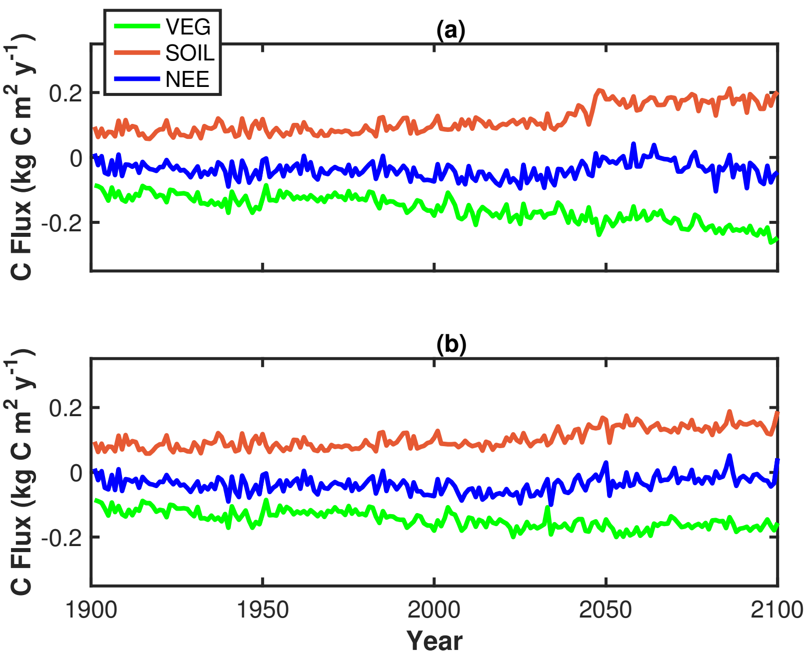


Fig. A2. S~~Total s~~imulated carbon fluxes ~~from the vegetation (VEG) and soil (SOIL) and net ecosystem exchange (NEE) from~~and components for ~~the year~~ 1900-~~ to ~~2100 based on historical and~~using~~ **(a)** RCP8.5 ~~(FTPC8.5)~~ and **(b)** RCP2.6 future ~~(FTPC2.6) forcing~~ scenarios at Stordalen.~~ mire~~ VEG = vegetation net primary production (NPP); soil = heterotrophic respiration; NEE = net ecosystem exchange; negative flux represents uptake from, positive flux release to the atmosphere.

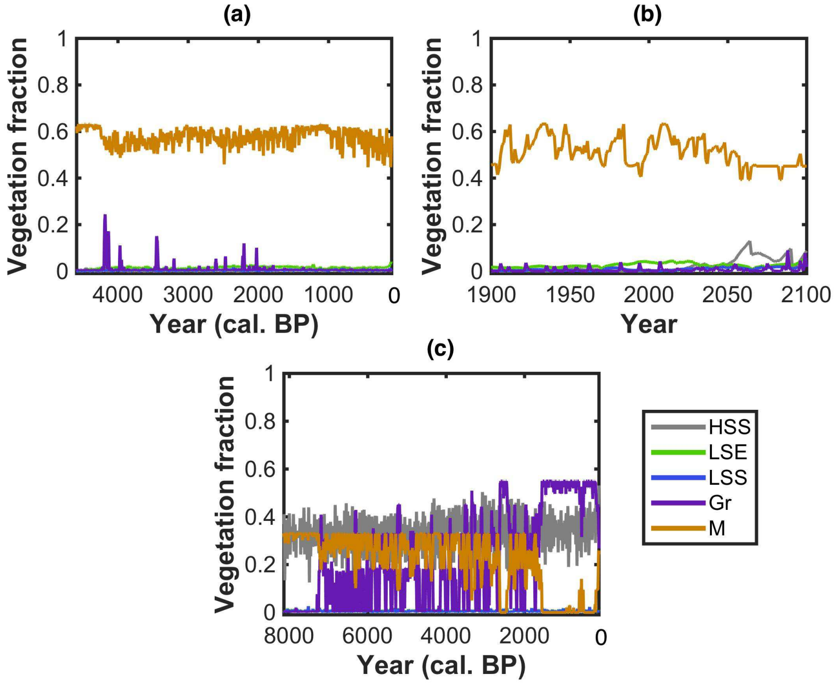


Fig. A3. Simulated vegetation fraction (10-year moving average) of simulated PFTs (Table 1) **(a)** for the last 4700 years at Stordalen, **(b)** for 1900-2100 at Stordalen following the historical simulation and RCP8.5 scenario and **(c)** for the last 8400 years at Mer Bleue.

~~Here HSS is high deciduous shrubs, LSE is low evergreen shrubs and LSS is low deciduous shrubs, Gr denotes graminoids and M is moss.~~

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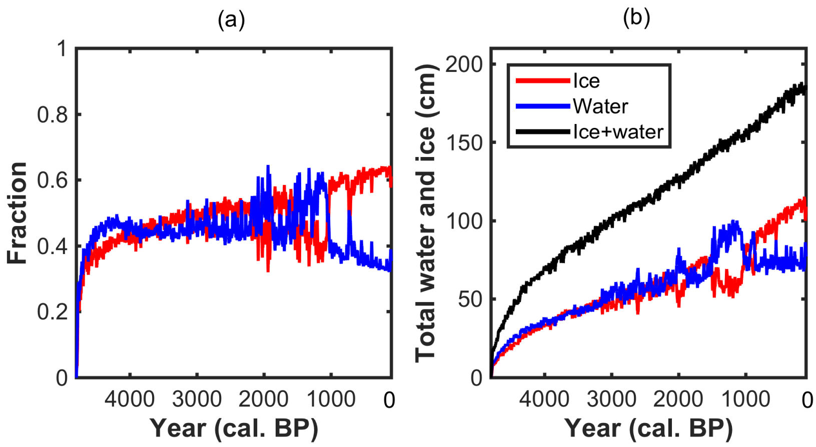
(a)
Fraction
Year (cal. BP)
(b)
Total water and ice (cm)
Year (cal. BP)
Ice
Water
Ice+water

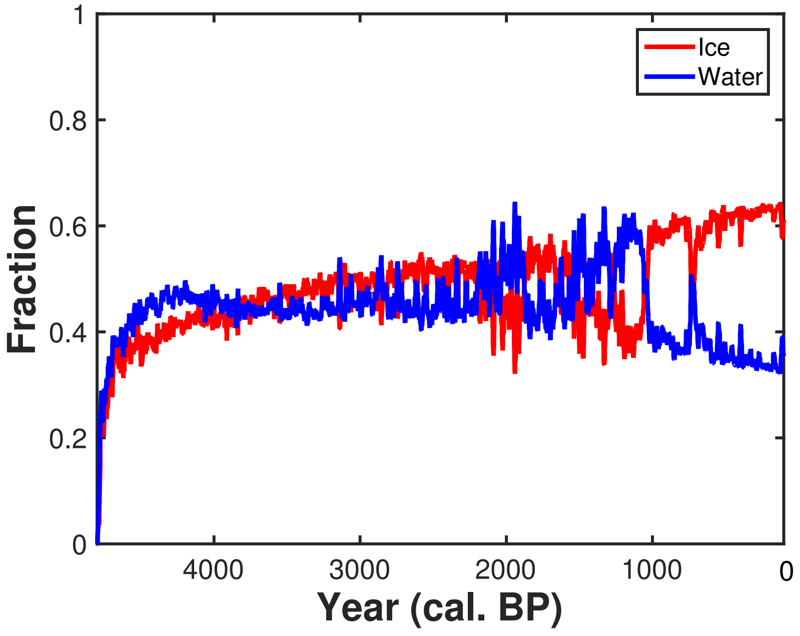

Fig. A4. (a) Total simulated (10-year moving average) ice and water content in the peat soil and (b) total simulated water and ice (in cm) for the last 4700 years at Stordalen.

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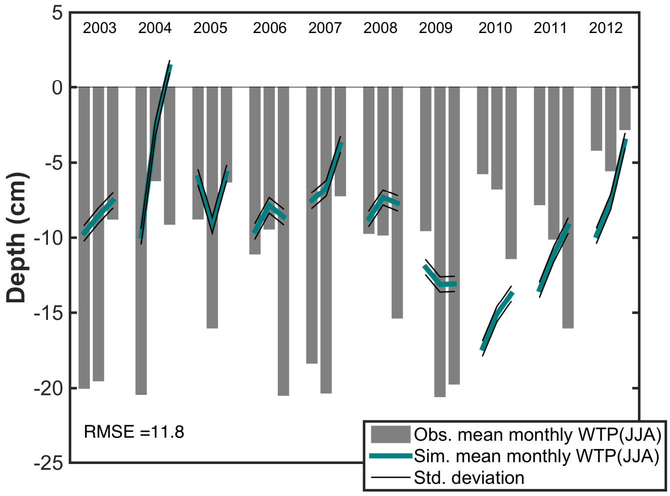

Fig. A5. Comparison between observed and simulated monthly mean summer (JJA) WTP for semi-wet patches in Stordalen for 2003-2012.

Table 1. Plant functional types (PFTs) simulated in this study, showing representative taxa, phenology, bio-climatic limits, water table position (WTP) threshold for establishment, prescribed root fractions in mineral soil layers, and initial decomposition rate for different litter fractions.

	Representative	**Phenology**	**Climate**	**Growth**	**Min/Max**	**Max**	**WTP**	**Root fraction**	**Litter**	**Initial**

~~**Table 1.** Plant functional types (PFTs) simulated in this study, showing representative example taxa, water table position (WTP) threshold for~~ ~~establishment and initial decomposition rate for different litter fractions.~~

PFT (abbreviation)	taxa		Zone	Form	temperature of the coldest month for establishment (°C)	GDD for establishment (°C day)	threshold (in cm)	Upper mineral soil (UM)	Lower mineral soil (LM)	fraction	decomposition rate (k_0)[c] (yr^{-1})
High summergreen shrub (HSS)	*Salix spp., Betula nana*	Summer green	Boreal-Temperate	Woody	-32.5/-	1000	< -25	0.65	0.35	Wood	0.055
										Leaf	0.1
										Root	0.1
										Seed	0.1
Low evergreen shrub (LSE)	*Vaccinium vitis-idaea, Andromeda polifolia* L.	Evergreen	Boreal-Temperate	Woody	-32.5/-	100	< -25	0.7	0.3	Wood	0.055
										Leaf	0.1
										Root	0.1
										Seed	0.1
Low summergreen shrub (LSS)	*Vaccinuim myrtillus, Vaccinium uliginosum, Betula nana* L.	Summer green	Boreal-Temperate	Woody	-32.5/-	100	< -25	0.7	0.3	Wood	0.055
										Leaf	0.1
										Root	0.1
										Seed	0.1
Graminoid (Gr)	*Carex rotundata Wg., Eriophorum vaginatum L.*	Evergreen	Boreal-Temperate	Herbaceous	-/-	-	> -10	0.9	0.1	Leaf	0.1
										Root	0.1
										Seed	0.1
Moss (M)	*Sphagnum* spp.	Evergreen	Boreal-Temperate	Herbaceous	-/15.5	-	< +5 and > -50	-	-	Leaf	0.055
										Seed	0.055

[c] Aerts et al. (1999), Frolking et al. (2002) and Moore et al. (2007)

Table 2. Model parameter values used in standard (STD) and validation (VLD) model experiments

Sl. no.	Parameter	Value: STD / VLD	Unit	Equation
1.	α	5.0	-	Eq. (4)
2.	β	0.064	-	Eq. (4)
3.	θ_{opt}	0.75	-	Eq. (4)
4.	T_{min} ~~Tmin~~	-4	°C	Eq. (5)
5.	Q_{10}	2	-	Eq. (5)
6.	ρ_{min} ~~ρ min~~	40	kg m^{-3}	Eq. (6)
7.	$\Delta\rho$	80	kg m^{-3}	Eq. (6)
8.	TH	STD: -30~~0~~ / VLD: -40~~0~~	c~~m~~m	Eq. (9)
9.	u	STD: 0.45 / VLD: 0.0	-	Eq. (10)
10.	ρ_o ~~ρ o~~	800	kg m^{-3} ~~-~~	Eq. (12)

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Table 3. Summary of hindcast and global change experiments

Experiment no.	**Experiment name**	**Description of hindcast and future experiments from 2000 to 2100**
1.	STD	Standard model experiment
2.	VLD	Validation model experiment
3.	T8.5	RCP8.5 temperature only
4.	P8.5	RCP8.5 precipitation only
5.	C8.5	RCP8.5 CO_2 only
6.	FTPC8.5	RCP8.5 including all treatments
7.	T2.6	RCP2.6 temperature only
8.	P2.6	RCP2.6 precipitation only
9.	C2.6	RCP2.6 CO_2 only
10.	FTPC2.6	RCP2.6 including all treatments

Table 4. Observed peat depth (m) compared with modelled peat depth (m), basal age, climatology, long-term apparent rate of carbon accumulation (LARCA) and total accumulated carbon (kg C m^{-2}) for the calibrated and validation sites together with 8 grid points in the Scandinavian region

Site no.	Site name	Peatland type	Country	Lat. (°N)	Lon. (°E)	MAAT (°C)	MAP (c~~m~~m yr^{-1})	Basal age (kyear cal. BP)	Modelled: Total carbon (LARCA) kg C m^{-2} (~~k~~g C m^{-2} yr^{-1})	Modelled: Total peat depth range (average) (in meters)	Observed: Total peat depth range (average) (in meters)	Reference
1.	Stordalen	Plasa mire	Sweden	68.5	19.0	-0.7	30~~0~~	4.7	94.6~~9~~ (20.0)	1.9 - 2.2 (2.1)	1.9 - 2.3 (2.1)	Kokfelt et al. (2010)
2.	Mer Bleue	Temperate bog	Canada	45.4	-75.5	5.8	91~~0~~	8.4	227~~1~~.9~~2~~ (27~~6~~.1~~3~~)	3.6 - 4.4 (4.05)	34.6~~0~~ - 5.9 (4.9)	Frolking et al. (2010)
3.	Kontolanrahka	Bog	Finland	60.78	22.78	4.6	57.4	4.9	159.7 (32.5)	2.7 - 3.4 (3.2)	4.0 - 6.0 (5.0)	Valiranta et al. (2007)
4.	Lakkasuo	Bog	Finland	61.78	24.30	3.1	70~~0~~	6.0	162.0 (27.0)	2.9 - 3.2 (3.0)	2.9 - 3.1 (3.0)	Tuittila et al. (2007)
5.	Fajemyr	Temperate tree bog	Sweden	56.27	13.55	6.2	70~~0~~	7.0	128.2 (18.3)	2.0 - 2.4 (2.2)	4.0 - 5.0 (4.5)	Lund et al. (2007)
6.	Kaamanen	Subarctic poor fen	Finland	69.14	27.30	-1.1	47~~0~~	7.0	75.3 (10.8)	1.1 - 1.5 (1.2)	0.3 - 1.4 (0.9)	Aurela et al. (2004)
7.	Degerö Stormyr	Boreal poor	Sweden	64.18	19.55	1.2	52.3	8.0	166.0 (20.7)	2.9 - 3.1	3.0 - 4.0	Sagerfors et al.

		fen								(3.0)	(3.5)	(2008)
8.	Lilla Backsjömyren	Mixed mire	Sweden	62.41	14.32	1.6	563	8.5	125.2 (31.3)	3.2 - 3.4 (3.3)	1.5 - 2.2 (1.9)	Andersson and Schoning (2010)
9.	Siikaneva	Boreal poor fen	Finland	61.83	24.18	3.3	713	9.0	156.2 (17.3)	2.6 - 2.7 (2.7)	2.0 - 4.0 (3.0)	Aurela et al. (2007)
10.	Ruosuo	Boreal poor fen	Finland	65.65	27.32	1.0	650	9.3	135.4 (14.5)	2.5 – 2.6 (2.5)	1.9 - 2.8 (2.4)	Makila et al. (2001)

Table 5. Observed dominant vegetation cover, long-term apparent rate of carbon accumulation (LARCA), ~~short-term~~annual net ecosystem exchange (NEE), and mean annual water table position (WTP) compared with mean modelled values (1990-2000) for the 3 ~~grid points~~peatland sites in Scandinavia.~~n region~~

Site (site no. in Table 4)	Fajemyr (5)	Degerö Stormyr (7)	Siikaneva (9)
Dominant vegetation	M, LSE, T	M, Gr	M, Gr, LSE
Modelled Dominant vegetation	M, LSE	M, Gr	M, Gr, LSE
LARCA ($g\ m^{-2}\ yr^{-1}$)	20-35	-	18.5
Modelled LARCA ($kg\ m^{-2}\ yr^{-1}$)	18.3	20.7	17.3
NEE ($g\ m^{-2}\ yr^{-1}$) (period)	~~16.0 27.0~~-29.4 to 23.6 (2003~~5~~-2009~~6~~)	~~12.9~~-48 to ~~-16.7~~-61 (2001-2005~~3~~)	-50.7~~6~~ to -59.1~~3~~ (2004-2005)
Modelled NEE ($g\ m^{-2}\ yr^{-1}$)	-35.1 to 47.2~~63.3 ± 17.1~~	-45 to 63~~30.6 ± 12.6~~	~~34.3 ± 28.0~~-24.6 to -34.5
WTP (cm)	0 to -20.0	-4.0 to -20.0	2.0 to -25.0
Modelled WTP (cm)	-15.2 ±1.83	-2.9 ± 0.99	1.85 ± 0.42
Reference	Lund et al. (2007)	Sagerfors et al. (2008)	Aurela et al. (2007)

Table S1. Comparison of functionality and scope of a representative set of current peatland models.

Schemes / **Models**	**Peatland**	**Permafrost**	**DGVM**	**Multiple annual peat layers**	**Spatial heterogeneity**	**Methane**	**Coupled to ESM**	**Single site**	**Global/Regional application**
This study	✔	✔	✔	✔	✔	✖	✖	✔	✔
Wu et al. (2016)	✔	✖	✖	✖	✖	✖	✔	✔	✔
Alexandrov et al. (2016)	✔	✖	✖	✖	✖	✖	✖	✖	✔
Tang et al. (2015b)	✔	✔	✔	✖	✖	✔	✖	✔	✔
Stocker et al. (2014)	✔	✖	✔	✖	✖	✖	✖	✖	✔
Morris et al. (2012)	✔	✖	✖	✖	✔	✖	✖	✔	✖
Schuldt et al. (2013)	✔	✖	✔	✖	✖	✔	✔	✔	✔
Kleinen et al. (2012)	✔	✖	✔	✖	✖	✖	✖	✔	✔
Heinemeyer et al. (2010)	✔	✖	✖	✔	✖	✖	✖	✔	✖
Frolking et al. (2010)	✔	✖	✖	✔	✖	✖	✖	✔	✖
Wania et al. (2009a)	✔	✔	✔	✖	✖	✔	✖	✖	✔
Ise et al. (2008)	✔	✖	✖	✖	✖	✖	✖	✔	✖
Bauer (2004)	✔	✖	✖	✔	✖	✖	✖	✔	✖
Hilbert et al. (2000)	✔	✖	✖	✖	✖	✖	✖	✔	✖
Clymo (1984)	✔	✖	✖	✖	✖	✖	✖	✔	✖
Ingram (1982)	✔	✖	✖	✖	✖	✖	✖	✔	✖

References:

Aerts, R., Verhoeven, J. T. A., and Whigham, D. F.: Plant-mediated controls on nutrient cycling in temperate fens and bogs, Journal, 80, 2170-2181,doi: 10.1890/0012-9658(1999)080[2170:pmconc]2.0.co;2, 1999.

Ahlström, A., Schurgers, G. & Smith, B. : The large influence of climate model bias on terrestrial carbon cycle simulations, Environmental Research Letters, in press., 2016.2016.

Ahlström, A., Smith, B., Lindström, J., Rummukainen, M., and Uvo, C. B.: GCM characteristics explain the majority of uncertainty in projected 21st century terrestrial ecosystem carbon balance, Biogeosciences, 10, 1517-1528,doi: 10.5194/bg-10-1517-2013, 2013.

Åkerman, H. J. and Johansson, M.: Thawing permafrost and thicker active layers in sub-arctic Sweden, Permafrost Periglacial Process., 19, 279-292,doi: 10.1002/ppp.626, 2008.

Alexandrov, G. A., Brovkin, V. A., and Kleinen, T.: The influence of climate on peatland extent in Western Siberia since the Last Glacial Maximum, Sci Rep, 6,doi: ARTN 2478410.1038/srep24784, 2016.

Anav, A., Friedlingstein, P., Kidston, M., Bopp, L., Ciais, P., Cox, P., Jones, C., Jung, M., Myneni, R., and Zhu, Z.: Evaluating the Land and Ocean Components of the Global Carbon Cycle in the CMIP5 Earth System Models, J. Clim., 26, 6801-6843,doi: 10.1175/Jcli-D-12-00417.1, 2013.

Andrews, T., Gregory, J. M., Webb, M. J., and Taylor, K. E.: Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models, Geophysical Research Letters, 39, 7,doi: 10.1029/2012gl051607, 2012.

Aslan-Sungur, G., Lee, X. H., Evrendilek, F., and Karakaya, N.: Large interannual variability in net ecosystem carbon dioxide exchange of a disturbed temperate peatland, Science of the Total Environment, 554, 192-202,doi: 10.1016/j.scitotenv.2016.02.153, 2016.

Baird, A. J., Milner, A. M., Blundell, A., Swindles, G. T., and Morris, P. J.: Microform-scale variations in peatland permeability and their ecohydrological implications, Journal of Ecology, 104, 531-544,doi: 10.1111/1365-2745.12530, 2016.

Bauer, I. E.: Modelling effects of litter quality and environment on peat accumulation over different time-scales, Journal of Ecology, 92, 661-674,doi: DOI 10.1111/j.0022-0477.2004.00905.x, 2004.

Belyea, L. R. and Baird, A. J.: Beyond "The limits to peat bog growth": Cross-scale feedback in peatland development, Ecol. Monogr., 76, 299-322,doi: 10.1890/0012-9615(2006)076[0299:btltpb]2.0.co;2, 2006.

Belyea, L. R. and Malmer, N.: Carbon sequestration in peatland: patterns and mechanisms of response to climate change, Global Change Biology, 10, 1043-1052,doi: 10.1111/j.1529-8817.2003.00783.x, 2004.

Bubier, J. L., Moore, T. R., and Crosby, G.: Fine-scale vegetation distribution in a cool temperate peatland, Canadian Journal of Botany-Revue Canadienne De Botanique, 84, 910-923,doi: 10.1139/b06-044, 2006.

Callaghan, T. V., Jonasson, C., Thierfelder, T., Yang, Z. L., Hedenas, H., Johansson, M., Molau, U., Van Bogaert, R., Michelsen, A., Olofsson, J., Gwynn-Jones, D., Bokhorst, S., Phoenix, G., Bjerke, J. W., Tommervik, H., Christensen, T. R., Hanna, E., Koller, E. K., and Sloan, V. L.: Ecosystem change and stability over multiple decades in the Swedish subarctic: complex processes and multiple drivers, Philosophical Transactions of the Royal Society B-Biological Sciences, 368,doi: 10.1098/rstb.2012.0488, 2013.

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

Choudhury, B. J., DiGirolamo, N. E., Susskind, J., Darnell, W. L., Gupta, S. K., and Asrar, G.: A biophysical process-based estimate of global land surface evaporation using satellite and ancillary data - II. Regional and global patterns of seasonal and annual variations, Journal of Hydrology, 205, 186-204,doi: 10.1016/s0022-1694(97)00149-2, 1998.

Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, Sarr, A., and Whetton, P.: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2007.2007.

Christensen, T., Jackowicz-Korczynski, M., Aurela, M., Crill, P., Heliasz, M., Mastepanov, M., and Friborg, T.: Monitoring the Multi-Year Carbon Balance of a Subarctic Palsa Mire with Micrometeorological Techniques, Ambio, 41, 207-217,doi: 10.1007/s13280-012-0302-5, 2012.

Christensen, T. R., Johansson, T. R., Akerman, H. J., Mastepanov, M., Malmer, N., Friborg, T., Crill, P., and Svensson, B. H.: Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, Geophysical Research Letters, 31,doi: L04501

10.1029/2003gl018680, 2004.

Clymo, R. S.: The limits to peat bog growth, Philos. Trans. R. Soc. Lond. Ser. B-Biol. Sci., 303, 605-654,doi: 10.1098/rstb.1984.0002, 1984.

Clymo, R. S.: Peat growth, Quaternary Landscapes. Eds Shane LCK, Cushing EJ. Minneapolis, University of Minnesota Press., 1991. 76-1121991.

Clymo, R. S.: Models of peat growth, Suo (Helsinki), 43, 127-136,doi: 10.1007/978-3-642-66760-2_9, 1992.

Clymo, R. S., Turunen, J., and Tolonen, K.: Carbon accumulation in peatland, Oikos, 81, 368-388,doi: 10.2307/3547057, 1998.

Euskirchen, E. S., McGuire, A. D., Kicklighter, D. W., Zhuang, Q., Clein, J. S., Dargaville, R. J., Dye, D. G., Kimball, J. S., McDonald, K. C., Melillo, J. M., Romanovsky, V. E., and Smith, N. V.: Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems, Global Change Biology, 12, 731-750,doi: 10.1111/j.1365-2486.2006.01113.x, 2006.

Fan, Z. S., McGuire, A. D., Turetsky, M. R., Harden, J. W., Waddington, J. M., and Kane, E. S.: The response of soil organic carbon of a rich fen peatland in interior Alaska to projected climate change, Global Change Biology, 19, 604-620,doi: 10.1111/gcb.12041, 2013.

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K. G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate-carbon cycle feedback analysis: Results from the (CMIP)-M-4 model intercomparison, J. Clim., 19, 3337-3353,doi: 10.1175/jcli3800.1, 2006.

Frolking, S., Roulet, N. T., Moore, T. R., Lafleur, P. M., Bubier, J. L., and Crill, P. M.: Modeling seasonal to annual carbon balance of Mer Bleue Bog, Ontario, Canada, Glob. Biogeochem. Cycle, 16,doi: 103010.1029/2001gb001457, 2002.

Frolking, S., Roulet, N. T., Moore, T. R., Richard, P. J. H., Lavoie, M., and Muller, S. D.: Modeling northern peatland decomposition and peat accumulation, Ecosystems, 4, 479-498,doi: 10.1007/s10021-001-0105-1, 2001.

Frolking, S., Roulet, N. T., Tuittila, E., Bubier, J. L., Quillet, A., Talbot, J., and Richard, P. J. H.: A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation, 1 Article, Earth System Dynamics, 1-21 pp., 2010.

Fronzek, S., Luoto, M., and Carter, T. R.: Potential effect of climate change on the distribution of palsa mires in subarctic Fennoscandia, Climate Research, 32, 1-12,doi: 10.3354/cr032001, 2006.

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., and Sitch, S.: Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model, Journal of Hydrology, 286, 249-270,doi: 10.1016/j.jhydrol.2003.09.029, 2004.

Gorham, E.: Northern peatlands - role in the carbon-cycle and probable responses to climatic warming, Ecological Applications, 1, 182-195,doi: 10.2307/1941811, 1991.

Hanna, E., Huybrechts, P., Janssens, I., Cappelen, J., Steffen, K., and Stephens, A.: Runoff and mass balance of the Greenland ice sheet: 1958-2003, J. Geophys. Res.-Atmos., 110,doi: 10.1029/2004jd005641, 2005.

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

Hilbert, D. W., Roulet, N., and Moore, T.: Modelling and analysis of peatlands as dynamical systems, Journal of Ecology, 88, 230-242,doi: 10.1046/j.1365-2745.2000.00438.x, 2000.

Hillel, D.: In: Environmental Soil Physics: Fundamentals, Applications, and Environmental Considerations, 1998.

Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., Griffith, B., Hollister, R. D., Hope, A., Huntington, H. P., Jensen, A. M., Jia, G. J., Jorgenson, T., Kane, D. L., Klein, D. R., Kofinas, G., Lynch, A. H., Lloyd, A. H., McGuire, A. D., Nelson, F. E., Oechel, W. C., Osterkamp, T. E., Racine, C. H., Romanovsky, V. E., Stone, R. S., Stow, D. A., Sturm, M., Tweedie, C. E., Vourlitis, G. L., Walker, M. D., Walker, D. A., Webber, P. J., Welker, J. M., Winker, K., and Yoshikawa, K.: Evidence and implications of recent climate change in northern Alaska and other arctic regions, Clim. Change, 72, 251-298,doi: 10.1007/s10584-005-5352-2, 2005.

Ingram, H. A. P.: Size and shape in raised mire ecosystems - a geophysical model, Nature, 297, 300-303,doi: 10.1038/297300a0, 1982.

IPCC: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013. NY, USA2013.

Ise, T., Dunn, A. L., Wofsy, S. C., and Moorcroft, P. R.: High sensitivity of peat decomposition to climate change through water-table feedback, Nat. Geosci., 1, 763-766,doi: 10.1038/ngeo331, 2008.

Johansson, M., Callaghan, T. V., Bosio, J., Akerman, H. J., Jackowicz-Korczynski, M., and Christensen, T. R.: Rapid responses of permafrost and vegetation to experimentally increased snow cover in sub-arctic Sweden, Environmental Research Letters, 8,doi: 10.1088/1748-9326/8/3/035025, 2013.

Johansson, T., Malmer, N., Crill, P. M., Friborg, T., Akerman, J. H., Mastepanov, M., and Christensen, T. R.: Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing, Global Change Biology, 12, 2352-2369,doi: 10.1111/j.1365-2486.2006.01267.x, 2006.

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

Kokfelt, U., Reuss, N., Struyf, E., Sonesson, M., Rundgren, M., Skog, G., Rosen, P., and Hammarlund, D.: Wetland development, permafrost history and nutrient cycling inferred from late Holocene peat and lake sediment records in subarctic Sweden, J. Paleolimn., 44, 327-342,doi: 10.1007/s10933-010-9406-8, 2010.

Lai, D. Y. F.: Methane Dynamics in Northern Peatlands: A Review, Pedosphere, 19, 409-4212009.

Lindroth, A., Lund, M., Nilsson, M., Aurela, M., Christensen, T. R., Laurila, T., Rinne, J., Riutta, T., Sagerfors, J., Strom, L., Tuovinen, J. P., and Vesala, T.: Environmental controls on the CO2 exchange in north European mires, Tellus Ser. B-Chem. Phys. Meteorol., 59, 812-825,doi: 10.1111/j.1600-0889.2007.00310.x, 2007.

Lloyd, J. and Taylor, J. A.: On the temperature-dependence of soil respiration, Funct. Ecol., 8, 315-323,doi: 10.2307/2389824, 1994.

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

Loranty, M. M. and Goetz, S. J.: Shrub expansion and climate feedbacks in Arctic tundra, Environmental Research Letters, 7, 3,doi: 10.1088/1748-9326/7/1/011005, 2012.

Lund, M., Christensen, T. R., Lindroth, A., and Schubert, P.: Effects of drought conditions on the carbon dioxide dynamics in a temperate peatland, Environmental Research Letters, 7,doi: Artn 04570410.1088/1748-9326/7/4/045704, 2012.

Malmer, N., Johansson, T., Olsrud, M., and Christensen, T. R.: Vegetation, climatic changes and net carbon sequestration in a North-Scandinavian subarctic mire over 30 years, Global Change Biology, 11, 1895-1909,doi: 10.1111/j.1365-2486.2005.01042.x, 2005.

Malmer, N. and Wallen, B.: Peat formation and mass balance in subarctic ombrotrophic peatlands around Abisko, northern Scandinavia. In: Ecological Bulletins; Plant ecology in the subarctic Swedish Lapland, Karlsson, P. S. and Callaghan, T. V. (Eds.), Ecological Bulletins, 1996.

McGuire, A. D., Christensen, T. R., Hayes, D., Heroult, A., Euskirchen, E., Kimball, J. S., Koven, C., Lafleur, P., Miller, P. A., Oechel, W., Peylin, P., Williams, M., and Yi, Y.: An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions, Biogeosciences, 9, 3185-3204,doi: 10.5194/bg-9-3185-2012, 2012.

Miller, P. A., Giesecke, T., Hickler, T., Bradshaw, R. H. W., Smith, B., Seppa, H., Valdes, P. J., and Sykes, M. T.: Exploring climatic and biotic controls on Holocene vegetation change in Fennoscandia, Journal of Ecology, 96, 247-259,doi: 10.1111/j.1365-2745.2007.01342.x, 2008.

Miller, P. A. and Smith, B.: Modelling Tundra Vegetation Response to Recent Arctic Warming, Ambio, 41, 281-291,doi: 10.1007/s13280-012-0306-1, 2012.

Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693-712,doi: 10.1002/joc.1181, 2005.

Moore, T. R., Bubier, J. L., and Bledzki, L.: Litter decomposition in temperate peatland ecosystems: The effect of substrate and site, Ecosystems, 10, 949-963,doi: 10.1007/s10021-007-9064-5, 2007.

Moore, T. R., Bubier, J. L., Frolking, S. E., Lafleur, P. M., and Roulet, N. T.: Plant biomass and production and CO2 exchange in an ombrotrophic bog, Journal of Ecology, 90, 25-36,doi: 10.1046/j.0022-0477.2001.00633.x, 2002.

Morris, P. J., Baird, A. J., and Belyea, L. R.: The DigiBog peatland development model 2: ecohydrological simulations in 2D, Ecohydrology, 5, 256-268,doi: 10.1002/eco.229, 2012.

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747-756,doi: 10.1038/nature08823, 2010.

Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P., and Lindroth, A.: Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire - a significant sink after accounting for all C-fluxes, Global Change Biology, 14, 2317-2332,doi: 10.1111/j.1365-2486.2008.01654.x, 2008.

Novak, M., Brizova, E., Adamova, M., Erbanova, L., and Bottrell, S. H.: Accumulation of organic carbon over the past 150 years in five freshwater peatlands in western and central Europe, Science of the Total Environment, 390, 425-436,doi: 10.1016/j.scitotenv.2007.10.011, 2008.

Nungesser, M. K.: Modelling microtopography in boreal peatlands: hummocks and hollows, Ecological Modelling, 165, 175-207,doi: 10.1016/s0304-3800(03)00067-x, 2003.

Olefeldt, D., Roulet, N. T., Bergeron, O., Crill, P., Backstrand, K., and Christensen, T. R.: Net carbon accumulation of a high-latitude permafrost palsa mire similar to permafrost-free peatlands, Geophysical Research Letters, 39,doi: 10.1029/2011gl050355, 2012.

Pope, V. D., Gallani, M. L., Rowntree, P. R., and Stratton, R. A.: The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3, Clim. Dyn., 16, 123-146,doi: 10.1007/s003820050009, 2000.

Pouliot, R., Rochefort, L., Karofeld, E., and Mercier, C.: Initiation of Sphagnum moss hummocks in bogs and the presence of vascular plants: Is there a link?, Acta Oecol.-Int. J. Ecol., 37, 346-354,doi: 10.1016/j.actao.2011.04.001, 2011.

Robinson, S. D. and Moore, T. R.: The influence of permafrost and fire upon carbon accumulation in high boreal peatlands, Northwest Territories, Canada, Arct. Antarct. Alp. Res., 32, 155-166,doi: 10.2307/1552447, 2000.

Rosswall, T., Veum, A. K., and Karenlampi, L.: Plant litter decomposition at fennoscandian tundra sites, 1975.

Roulet, N. T., Lafleur, P. M., Richard, P. J. H., Moore, T. R., Humphreys, E. R., and Bubier, J.: Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland, Global Change Biology, 13, 397-411,doi: 10.1111/j.1365-2486.2006.01292.x, 2007.

Saelthun, N. R. and Barkved, L.: Climate Change Scenarios for the SCANNET Region, Norsk institutt for vannforskning (NIVA), Rep SNO 4663-2003, 742003.

Schuldt, R. J., Brovkin, V., Kleinen, T., and Winderlich, J.: Modelling Holocene carbon accumulation and methane emissions of boreal wetlands - an Earth system model approach, Biogeosciences, 10, 1659-1674,doi: 10.5194/bg-10-1659-2013, 2013.

Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., and Martikainen, P. J.: CO2 fluxes from peat in boreal mires under varying temperature and moisture conditions, Journal of Ecology, 84, 219-228,doi: 10.2307/2261357, 1996.

Sitch, S., Huntingford, C., Gedney, N., Levy, P. E., Lomas, M., Piao, S. L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C. D., Prentice, I. C., and Woodward, F. I.: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs), Global Change Biology, 14, 2015-2039,doi: 10.1111/j.1365-2486.2008.01626.x, 2008.

Smith, B., Prentice, I. C., and Sykes, M. T.: Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space, Glob. Ecol. Biogeogr., 10, 621-637,doi: 10.1046/j.1466-822X.2001.t01-1-00256.x, 2001.

Smith, B., Warlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., and Zaehle, S.: Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model, Biogeosciences, 11, 2027-2054,doi: 10.5194/bg-11-2027-2014, 2014.

Sonesson, M.: Ecology of a subarctic mire, Swedish Natural Science Research Council., Stockholm, Sweden, 1980.

Stocker, B. D., Spahni, R., and Joos, F.: DYPTOP: a cost-efficient TOPMODEL implementation to simulate sub-grid spatio-temporal dynamics of global wetlands and peatlands, Geosci. Model Dev., 7, 3089-3110,doi: 10.5194/gmd-7-3089-2014, 2014.

Strandberg, G., Kjellstrom, E., Poska, A., Wagner, S., Gaillard, M. J., Trondman, A. K., Mauri, A., Davis, B. A. S., Kaplan, J. O., Birks, H. J. B., Bjune, A. E., Fyfe, R., Giesecke, T., Kalnina, L., Kangur, M., van der Knaap, W. O., Kokfelt, U., Kunes, P., Latalowa, M., Marquer, L., Mazier, F., Nielsen, A. B., Smith, B., Seppa, H., and Sugita, S.: Regional climate model simulations for Europe at 6 and 0.2 k BP: sensitivity to changes in anthropogenic deforestation, Climate of the Past, 10, 661-680,doi: 10.5194/cp-10-661-2014, 2014.

Sullivan, P. F., Arens, S. J. T., Chimner, R. A., and Welker, J. M.: Temperature and microtopography interact to control carbon cycling in a high arctic fen, Ecosystems, 11, 61-76,doi: 10.1007/s10021-007-9107-y, 2008.

Swindles, G. T., Morris, P. J., Mullan, D., Watson, E. J., Turner, T. E., Roland, T. P., Amesbury, M. J., Kokfelt, U., Schoning, K., Pratte, S., Gallego-Sala, A., Charman, D. J., Sanderson, N., Garneau, M., Carrivick, J. L., Woulds, C., Holden, J., Parry, L., and Galloway, J. M.: The long-term fate of permafrost peatlands under rapid climate warming, Sci Rep, 5, 6,doi: 10.1038/srep17951, 2015.

Tang, J., Miller, P. A., Crill, P. M., Olin, S., and Pilesjo, P.: Investigating the influence of two different flow routing algorithms on soil-water-vegetation interactions using the dynamic ecosystem model LPJ-GUESS, Ecohydrology, 8, 570-583,doi: 10.1002/eco.1526, 2015a.

Tang, J., Miller, P. A., Persson, A., Olefeldt, D., Pilesjo, P., Heliasz, M., Jackowicz-Korczynski, M., Yang, Z., Smith, B., Callaghan, T. V., and Christensen, T. R.: Carbon budget estimation of a subarctic catchment using a dynamic ecosystem model at high spatial resolution, Biogeosciences, 12, 2791-2808,doi: 10.5194/bg-12-2791-2015, 2015b.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Glob. Biogeochem. Cycle, 23,doi: Artn Gb202310.1029/2008gb003327, 2009.

Thonicke, K., Venevsky, S., Sitch, S., and Cramer, W.: The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model, Glob. Ecol. Biogeogr., 10, 661-677,doi: DOI 10.1046/j.1466-822x.2001.00175.x, 2001.

Tomlinson, R. W.: Soil carbon stocks and changes in the Republic of Ireland, Journal of Environmental Management, 76, 77-93,doi: 10.1016/j.jenvman.2005.02.001, 2005.

Turunen, J., Tomppo, E., Tolonen, K., and Reinikainen, A.: Estimating carbon accumulation rates of undrained mires in Finland - application to boreal and subarctic regions, Holocene, 12, 69-80,doi: 10.1191/0959683602hl522rp, 2002.

Wania, R., Ross, I., and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 1. Evaluation and sensitivity of physical land surface processes, Glob. Biogeochem. Cycle, 23,doi: Gb301410.1029/2008gb003412, 2009a.

Wania, R., Ross, I., and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 2. Evaluation and sensitivity of vegetation and carbon cycle processes, Glob. Biogeochem. Cycle, 23,doi: Gb301510.1029/2008gb003413, 2009b.

Weltzin, J. F., Harth, C., Bridgham, S. D., Pastor, J., and Vonderharr, M.: Production and microtopography of bog bryophytes: response to warming and water-table manipulations, Oecologia, 128, 557-565,doi: 10.1007/s004420100691, 2001.

Whiting, G. J. and Chanton, J. P.: Primary production control of methane emission from wetlands, Nature, 364, 794-795,doi: 10.1038/364794a0, 1993.

Wieder, R. K.: Past, present, and future peatland carbon balance: An empirical model based on Pb-210-dated cores, Ecological Applications, 11, 327-342,doi: 10.2307/3060892, 2001.

Wu, Y. Q., Verseghy, D. L., and Melton, J. R.: Integrating peatlands into the coupled Canadian Land Surface Scheme (CLASS) v3.6 and the Canadian Terrestrial Ecosystem Model (CTEM) v2.0, Geosci. Model Dev., 9, 2639-2663,doi: 10.5194/gmd-9-2639-2016, 2016.

Yang, Z., Sykes, M. T., Hanna, E., and Callaghan, T. V.: Linking Fine-Scale Sub-Arctic Vegetation Distribution in Complex Topography with Surface-Air-Temperature Modelled at 50-m Resolution, Ambio, 41, 292-302,doi: 10.1007/s13280-012-0307-0, 2012.

Yu, Z. C.: Northern peatland carbon stocks and dynamics: a review, Biogeosciences, 9, 4071-4085,doi: 10.5194/bg-9-4071-2012, 2012.

Yu, Z. C., Beilman, D. W., and Jones, M. C.: Sensitivity of Northern Peatland Carbon Dynamics to Holocene Climate Change. In: Carbon Cycling in Northern Peatlands, Baird, A. J., Belyea, L. R., Comas, X., Reeve, A. S., and Slater, L. D. (Eds.), Geophysical Monograph Series, 2009.

Yu, Z. C., Loisel, J., Brosseau, D. P., Beilman, D. W., and Hunt, S. J.: Global peatland dynamics since the Last Glacial Maximum, Geophysical Research Letters, 37, 5,doi: 10.1029/2010gl043584, 2010.

Yukimoto, S., Adachi, Y., Hosaka, M., Sakami, T., Yoshimura, H., Hirabara, M., Tanaka, T. Y., Shindo, E., Tsujino, H., Deushi, M., Mizuta, R., Yabu, S., Obata, A., Nakano, H., Koshiro, T., Ose, T., and Kitoh, A.: A New Global Climate Model of the Meteorological Research Institute: MRI-CGCM3-Model Description and Basic Performance, J. Meteorol. Soc. Jpn., 90A, 23-64,doi: 10.2151/jmsj.2012-A02, 2012.

Zhang, W., Jansson, C., Miller, P. A., Smith, B., and Samuelsson, P.: Biogeophysical feedbacks enhance the Arctic terrestrial carbon sink in regional Earth system dynamics, Biogeosciences, 11, 5503-5519,doi: 10.5194/bg-11-5503-2014, 2014.

Zimov, S. A., Schuur, E. A. G., and Chapin, F. S.: Permafrost and the global carbon budget, Science, 312, 1612-1613,doi: 10.1126/science.1128908, 2006.

~~References~~

~~Aerts, R., Verhoeven, J. T. A., and Whigham, D. F.: Plant-mediated controls on nutrient cycling in temperate fens and bogs, Journal, 80, 2170-2181,doi: 10.1890/0012-9658(1999)080[2170:pmconc]2.0.co;2, 1999.~~

~~Åkerman, H. J. and Johansson, M.: Thawing permafrost and thicker active layers in sub-arctic Sweden, Permafrost Periglacial Process., 19, 279-292,doi: 10.1002/ppp.626, 2008.~~

~~Ahlström, A., Schurgers, G. & Smith, B. : The large influence of climate model bias on terrestrial carbon cycle simulations, Environmental Research Letters, in press., 2016.~~

~~Ahlström, A., Smith, B., Lindstrom, J., Rummukainen, M., and Uvo, C. B.: GCM characteristics explain the majority of uncertainty in projected 21st century terrestrial ecosystem carbon balance, Biogeosciences, 10, 1517-1528,doi: 10.5194/bg-10-1517-2013, 2013.~~

~~Anav, A., Friedlingstein, P., Kidston, M., Bopp, L., Ciais, P., Cox, P., Jones, C., Jung, M., Myneni, R., and Zhu, Z.: Evaluating the Land and Ocean Components of the Global Carbon Cycle in the CMIP5 Earth System Models, J. Clim., 26, 6801-6843,doi: 10.1175/Jcli-D-12-00417.1, 2013.~~

~~Andersson, S. and Schoning, K.: Surface wetness and mire development during the late Holocene in central Sweden, Boreas, 39, 749-760,doi: 10.1111/j.1502-3885.2010.00157.x, 2010.~~

~~Andrews, T., Gregory, J. M., Webb, M. J., and Taylor, K. E.: Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models, Geophysical Research Letters, 39, 7,doi: 10.1029/2012gl051607, 2012.~~

~~Aurela, M., Laurila, T., and Tuovinen, J. P.: The timing of snow melt controls the annual CO2 balance in a subarctic fen, Geophysical Research Letters, 31, 4,doi: 10.1029/2004gl020315, 2004.~~

~~Aurela, M., Riutta, T., Laurila, T., Tuovinen, J. P., Vesala, T., Tuittila, E. S., Rinne, J., Haapanala, S., and Laine, J.: CO2 exchange of a sedge fen in southern Finland - The impact of a drought period, Tellus Ser. B-Chem. Phys. Meteorol., 59, 826-837,doi: 10.1111/j.1600-0889.2007.00309.x, 2007.~~

~~Belyea, L. R. and Baird, A. J.: Beyond "The limits to peat bog growth": Cross-scale feedback in peatland development, Ecol. Monogr., 76, 299-322,doi: 10.1890/0012-9615(2006)076[0299:btltpb]2.0.co;2, 2006.~~

~~Belyea, L. R. and Malmer, N.: Carbon sequestration in peatland: patterns and mechanisms of response to climate change, Global Change Biology, 10, 1043-1052,doi: 10.1111/j.1529-8817.2003.00783.x, 2004.~~

~~Bubier, J. L., Moore, T. R., and Crosby, G.: Fine-scale vegetation distribution in a cool temperate peatland, Canadian Journal of Botany-Revue Canadienne De Botanique, 84, 910-923,doi: 10.1139/b06-044, 2006.~~

~~Callaghan, T. V., Jonasson, C., Thierfelder, T., Yang, Z. L., Hedenas, H., Johansson, M., Molau, U., Van Bogaert, R., Michelsen, A., Olofsson, J., Gwynn-Jones, D., Bokhorst, S., Phoenix, G., Bjerke, J. W., Tommervik, H., Christensen, T. R., Hanna, E., Koller, E. K., and Sloan, V. L.: Ecosystem change and stability over multiple decades in the Swedish subarctic: complex processes and multiple drivers, Philosophical Transactions of the Royal Society B-Biological Sciences, 368,doi: 10.1098/rstb.2012.0488, 2013.~~

~~Charman, D. J., Beilman, D. W., Blaauw, M., Booth, R. K., Brewer, S., Chambers, F. M., Christen, J. A., Gallego-Sala, A., Harrison, S. P., Hughes, P. D. M., Jackson, S. T., Korhola, A., Mauquoy, D., Mitchell, F. J. G., Prentice, I. C., van der Linden, M., De Vleeschouwer, F., Yu, Z. C., Alm, J., Bauer, I. E., Corish, Y. M. C., Garneau, M., Hohl, V., Huang, Y., Karofeld, E., Le Roux, G., Loisel, J., Moschen, R., Nichols, J. E., Nieminen, T. M., MacDonald, G. M., Phadtare, N. R., Rausch, N., Sillasoo, U., Swindles, G. T., Tuittila, E. S., Ukonmaanaho, L., Valiranta, M., van Bellen, S., van Geel,~~

~~B., Vitt, D. H., and Zhao, Y.: Climate-related changes in peatland carbon accumulation during the last millennium, Biogeosciences, 10, 929-944,doi: 10.5194/bg-10-929-2013, 2013.~~
~~Choudhury, B. J., DiGirolamo, N. E., Susskind, J., Darnell, W. L., Gupta, S. K., and Asrar, G.: A biophysical process-based estimate of global land surface evaporation using satellite and ancillary data - II. Regional and global patterns of seasonal and annual variations, Journal of Hydrology, 205, 186-204,doi: 10.1016/s0022-1694(97)00149-2, 1998.~~
~~Christensen, J. H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, Sarr, A., and Whetton, P.: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2007.2007.~~
~~Christensen, T., Jackowicz-Korczynski, M., Aurela, M., Crill, P., Heliasz, M., Mastepanov, M., and Friborg, T.: Monitoring the Multi-Year Carbon Balance of a Subarctic Palsa Mire with Micrometeorological Techniques, Ambio, 41, 207-217,doi: 10.1007/s13280-012-0302-5, 2012.~~
~~Christensen, T. R., Johansson, T. R., Akerman, H. J., Mastepanov, M., Malmer, N., Friborg, T., Crill, P., and Svensson, B. H.: Thawing sub-arctic permafrost: Effects on vegetation and methane emissions, Geophysical Research Letters, 31,doi: L04501~~
~~10.1029/2003gl018680, 2004.~~
~~Clymo, R. S.: The limits to peat bog growth, Philos. Trans. R. Soc. Lond. Ser. B-Biol. Sci., 303, 605-654,doi: 10.1098/rstb.1984.0002, 1984.~~
~~Clymo, R. S.: Models of peat growth, Suo (Helsinki), 43, 127-136,doi: 10.1007/978-3-642-66760-2_9, 1992.~~
~~Clymo, R. S.: Peat growth, Quaternary Landscapes. Eds Shane LCK, Cushing EJ. Minneapolis, University of Minnesota Press., 1991. 76-1121991.~~
~~Clymo, R. S., Turunen, J., and Tolonen, K.: Carbon accumulation in peatland, Oikos, 81, 368-388,doi: 10.2307/3547057, 1998.~~
~~Crank, J. and Nicolson, P.: A practical method for numerical evaluation of solutions of partial differential equations of the heat-conduction type, Advances in Computational Mathematics, 6, 207-226,doi: 10.1007/bf02127704, 1996.~~
~~Euskirchen, E. S., McGuire, A. D., Kicklighter, D. W., Zhuang, Q., Clein, J. S., Dargaville, R. J., Dye, D. G., Kimball, J. S., McDonald, K. C., Melillo, J. M., Romanovsky, V. E., and Smith, N. V.: Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems, Global Change Biology, 12, 731-750,doi: 10.1111/j.1365-2486.2006.01113.x, 2006.~~
~~Fan, Z. S., McGuire, A. D., Turetsky, M. R., Harden, J. W., Waddington, J. M., and Kane, E. S.: The response of soil organic carbon of a rich fen peatland in interior Alaska to projected climate change, Global Change Biology, 19, 604-620,doi: 10.1111/gcb.12041, 2013.~~
~~Friedlingstein, P., Cox, P., Betts, R., Bopp, L., Von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H. D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schnitzler, K. G., Schnur, R., Strassmann, K., Weaver, A. J., Yoshikawa, C., and Zeng, N.: Climate-carbon cycle feedback analysis: Results from the (CMIP)-M-4 model intercomparison, J. Clim., 19, 3337-3353,doi: 10.1175/jcli3800.1, 2006.~~
~~Frolking, S., Roulet, N. T., Moore, T. R., Lafleur, P. M., Bubier, J. L., and Crill, P. M.: Modeling seasonal to annual carbon balance of Mer Bleue Bog, Ontario, Canada, Glob. Biogeochem. Cycle, 16,doi: 103010.1029/2001gb001457, 2002.~~
~~Frolking, S., Roulet, N. T., Moore, T. R., Richard, P. J. H., Lavoie, M., and Muller, S. D.: Modeling northern peatland decomposition and peat accumulation, Ecosystems, 4, 479-498,doi: 10.1007/s10021-001-0105-1, 2001.~~

~~Frolking, S., Roulet, N. T., Tuittila, E., Bubier, J. L., Quillet, A., Talbot, J., and Richard, P. J. H.: A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation, 1 Article, Earth System Dynamics, 1-21 pp., 2010.~~

~~Fronzek, S., Luoto, M., and Carter, T. R.: Potential effect of climate change on the distribution of palsa mires in subarctic Fennoscandia, Climate Research, 32, 1-12,doi: 10.3354/cr032001, 2006.~~

~~Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., and Sitch, S.: Terrestrial vegetation and water balance - hydrological evaluation of a dynamic global vegetation model, Journal of Hydrology, 286, 249-270,doi: 10.1016/j.jhydrol.2003.09.029, 2004.~~

~~Gorham, E.: Northern peatlands - role in the carbon-cycle and probable responses to climatic warming, Ecological Applications, 1, 182-195,doi: 10.2307/1941811, 1991.~~

~~Hanna, E., Huybrechts, P., Janssens, I., Cappelen, J., Steffen, K., and Stephens, A.: Runoff and mass balance of the Greenland ice sheet: 1958-2003, J. Geophys. Res.-Atmos., 110,doi: 10.1029/2004jd005641, 2005.~~

~~Hilbert, D. W., Roulet, N., and Moore, T.: Modelling and analysis of peatlands as dynamical systems, Journal of Ecology, 88, 230-242,doi: 10.1046/j.1365-2745.2000.00438.x, 2000.~~

~~Hillel, D.: In: Environmental Soil Physics: Fundamentals, Applications, and Environmental Considerations, 1998.~~

~~Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin, F. S., Dyurgerov, M. B., Fastie, C. L., Griffith, B., Hollister, R. D., Hope, A., Huntington, H. P., Jensen, A. M., Jia, G. J., Jorgenson, T., Kane, D. L., Klein, D. R., Kofinas, G., Lynch, A. H., Lloyd, A. H., McGuire, A. D., Nelson, F. E., Oechel, W. C., Osterkamp, T. E., Racine, C. H., Romanovsky, V. E., Stone, R. S., Stow, D. A., Sturm, M., Tweedie, C. E., Vourlitis, G. L., Walker, M. D., Walker, D. A., Webber, P. J., Welker, J. M., Winker, K., and Yoshikawa, K.: Evidence and implications of recent climate change in northern Alaska and other arctic regions, Clim. Change, 72, 251-298,doi: 10.1007/s10584-005-5352-2, 2005.~~

~~IPCC: Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013. NY, USA2013.~~

~~Ise, T., Dunn, A. L., Wofsy, S. C., and Moorcroft, P. R.: High sensitivity of peat decomposition to climate change through water-table feedback, Nat. Geosci., 1, 763-766,doi: 10.1038/ngeo331, 2008.~~

~~Johansson, M., Callaghan, T. V., Bosio, J., Akerman, H. J., Jackowicz-Korczynski, M., and Christensen, T. R.: Rapid responses of permafrost and vegetation to experimentally increased snow cover in sub-arctic Sweden, Environmental Research Letters, 8,doi: 10.1088/1748-9326/8/3/035025, 2013.~~

~~Johansson, T., Malmer, N., Crill, P. M., Friborg, T., Akerman, J. H., Mastepanov, M., and Christensen, T. R.: Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing, Global Change Biology, 12, 2352-2369,doi: 10.1111/j.1365-2486.2006.01267.x, 2006.~~

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

~~Kokfelt, U., Reuss, N., Struyf, E., Sonesson, M., Rundgren, M., Skog, G., Rosen, P., and Hammarlund, D.: Wetland development, permafrost history and nutrient cycling inferred from late Holocene peat and lake sediment records in subarctic Sweden, J. Paleolimn., 44, 327-342,doi: 10.1007/s10933-010-9406-8, 2010.~~

~~Lafleur, P. M., Roulet, N. T., Bubier, J. L., Frolking, S., and Moore, T. R.: Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog, Glob. Biogeochem. Cycle, 17,doi: 10.1029/2002gb001983, 2003.~~

~~Lai, D. Y. F.: Methane Dynamics in Northern Peatlands: A Review, Pedosphere, 19, 409-4212009.~~

~~Lindroth, A., Lund, M., Nilsson, M., Aurela, M., Christensen, T. R., Laurila, T., Rinne, J., Riutta, T., Sagerfors, J., Strom, L., Tuovinen, J. P., and Vesala, T.: Environmental controls on the CO2 exchange in north European mires, Tellus Ser. B-Chem. Phys. Meteorol., 59, 812-825,doi: 10.1111/j.1600-0889.2007.00310.x, 2007.~~

~~Lloyd, J. and Taylor, J. A.: On the temperature-dependence of soil respiration, Funct. Ecol., 8, 315-323,doi: 10.2307/2389824, 1994.~~

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

~~Loranty, M. M. and Goetz, S. J.: Shrub expansion and climate feedbacks in Arctic tundra, Environmental Research Letters, 7, 3,doi: 10.1088/1748-9326/7/1/011005, 2012.~~

~~Lund, M., Lindroth, A., Christensen, T. R., and Strom, L.: Annual CO2 balance of a temperate bog, Tellus Ser. B-Chem. Phys. Meteorol., 59, 804-811,doi: 10.1111/j.1600-0889.2007.00303.x, 2007.~~

~~Makila, M., Saarnisto, M., and Kankainen, T.: Aapa mires as a carbon sink and source during the Holocene, Journal of Ecology, 89, 589-599,doi: 10.1046/j.0022-0477.2001.00586.x, 2001.~~

~~Malmer, N., Johansson, T., Olsrud, M., and Christensen, T. R.: Vegetation, climatic changes and net carbon sequestration in a North-Scandinavian subarctic mire over 30 years, Global Change Biology, 11, 1895-1909,doi: 10.1111/j.1365-2486.2005.01042.x, 2005.~~

~~Malmer, N. and Wallen, B.: Peat formation and mass balance in subarctic ombrotrophic peatlands around Abisko, northern Scandinavia. In: Ecological Bulletins; Plant ecology in the subarctic Swedish Lapland, Karlsson, P. S. and Callaghan, T. V. (Eds.), Ecological Bulletins, 1996.~~

~~McGuire, A. D., Christensen, T. R., Hayes, D., Heroult, A., Euskirchen, E., Kimball, J. S., Koven, C., Lafleur, P., Miller, P. A., Oechel, W., Peylin, P., Williams, M., and Yi, Y.: An assessment of the carbon balance of Arctic tundra: comparisons among observations, process models, and atmospheric inversions, Biogeosciences, 9, 3185-3204,doi: 10.5194/bg-9-3185-2012, 2012.~~

~~Miller, P. A., Giesecke, T., Hickler, T., Bradshaw, R. H. W., Smith, B., Seppa, H., Valdes, P. J., and Sykes, M. T.: Exploring climatic and biotic controls on Holocene vegetation change in Fennoscandia, Journal of Ecology, 96, 247-259,doi: 10.1111/j.1365-2745.2007.01342.x, 2008.~~

~~Miller, P. A. and Smith, B.: Modelling Tundra Vegetation Response to Recent Arctic Warming, Ambio, 41, 281-291,doi: 10.1007/s13280-012-0306-1, 2012.~~

~~Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, Int. J. Climatol., 25, 693-712,doi: 10.1002/joc.1181, 2005.~~

~~Moore, T. R., Bubier, J. L., and Bledzki, L.: Litter decomposition in temperate peatland ecosystems: The effect of substrate and site, Ecosystems, 10, 949-963,doi: 10.1007/s10021-007-9064-5, 2007.~~

~~Moore, T. R., Bubier, J. L., Frolking, S. E., Lafleur, P. M., and Roulet, N. T.: Plant biomass and production and CO2 exchange in an ombrotrophic bog, Journal of Ecology, 90, 25-36,doi: 10.1046/j.0022-0477.2001.00633.x, 2002.~~

~~Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., Carter, T. R., Emori, S., Kainuma, M., Kram, T., Meehl, G. A., Mitchell, J. F. B., Nakicenovic, N., Riahi, K., Smith, S. J., Stouffer, R. J., Thomson, A. M., Weyant, J. P., and Wilbanks, T. J.: The next generation of scenarios for climate change research and assessment, Nature, 463, 747-756,doi: 10.1038/nature08823, 2010.~~

~~Nilsson, M., Sagerfors, J., Buffam, I., Laudon, H., Eriksson, T., Grelle, A., Klemedtsson, L., Weslien, P., and Lindroth, A.: Contemporary carbon accumulation in a boreal oligotrophic minerogenic mire - a significant sink after accounting for all C-fluxes, Global Change Biology, 14, 2317-2332,doi: 10.1111/j.1365-2486.2008.01654.x, 2008.~~

~~Nungesser, M. K.: Modelling microtopography in boreal peatlands: hummocks and hollows, Ecological Modelling, 165, 175-207,doi: 10.1016/s0304-3800(03)00067-x, 2003.~~

~~Olefeldt, D., Roulet, N. T., Bergeron, O., Crill, P., Backstrand, K., and Christensen, T. R.: Net carbon accumulation of a high-latitude permafrost palsa mire similar to permafrost-free peatlands, Geophysical Research Letters, 39,doi: 10.1029/2011gl050355, 2012.~~

~~Pope, V. D., Gallani, M. L., Rowntree, P. R., and Stratton, R. A.: The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3, Clim. Dyn., 16, 123-146,doi: 10.1007/s003820050009, 2000.~~

~~Pouliot, R., Rochefort, L., Karofeld, E., and Mercier, C.: Initiation of Sphagnum moss hummocks in bogs and the presence of vascular plants: Is there a link?, Acta Oecol.-Int. J. Ecol., 37, 346-354,doi: 10.1016/j.actao.2011.04.001, 2011.~~

~~Robinson, S. D. and Moore, T. R.: The influence of permafrost and fire upon carbon accumulation in high boreal peatlands, Northwest Territories, Canada, Arct. Antarct. Alp. Res., 32, 155-166,doi: 10.2307/1552447, 2000.~~

~~Rosswall, T., Veum, A. K., and Karenlampi, L.: Plant litter decomposition at fennoscandian tundra sites, 1975.~~

~~Roulet, N. T., Lafleur, P. M., Richard, P. J. H., Moore, T. R., Humphreys, E. R., and Bubier, J.: Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland, Global Change Biology, 13, 397-411,doi: 10.1111/j.1365-2486.2006.01292.x, 2007.~~

~~Saelthun, N. R. and Barkved, L.: Climate Change Scenarios for the SCANNET Region, Norsk institutt for vannforskning (NIVA), Rep SNO 4663-2003, 742003.~~

~~Sagerfors, J., Lindroth, A., Grelle, A., Klemedtsson, L., Weslien, P., and Nilsson, M.: Annual CO2 exchange between a nutrient-poor, minerotrophic, boreal mire and the atmosphere, Journal of Geophysical Research-Biogeosciences, 113, 15,doi: 10.1029/2006jg000306, 2008.~~

~~Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., and Martikainen, P. J.: CO2 fluxes from peat in boreal mires under varying temperature and moisture conditions, Journal of Ecology, 84, 219-228,doi: 10.2307/2261357, 1996.~~

~~Sitch, S., Huntingford, C., Gedney, N., Levy, P. E., Lomas, M., Piao, S. L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C. D., Prentice, I. C., and Woodward, F. I.: Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs), Global Change Biology, 14, 2015-2039,doi: 10.1111/j.1365-2486.2008.01626.x, 2008.~~

~~Smith, B., Prentice, I. C., and Sykes, M. T.: Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space, Glob. Ecol. Biogeogr., 10, 621-637,doi: 10.1046/j.1466-822X.2001.t01-1-00256.x, 2001.~~

~~Sonesson, M.: Ecology of a subarctic mire, Swedish Natural Science Research Council., Stockholm, Sweden, 1980.~~

~~Strandberg, G., Kjellstrom, E., Poska, A., Wagner, S., Gaillard, M. J., Trondman, A. K., Mauri, A., Davis, B. A. S., Kaplan, J. O., Birks, H. J. B., Bjune, A. E., Fyfe, R., Giesecke, T., Kalnina, L., Kangur, M., van der Knaap, W. O., Kokfelt, U., Kunes, P., Latalowa, M., Marquer, L., Mazier, F., Nielsen, A. B., Smith, B., Seppa, H., and Sugita, S.: Regional climate model simulations for Europe at 6 and 0.2 k BP: sensitivity to changes in anthropogenic deforestation, Climate of the Past, 10, 661-680,doi: 10.5194/cp-10-661-2014, 2014.~~

~~Sturm, M., Schimel, J., Michaelson, G., Welker, J. M., Oberbauer, S. F., Liston, G. E., Fahnestock, J., and Romanovsky, V. E.: Winter biological processes could help convert arctic tundra to shrubland, Bioscience, 55, 17-26,doi: 10.1641/0006-3568(2005)055[0017:wbpchc]2.0.co;2, 2005.~~

~~Sullivan, P. F., Arens, S. J. T., Chimner, R. A., and Welker, J. M.: Temperature and microtopography interact to control carbon cycling in a high arctic fen, Ecosystems, 11, 61-76,doi: 10.1007/s10021-007-9107-y, 2008.~~

~~Tang, J., Miller, P. A., Crill, P. M., Olin, S., and Pilesjo, P.: Investigating the influence of two different flow routing algorithms on soil-water-vegetation interactions using the dynamic ecosystem model LPJ-GUESS, Ecohydrology, 8, 570-583,doi: 10.1002/eco.1526, 2015.~~

~~Tang, J., Miller, P. A., Persson, A., Olefeldt, D., Pilesjo, P., Heliasz, M., Jackowicz-Korczynski, M., Yang, Z., Smith, B., Callaghan, T. V., and Christensen, T. R.: Carbon budget estimation of a subarctic~~

~~catchment using a dynamic ecosystem model at high spatial resolution, Biogeosciences, 12, 2791-2808,doi: 10.5194/bg-12-2791-2015, 2015b.~~

~~Thonicke, K., Venevsky, S., Sitch, S., and Cramer, W.: The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model, Glob. Ecol. Biogeogr., 10, 661-677,doi: DOI 10.1046/j.1466-822x.2001.00175.x, 2001.~~

~~Tuittila, E. S., Valiranta, M., Laine, J., and Korhola, A.: Quantifying patterns and controls of mire vegetation succession in a southern boreal bog in Finland using partial ordinations, Journal of Vegetation Science, 18, 891-902,doi: 10.1111/j.1654-1103.2007.tb02605.x, 2007.~~

~~Turunen, J., Tomppo, E., Tolonen, K., and Reinikainen, A.: Estimating carbon accumulation rates of undrained mires in Finland - application to boreal and subarctic regions, Holocene, 12, 69-80,doi: 10.1191/0959683602hl522rp, 2002.~~

~~Valiranta, M., Korhola, A., Seppa, H., Tuittila, E. S., Sarmaja-Korjonen, K., Laine, J., and Alm, J.: High-resolution reconstruction of wetness dynamics in a southern boreal raised bog, Finland, during the late Holocene: a quantitative approach, Holocene, 17, 1093-1107,doi: 10.1177/0959683607082550, 2007.~~

~~Wania, R., Ross, I., and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 1. Evaluation and sensitivity of physical land surface processes, Glob. Biogeochem. Cycle, 23,doi: Gb3014~~
~~10.1029/2008gb003412, 2009a.~~

~~Wania, R., Ross, I., and Prentice, I. C.: Integrating peatlands and permafrost into a dynamic global vegetation model: 2. Evaluation and sensitivity of vegetation and carbon cycle processes, Glob. Biogeochem. Cycle, 23,doi: Gb3015~~
~~10.1029/2008gb003413, 2009b.~~

~~Weltzin, J. F., Harth, C., Bridgham, S. D., Pastor, J., and Vonderharr, M.: Production and microtopography of bog bryophytes: response to warming and water-table manipulations, Oecologia, 128, 557-565,doi: 10.1007/s004420100691, 2001.~~

~~Whiting, G. J. and Chanton, J. P.: Primary production control of methane emission from wetlands, Nature, 364, 794-795,doi: 10.1038/364794a0, 1993.~~

~~Wieder, R. K.: Past, present, and future peatland carbon balance: An empirical model based on Pb-210-dated cores, Ecological Applications, 11, 327-342,doi: 10.2307/3060892, 2001.~~

~~Yang, Z., Sykes, M. T., Hanna, E., and Callaghan, T. V.: Linking Fine-Scale Sub-Arctic Vegetation Distribution in Complex Topography with Surface-Air-Temperature Modelled at 50-m Resolution, Ambio, 41, 292-302,doi: 10.1007/s13280-012-0307-0, 2012.~~

~~Yu, Z. C.: Northern peatland carbon stocks and dynamics: a review, Biogeosciences, 9, 4071-4085,doi: 10.5194/bg-9-4071-2012, 2012.~~

~~Yu, Z. C., Beilman, D. W., and Jones, M. C.: Sensitivity of Northern Peatland Carbon Dynamics to Holocene Climate Change. In: Carbon Cycling in Northern Peatlands, Baird, A. J., Belyea, L. R., Comas, X., Reeve, A. S., and Slater, L. D. (Eds.), Geophysical Monograph Series, 2009.~~

~~Yu, Z. C., Loisel, J., Brosseau, D. P., Beilman, D. W., and Hunt, S. J.: Global peatland dynamics since the Last Glacial Maximum, Geophysical Research Letters, 37, 5,doi: 10.1029/2010gl043584, 2010.~~

~~Yukimoto, S., Adachi, Y., Hosaka, M., Sakami, T., Yoshimura, H., Hirabara, M., Tanaka, T. Y., Shindo, E., Tsujino, H., Deushi, M., Mizuta, R., Yabu, S., Obata, A., Nakano, H., Koshiro, T., Ose, T., and Kitoh, A.: A New Global Climate Model of the Meteorological Research Institute: MRI-CGCM3-Model Description and Basic Performance, J. Meteorol. Soc. Jpn., 90A, 23-64,doi: 10.2151/jmsj.2012-A02, 2012.~~

~~Zhang, W., Jansson, C., Miller, P. A., Smith, B., and Samuelsson, P.: Biogeophysical feedbacks enhance the Arctic terrestrial carbon sink in regional Earth system dynamics, Biogeosciences, 11, 5503-5519,doi: 10.5194/bg-11-5503-2014, 2014.~~

~~Zimov, S. A., Schuur, E. A. G., and Chapin, F. S.: Permafrost and the global carbon budget, Science, 312, 1612-1613,doi: 10.1126/science.1128908, 2006.~~