Biogeosciences
Discussions

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Interactive comment on "Modeling the hydrology and physiology of *Sphagnum* moss in a northern temperate bog" *by* Xiaoying Shi et al.

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Reviewer 2

In this study, new plant functional type (PFT) describing Sphagnum –moss, abundant in boreal and arctic peatlands, is incorporated into the land model component ELM of the Earth System model E3SM to better represent carbon, water and nutrient cycling in boreal and arctic regions. The ELM with the newly proposed Sphagnum-PFT was parameterized and evaluated against data collected under ambient conditions and under climate-change experiment conducted at an ombrothrophic bog in Minnesota, US. Further, the model is used to predict changes in moss and vascular plant productivity, biomass accumulation and water table level for combined temperature and CO_2

increase scenarios. The article is well written and fits topically under the scope of BG. However, the relevance for larger scientific community is limited as the study is centered on development of a specific land model and testing for a specific site. I therefore consider the study as border line case for BG and maybe fits better into a more specific model development journal such as Geoscientific Model Development. However, this is up to the Editor to decide.

The primary goal of the SPRUCE project is to test how vulnerable an important Carbon-rich terrestrial ecosystem is to atmospheric and climatic change by warming the entire soil profile and measuring whether large amounts of CO_2 and CH_4 are emitted The regression design allows the derivation of key temperature response functions for mechanistic ecosystem processes that can be used for model validation and improvement. In this study, we introduce a moss PFT into the land model component (ELM) of the Energy Exascale Earth System Model (E3SM). Then, we evaluate our updated model against numerous measurements. We also apply the updated ELM to explore how an ombrotrophic, raised-dome bog peatland ecosystem will respond to different scenarios of warming and elevated atmospheric CO_2 concentration. The model development is only part of our goal, and we mainly focus on using the model to investigate the peatland ecosystem responses to changing climate and the feedbacks.

In recent years there has been strong interest on including Sphagnum as well as feather mosses and other bryophytes into land-surface models. In addition to the references listed in the Introduction the authors should take a look and cite the recent works of Philip Porada and colleagues (Porada et al., 2013, 2016), as well as note the inclusion of moss-PFT into ORCHIDEE-model (Druel et al., 2017). The authors should also be more explicit how their study builds on and improves the existing knowledge and methods to describe Sphagnum mosses in land surface models. If the study is to be published in BG, the results and methods should in my opinion be generalized and better interpreted against existing literature. Currently, the discussion, in particular Section 5.3, reads more as a research plan for future development of a specific land

surface model.

We had added "Druel et al. (2017) investigated the vegetation-climate feedbacks in high latitudes by implementing the nonvascular plants including bryophytes and lichens to the global land surface model ORCHIFEE. Porada et al. (2016) integrated a stand-alone dynamic non-vascular vegetation model LiBry (Porada et al., 2013) to land surface scheme JSBACH, but LiBry and JSBACH mainly represent bryophyte and lichen growth on upland forest floor sites, not for wetland sites. Chadburn et al. (2015) introduced a new moss PFT to JULES land surface model and treated the thermal conductivity of moss depending on its water content." to the introduction Section and cited these literatures (L137-144). We also added a new section '2.2 Non-vascular plants: Sphagnum mosses' to Section 2 Model description to describe more details how we implement our Sphagnum mosses into our model (L184-199). For the future model development Section 5.3, we embedded into Section 5.1 and 5.2 as the other reviewer also suggested.

My general comments are as follows: 1) Modeling Sphagnum water content Sphagnum total water content is sum of two pools: $W_{tot} = W_{internal} + W_{surface}$ There are few remarks / comments that should be made. First, $W_{internal}$ is described as non-linear function of top soil water content and thus immediately adjust to changes in soil water content (or water table). This approach thus assumes that in Sphagnum, $W_{internal}$ is at hydrostatic equilibrium with soil water potential (or water content) as defined through water-retention characteristics of the peat-Sphagnum continuum. Moreover, it assumes that hydraulic conductivity is sufficiently large so that Sphagnum water content is never decoupled from soil water content. Such assumptions may not hold in case water table (WT) drops deep during prolonged dry periods, more propable in future climat

The equilibration time between peat moisture and moss water content is reasonable fast, but the timescales for rewetting should change as the peat dries since the cross section for capillary rise will decline and thus the maximum flux to the surface will

decline. So at some point, between gravity potential and reduced hydraulic conductivity the capillarity will not satisfy evaporative demand. But for the simplicity, we currently used the empirical representation of water content in our model for both hummock and hollow Sphagnum (as we responded above for the first viewer's comment).The function of Sphagnum water content to soil water content or to water table depth used by Walker et al. (2017) for the same site was empirical and may not be representative for the peatland ecosystem. We will treat Sphagnum as the top soil layer to allow water movement to occur along pressure gradients and thus consistently simulate Sphagnum water content. These related contents have been added to the discussion Section 5.1 L 678-739.

What is author's conclusion on generality of $W_{internal}$ – soil water content relationship (Fig. 1) among Sphagnum species (hummock vs. hollow –preferences)? And how $W_{internal}$ and $W_{external}$ pools were separated from the gravimetric measurements of water content in Sphagnum to derive relationship between $W_{internal}$ and soil water content?

During the calibrations, we used intact monoliths collected from multiple locations. The monoliths included both hummock and hollow species, but they were not separated during destructive measurements, since we needed an integrated measurement for comparison against the subsurface soil water content sensors. We have clarified this information to the water content dynamics of Sphagnum mosses Section (L215-220). "There are large differences in the density and traits of the different species and microtopography that would result in different relationships with soil water content. This is a difficult problem since the heterogeneity of the hummock hollow ecosystem is so great. Even so, our calibrations and measurements represent a strong effort to help reduce the uncertainty. Other efforts have not been as successful, including using remote sensed water band index and destructive surface sampling for stable water isotopes. We continue to explore new non-destructive measurements, including leaf wetness sensors, and hope to refine the measurements as the project evolves." has

been added to discussion Section 5.1 L723-731.

Second, the Wsurface is filled by interception of rainfall (how about condensation?) and drained by evaporation. I wonder how the surface storage capacity is described and parameterized and whether Wsurface and Winteral are completely independent water pools? See also Porada et al. (2018).

Surface storage of Sphagnum is described in Eq. 2 (the ELM default algorithms for representing canopy water, details as described by Oleson et al., 2013). The Sphagnum moss canopy water (canopy_water) is simulated by a function of interception, canopy drip, dew (was added to L240) and canopy evaporation.We treat Wsurface and Winternal as independent pools. Porada et al. (2018) used a process-based numerical simulation model to show that non-vascular vegetation contributes substantially to global rainfall interception and it was an interesting paper.

Third, the authors should describe how evapo(transpi)ration from Sphagnum-PFT is modeled and how it differs from vascular-PFT's. From which water pools evaporation takes place and how evaporation rate or surface conductance depend on Sphagnum characteristics and near-ground microclimate. How and whether evaporation is restricted with decreasing water content? This is required to understand e.g. how SLA and leaf C:N ratio can affect evapotranspiration and interpret the results of sensitivity analysis in Fig 2.

We use the same framework as for vascular PFTs (as described in the new Section 2.2 Non-vascular plants: Sphagnum mosses, L184-199), but the Ball-Berry slope term is assumed to be zero and the intercept term is the conductance term as a function of water content. Drying impacts the conductance and affects evaporation of the internal water. The SLA and leaf C:N ratio parameters are strong controls on Vcmax, and therefore overall productivity and Sphagnum moss LAI. The high sensitivities occur because LAI is a strong control on evapo(transp)iration.

2) Modeling Sphagnum photosynthesis Standard Farquhar-approach is used to sim-

ulate Sphagnum net CO_2 demand given air chloroplast conductance described as non-linear function of Wtot (eq. 6, from Williams and Flanagan, 1998). In addition, submerging of Sphagnum is assumed to 'kill' CO_2 diffusion and thus a restriction to photosynthetic uptake is applied and described as linear function of submerged to total photosynthesizing height (here 0.05m) of the moss. Does the implementation of moss photosynthesis follow Walker et al. (2017)?

Walker et al. also uses the conductance equation from Williams and Flanagan but has a different implementation of the Farquhar model and did not calculate evaporation from the Sphagnum surface. We have added "Submergence in Walker et al. (2017) was expressed as photosynthesising stem area index (SAI) as a logistic function of water table depth. Maximum SAI of 3 was used and the parameter combination that most closely described the GPP data gave a range of water table depth from -10 cm for complete submergence and SAI of ~2.5 at 10 cm. This allowed for a range of processes such as floatation of Sphagnum with the water table, and adhesion of water to the Sphagnum capitula." to main text L308-313.

I like the approach but wonder whether the relatively poor match between modeled and 'measured' moss GPP (Fig 3) can be due i) to ill-represented or omitted temperature response or seasonal acclimation of Vcmax etc., ii) biased Sphagnum temperature (how was it modeled – from surface energy balance?) or ii) too strong submerge-impact. As Sphagnum moss has high leaf (or shoot) area, radiation decays rapidly with canopy depth and thus the top centimeter(s) of the shoot system are responsible of majority of photosynthetic activity. For instance, Niinemets and Tobias (2014) and Zotz and Kahler (2007) show light attenuation profiles and photosynthesis profiles for some moss species. Considering typical characteristics (color) of Sphagnum-canopy, assuming CO_2 uptake is evenly distributed across top 5cm may lead to overestimated submerge-impact.

We use the default formulation for acclimation of Vcmax in ELM which is based on a 10-day mean growing temperature. At this point we don't have sufficient measure-

ments to test this assumption,but we can prioritize these measurements in the future. Sphagnum temperature is computed from surface energy balance but because we don't consider the shading effects from trees and shrubs, this may be overestimated. Biases in predicted water table height contribute to errors in the calculated submergence effect. Improving these biases and assuming an exponential rather than a linear CO_2 uptake profile may improve representation of the submergence effect. All these aspects may be attribute to the biases of simulated Sphagnum GPP We can consider this in the future when we have more detailed measurements. We have added this content to discussion Section 5.1 L 652-662.

I also wonder whether the soil-respired CO_2 leads the Sphagnum to operate in CO_2 enriched atmosphere already in current conditions and whether this would lead to overestimated increase of GPP at 900 ppm as photosynthetic CO_2-response curve has saturating shape?

"Preliminary isotopic measurements imply a significant fraction of carbon assimilated by the moss may come from subsurface respired CO_2 (i.e., CO_2 with older 14C signatures predating bomb carbon that can only be sourced from deeper peat, Hanson et al. 2017). However, the observed elevated CO_2 response is smaller than simulated (Hanson et al., 2020). Understanding the drivers of elevated CO_2 response or lack thereof is a key topic for future work and we will consider this effect in future assessments of the isotopic C budgets for the SPRUCE study." was added to L856-863.

In results L530-534 it is stated that modeled Sphagnum biomass correlates with water table and best correlation is found at with 3-month timelag. For GPP and NPP the instantaneous dependence on WT is from Fig 1. and eq. 6. Please describe how NPP is allocated into biomass and how the growth dynamics of Sphagnum-PFT is modeled; can this explain the timelag?

"NPP is allocated instantaneously into biomass. A positive NPP anomaly caused by water table shifts leads to higher LAI, which also increases future productivity for some

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amount of time even if the water table returns to normal. Sphagnum biomass has a 1-year turnover time in the simulation. This combination of effects leads to a roughly 3-month timelag." has been added to L606-610.

3) Modeled carbon cycle components and responses to warming and elevated CO_2 For the reader to understand the modeled carbon cycle responses, it is necessary that ELM 'tiling scheme', pathway from NPP to biomass growth and between-PFT competition are better described in Section 2.1 and/or 3.3. That is, present information such as L627-634 earlier in the manuscript. Are shrubs and Sphagnum present as independent tiles or do they occur below the overstory trees?

The default ELM has 16 PFTs and bare ground. For this study, we only included 4 PFTs which are the dominant PFTs for our study site, including boreal evergreen needleleaf tree (Picea), boreal deciduous needleleaf tree (Larix), boreal deciduous shrub (representing several shrub species), and the newly introduced Sphagnum moss PFT (we already mentioned in 3.3 Section, L363-366). Based on the reviewer's suggestion, we moved the related content 'Currently ELM_SPRUCE does not include light competition among multiple PFTs, and thus does not represent cross-PFT shading effects. Our model also allows the canopy density of PFTs to change prognostically, and their fraction cover held constant.' from the original L 627-634 to Section 3.3 L 366-369.

4) Title: "Modeling the hydrology and physiology of Sphagnum moss in a northern temperate bog" should be revised to match the manuscript content. The study is on extending the land-surfacemodel with Sphagnum-PFT and simulating response of moss and vascular vegetation productivity to warming and increasing atmospheric CO_2.

We plan to use this as the title "Extending a land-surface model with Sphagnum moss to simulate responses of a northern temperate bog to whole-ecosystem warming and elevated CO_2".

Specific comments: L98: water and exchanges within peatland and between peatland and atmosphere?

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we already modified the related content to 'water and exchanges within peatland and between peatland and atmosphere (L100-101).'

L 146-147: new chapter – study Aims.

A new paragraph to show the study objective starts with L157 'In this study, we introduce a new Sphagnum moss PFT into the model. . .' as suggested.

L178-179: Evaporation depends on evaporative demand (VPD; available energy), moss-atmosphere conductance (moss canopy structure, roughness and flow characteristics) and available water pool. The latter is then depends on capillary rise from water table.

We rewrote the related content to 'Since evaporation at the Sphagnum surface depends on atmospheric water vapor deficit, moss-atmosphere conductance and available water pool which depends on capillary wicking of water up to the surface' (L211-213)

L196: canopy_water _ can_water

Thank you for catching this point. We changed canopy_water to can_water (L239).

L211: eq. 6 uses total water content, not Winternal

We used the total water content to calculate the total conductance to CO2 in equation 6, which is consistent with Williams and Flanagan (1998) and Goetz and Price (2015). We reorganized this paragraph and got rid of 'The internal water content of Sphagnum mosses is observed to affect photosynthesis by constraining the length of the diffusive path for CO2 through the variably-hydrated external hyaline cells to the carbon fixation sites (Robroek et al., 2009; Rydin and Jeglum, 2006)'. (L256-264)

L238-239: this assumes boundary-layer conductance » moss surface – chloroplast conductance; assumption is ok but could be mentioned. Note also that maximum g_tc may vary among Sphagnum species?

We added the related content "To be noted that we assume that the boundary layer

conductance is greater than moss surface layer conductance, and the moss surface layer conductance is greater than chloroplast conductance." to the manuscript to L302-304.

L284: what is pre-treatment data?

Pre-treatment data is the data which was collected prior to initiation of the warming and CO2 treatments, and this was added to L349-350.

L363-367: please elaborate whether the data used in parameter optimization is independent of data used in model testing (Fig. 3-4)

The sphagnum GPP in Fig. 3 was not used in the parameter optimization. For the Fig.4, the sphagnum NPP of year 2015-2017 is independent of the optimization, and only above biomass of trees and stem carbon of shrub for year 2012 and 2013 was used for the optimization. We added the years for the data which were used to constrain the model (L433-437), and also added the explanation to Fig.3 and 4 legend.

L393: point should be (*)

Thank you for pointing this out. We changed from point to * (L463).

L479-480: Just curious - why year 2012 was an exception? Were env. drivers different?

Sphagnum production in 2012 was high primarily because of especially high productivity in the hollows during the summer.We double checked the climatical forcing data and did not find the temperature and precipitation were abnormal for year 2012.

L522: Fig. 5: what is driving the strong inter-annual variability of Sphagnum and shrub NPP (annual variability has different sign among these PFT's). Is this mainly due to WT height and does root zone water content affect vascular PFT photosynthesis (O2-stress in wet conditions)?

There are strong inter-annual variabilities of Sphagnum and shrub NPP. For example，the variabilities of Sphagnum and shrub have different signs for years 2020 and

2021 (Fig.5). We compared the BTRAN (representing soil water stress) of shrub for these two years and found that BTRAN may be the driving factor of shrub's variability. The hummock Sphagnum inter-annual variability is mainly driven by water table height with about 3-month lag (Fig.6). The hollow Sphagnum NPP of year 2020 for +0.00oC, +2.25oC, + 4.5oC and +6.75oC temperature levels is lower than the corresponding NPP of year 2021, but it is the opposite way for the +9.00oC condition. The water table is higher for year 2020 than that of year 2021.This implicated that the submerge effect influences the inter-annual variability of hollow Sphagnum NPP. But the inter-annual variabilities are very complicated and it is out of our scope for this study. Thus, we do not plan to include this content to the manuscript text. In addition, we don't currently model the effects of O2 stress in the root zone.

L616-618: this is quite trivial result as Sphagnum water content was made proportional to soil water content (and hence WT).

We changed "Sphagnum growing on hummocks, on the other hand, showed negative warming responses and strong dependency on water table height" to "Sphagnum growing on hummocks, on the other hand, showed negative warming responses and related to the strong dependency on water table height." (L776-778).

L659: The question is that to which extent the parameterization from S1-Bog be generalized to other peatlands?

The algorithms used to represent moss (e.g. Williams and Flanagan) are transferable to and have been applied by other modeling groups in other peatlands. However, we expect that certain parameters will vary, for example, the microtopographic parameters, the relationship between peat moisture and internal water content, and moss properties such as C:N ratio. The parameter sensitivity analysis informs us as to the most important parameters responsible for prediction uncertainties, and can inform how to prioritize these measurements. Collecting these measurements from a variety of sites will be a necessary preliminary exercise (L 916-923).

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L667: See e.g. Beringer et al. (2001) and Porada et al. (2016) who have already done this.

Thanks for pointing these two literatures. We added them to the text and listed as references (L738-739).