We thank an anonymous reviewer and Dr. Nigel Roulet for the time and the care that they have taken in providing helpful comments on our manuscript. Their comments, followed by our responses in bold, are listed below.

Review 1 (Anonymous)

This manuscript presents a description and initial evaluation of a new peatland model built for the Canadian Land Surface Scheme (CLASS) and the associated Canadian Terrestrial Ecosystem Model (CTEM). The manuscript does an excellent job introducing the importance of accurately modeling peatlands within earth system models, and includes a well-written, brief review of existing peatland models before presenting the new model developments. The conceptual description of the new peatland model is well written and clear, and the evaluation against eddy covariance flux measurements, water table measurements, and soil temperatures is well presented and generally well designed. The model itself appears to do a good job of incorporating current understanding of peatland vegetation and soil processes, and should be a useful tool for simulating peatlands going into the future. I think there is some room for improvement in the technical descriptions of the model equations and the flux data used to evaluate the model. I also think that the conclusion that separate parameterizations for bogs and fens are unnecessary for this model is not adequately supported by the results, and may need to be reexamined or supported with more evidence.

We thank the reviewer for his/her time and for these thorough and thoughtful comments.

0.1 Model equations

I think some of the equations may need another step of proofreading. Some of the notation is unclear, and there may be some errors in the equations. Specifically, Equations 10-17 may need another look.

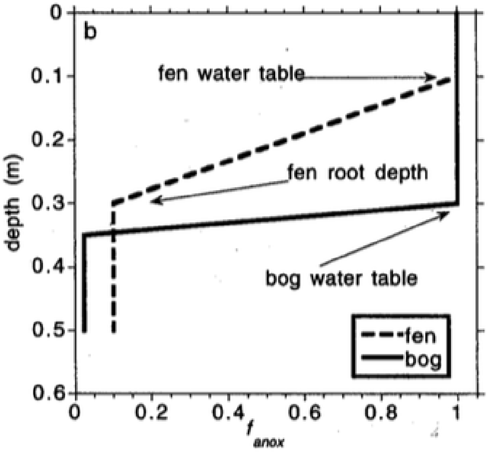
Eq. 10 and 12: The integrals do not look correct. Integrating temperature over depth doesn't make much sense, unless it's intended to be an average temperature with depth. In that case, the integral should be divided by the depth that it's being integrated over. In addition, d_{wt} appears in these equations and is never defined. Is it meant to be z_{wt}? $Q_{10,a}$ and $Q_{10,o}$ are not explicitly defined. I assume that these are derived from the Q_{10} function in Eq. 11 using either $T_{s,a}$ or $T_{s,o}$ from Eq. 12, but this should be explicitly stated. Finally, I think the equations for $f_{T,o}$ and $T_{s,o}$ should be integrating from 0 (the soil surface) instead of 1 (which would be starting at 1 m depth).

We thank the reviewer for pointing out these inconsistencies. We have changed d_p and d_{wt} to z_p and z_{wt}, and inserted the following sentence: "The Q_{10} values of the anoxic and the oxic zones of the soil are indicated as $Q_{10,a}$ and $Q_{10,o}$." We have modified the equations as follows:

- **Changed equation 10 to** $\begin{cases} f_{T,o} = Q_{10,o}{}^{\left(\int_0^{z_{wt}} T_j - 15\right)/10} \\ f_{T,a} = Q_{10,a}{}^{\left(\int_{z_{wt}}^{z_p} T_j - 15\right)/10} \end{cases}$
- **Changed equation 12 to** $\begin{cases} T_{s,o} = \int_0^{z_{wt}} T_j / (z_{wt}) \\ T_{s,a} = \int_{z_{wt}}^{z_p} T_j / \left(z_p - z_{wt}\right) \end{cases}$

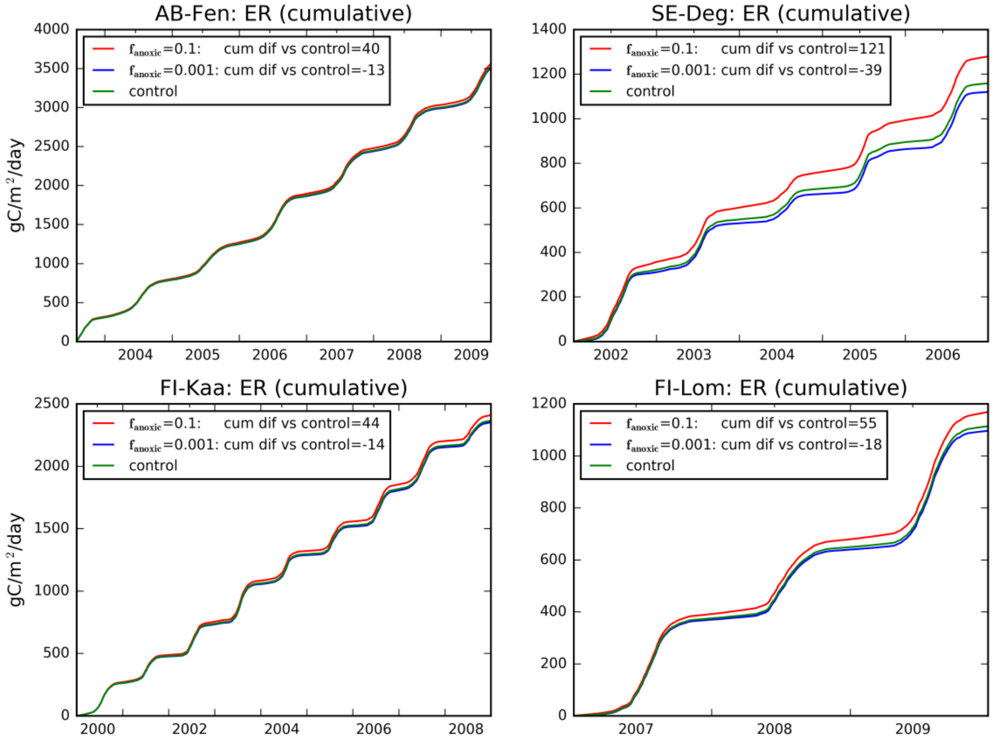
As a general point, it's not easy to visualize the k values resulting from equations 13 and 14. These values are central to the resulting heterotrophic respiration, and a crucial part of the argument that different fen and bog parameterizations don't matter for the model's accuracy. I would suggest adding a figure that shows how k varies with water table depth, for both fen and bog parameterizations. I tried making my own figure (which I've attached), but I'm not sure it's totally accurate. Having such a figure in the paper would really help readers interpret the general behavior of the model with respect to water table, and would be really helpful for understanding why bog and fen parameterizations do or do not cause differences in simulated fluxes. When I plotted these equations, the anoxic decomposition rates had some very sharp transitions at water table depth of 0.3 m, which didn't seem very realistic.

We have added a figure illustrating the variation of the k values with water table depth, as suggested. The sharp transition of anoxic decomposition rate at 0.3 m is based on Figure 1b in Frolking (2001), reproduced below. As noted in section 2.1 of our manuscript, this value is widely accepted as a representative estimate of the depth dividing the acrotelm and catotelm. In reality, of course, this depth will vary among peatlands. When our peatland model is implemented in climate mode, it is planned that spinup tests will be run to assess the spatial variability of this depth, and adjustments will be made equations 13 and 14 if necessary. We have added the above explanation to the paper.



As a final issue related to these equations: on page 10100, line 22: The model described here applies a factor of 0.025 to anaerobic decomposition, citing Frolking et al (2010). In Frolking et al (2010), the decomposition rate of anoxic carbon is in fact 0.001 (see Table 2 in that paper, where the parameter is described as "decomposition rate reduction factor at ‘full persistent’ anoxia.") The value of 0.025 used here actually appears in Frolking et al (2001), Table 1. Note that in that context, 0.025 is the value used for bogs, and a value of 0.1 is used for fens. In this manuscript, the bog value of 0.025 is used for both peatland types, and as well as being referenced to the incorrect paper. This seems like an important omission given the later argument that fens and bogs are not significantly different in this model.

We have added the reference to Frolking et al. (2001). The value of the decomposition rate reduction factor is a matter of some uncertainty, varying in the Frolking papers as the reviewer has pointed out between 0.001, 0.025 and 0.1. In the absence of empirical support for the choice of which value to use, or for using different values for bogs and fens, we calibrated it based on a set of experimental simulations at the Mer Bleue bog (MB-Bog) and the Alberta treed fen (AB-fen). We found that using a constant value of 0.025 produced the best soil respiration results at these two sites. We have inserted the above explanation in the paper and also added a test in section 4.5 demonstrating the relative insensitivity of the model to this parameter (see the plot below).



0.2 Flux measurements used for evaluation

I think the origin of the eddy covariance fluxes used for evaluation should be described in more detail. In the manuscript, site parameters are listed in Table 4, but there is very little information about the origin of the fluxes. Were they downloaded from the Fluxnet database, or individually contributed by site PIs? Were they the result of standardized Fluxnet processing, or individual site processing procedures? What FLUXNET-defined level of data were used? What kind of filtering, gap filling, and quality control were done? Given that the observed fluxes in Figures 7-9 are quite noisy, and the clearly unrealistic QE for one site-year in Fig. 5, it's important to know whether these fluxes were screened for common sources of unrealistic values in eddy covariance (low turbulence, wind directions identified as unrepresentative, equipment problems). Some of the large outliers in Fig. 9 could be related to suboptimal atmospheric conditions, and it's important to know whether these measurements were screened for these types of known issues before being compared with the model.

ER and GPP are not strictly measured using eddy covariance, but are derived from NEP measurements using a range of partitioning techniques. A commonly used method is to fit nighttime NEP to a nonlinear function of temperature, and/or daytime NEP to a nonlinear function of PAR (see Stoy et al, 2006, Desai et al 2008, and Lasslop et al 2009). If this partitioning method was used, it makes comparisons with models problematic because the modeled values are being compared to another [dataconstrained] model rather than to actual observations. It’s really important to describe the partitioning method so readers can appropriately evaluate the results.

When calculating average fluxes, eddy covariance measurements are typically gap- filled, because varying atmospheric conditions, equipment issues, and quality control invariably produce gaps in data. What kind of gap-filling was applied to these eddy covariance measurements before they were compared with the model results? Gap filling is usually conducted in tandem with ER and GPP partitioning, and can introduce the same nonlinear models to the dataset (see Moffat et al 2007 for a comprehensive review). Was any gap filling applied to latent and sensible heat fluxes? If not, daily sums could be biased because data availability is generally lower at night than during the day.

There is no discussion of the inherent uncertainty in eddy covariance measurements, which is highly relevant when they are being used to evaluate a model. See Richardson et al (2006) for a starting point.

We added the following paragraphs to section 3.1:

Data were obtained from the FLUXNET database (http://fluxnet.ornl.gov/). For each site and for each downloaded variable, the highest available data level was used. The meteorological drivers for the model were obtained from level 4 (gap-filled and quality-controlled) data, except for the wind speed, which was obtained from level 3 and surface pressure from level 2 data. Carbon fluxes were obtained from level 4 daily average data when available. The observed GPP and NEP in the FLUXNET database were derived from the observed NEP and the assumed relation between NEP, temperature and photosynthetically active radiation (PAR). The remaining fluxes were averaged from half hourly level 2 and level 3 data.

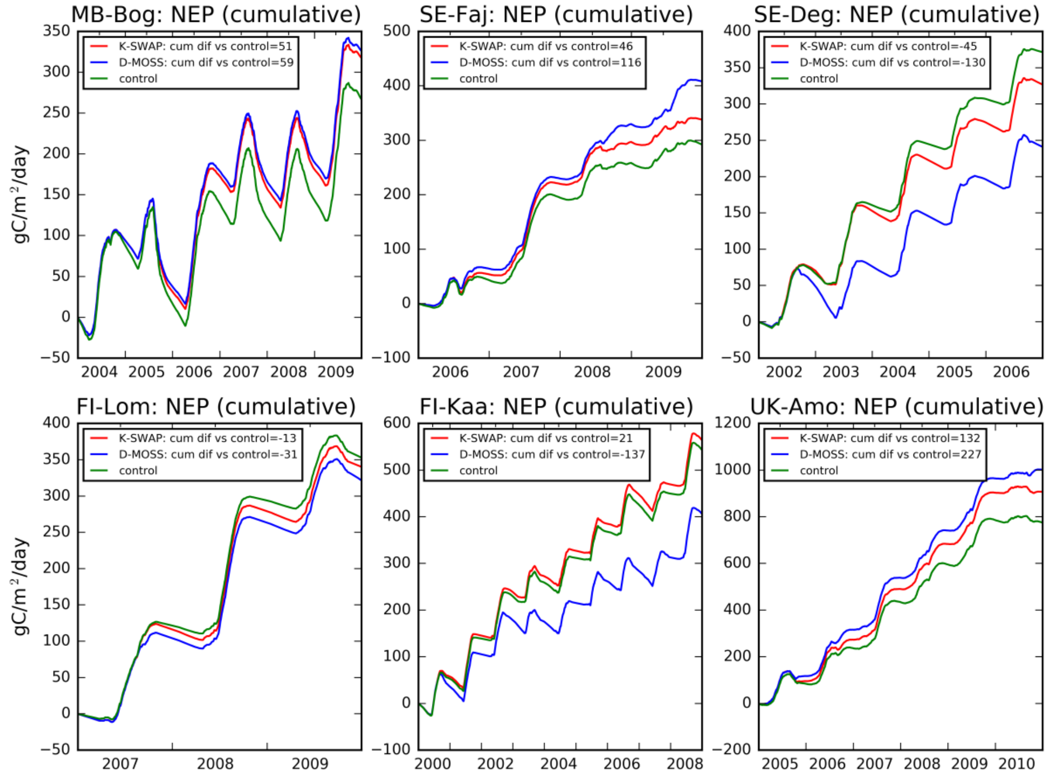
In the model evaluation, it must be borne in mind that eddy covariance measurements of turbulent fluxes of energy, water and carbon are subject to inherent uncertainties and errors related to atmospheric conditions such a low turbulence and wind direction, or to equipment malfunction. For this reason we selected a relatively large number of test sites with multi-year datasets, and focused on long-term averages for the validation. We also included in the evaluation variables such as water table depth, soil temperature and snow depth, which are not dependent on turbulent flux measurements.

0.3 Conclusions regarding differences between bogs and fens

Figure 13 shows differences in r^2 and RMSE after changing model parameters related to the separate fen and bog parameterizations. From the K-SWAP test, it is clear that these separate parameterizations do not significantly change the model’s fidelity to observations (measured using those two error metrics) over the time scales being investigated here. Based on this, the authors conclude that "it is not necessary to distinguish between fens and bogs." I think this conclusion is not supported by this analysis for a few reasons.

1. These results do say something about the specific parameterization being used here, but that is not enough to draw general conclusions about modeling fen and bog ecosystems. Based on the figure I attached, it’s clear that, with this parameterization, decomposition rates below the water table are so low as to be essentially negligible. Any differences between fen and bog decomposition rates below the water table would therefore have very little influence on total fluxes. However, the previous manuscript that is the source of a key parameter f_{anoxic} in fact had a very large difference between bogs and fens originally (which is not reproduced in this manuscript). It’s possible that a different parameter set could yield very large differences between simulations of bogs and fens. So, it’s correct to say that this model with these parameters does not predict much difference between bogs and fens. But a different parameterization that produces equally good (or better) results compared to observations might be much more sensitive. I think it’s premature to conclude that the difference between fens and bogs can be ignored entirely.

As noted above, we have added to the sensitivity analysis a test of the effect of varying f_{anoxic}. We have also included cumulative plots of the carbon fluxes for this and the other two sensitivity tests (reproduced below), to demonstrate that for our purposes at least, and to a first order approximation, we can neglect the differences between fens and bogs for our particular application in climate models.



2. These simulations incorporated differences between bogs and fens that a global model would not have access to. Specifically, the plant functional types used to drive the model runs are different between fens and bogs, and could drive large differences in global model simulations depending on what vegetation is assumed to dominate different peatlands. Real fens and bogs have very different dominant plant communities, hydrology, and soil properties that can drive differing ecological behaviors (for example, see Sulman et al 2010). On the other hand, some studies have concluded that peatland type is not the primary driver (e.g. Humphreys et al 2006). A review of literature related to ecological differences between fens and bogs and how they might affect or not affect model simulations would really add to the discussion. The section of the discussion addressing this issue (Section 4.5) does not contain any citations to literature addressing observed contrasts or similarities between fen and bog ecology and biogeochemistry, and this argument is begging for some more context.

We agree that real fens and bogs have very different plant communities, hydrology etc. In global climate model applications, these vegetation distributions will be either assigned on the basis of global land cover datasets, or derived from spin-up runs with a dynamic vegetation model. In either case, the location of peat soils will be specified at the model initialization stage, and the various peatlands will develop either bog or fen characteristics

depending on the climatic forcings. We have added the following sentences in the introductory section outlining the differences between bogs and fens:

Peatlands can be classified as either fens or bogs. Bogs are dependent upon precipitation for water and nutrients while fens receive additional contributions from ground and surface waters (Rydin and Jeglum, 2006). The different sources of nutrients between bogs and fens leads to differences in their physical state including hydrology, soil and water chemistry, vegetation, and nutrient availability. These differences can lead to differences in the fluxes of carbon from these fens vs. bogs, e.g. fen methane emissions are more sensitive to vegetation type but less sensitive to temperature than bogs (Turetsky et al. 2014). Fens generally produce the most methane with water tables at or above the peat surface, while bogs produce the most methane with the water table below the peat surface (Turetsky et al. 2014).

Rydin, H. and Jeglum, J.: The Biology of Peatlands, Oxford Univ. Press, Oxford, United Kingdom., 2006.

Turetsky, M. R., Kotowska, A., Bubier, J., Dise, N. B., Crill, P., Hornibrook, E. R. C., Minkkinen, K., Moore, T. R., Myers-Smith, I. H., Nykänen, H., Olefeldt, D., Rinne, J., Saarnio, S., Shurpali, N., Tuittila, E.-S., Waddington, J. M., White, J. R., Wickland, K. P. and Wilmking, M.: A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands, Glob. Chang. Biol., 20(7), 2183–2197, 2014.

3. The evaluation shown in Figure 13 is not really adequate to establish that there is no important difference between results using fen and bog parameterizations. The only data presented are RMSE and r^2, which only allow evaluation of the results with regard to a quite noisy observation-based dataset. It's quite likely that the parameter change introduces a small but significant persistent bias in heterotrophic respiration. This might not show up over short (several year) time scales, but could lead to large differences in peat carbon pools after decades or centuries of integration (which are the time scales of greatest interest for peatlands). Because eddy covariance data includes inherent uncertainty due to turbulence and micrometeorological variations, even an important difference in model predictions could be obscured by this minimum noise level in the analyses used here. It would be much more illuminating to see a comparison of modeled ER, or cumulative NEP, with the different parameter sets in order to evaluate how sensitive the model is to these differences. Even a comparison of time series between model and observations might reveal some persistent biases at seasonal or annual time scales that are too small to show up in the total RMSE and r^2 numbers.

We agree that plots of cumulative NEP provide instructive additional information, and we have added them to the sensitivity analysis as shown in the plots presented above.

0.4 Additional specific comments

- 10091, Line 10: A net C uptake of 3.3 GtC/year compared to the 5.0 GtC/year net C uptake seems awfully high. Are these estimates directly comparable?

The net C uptake value of 3.3 GtC/yr was calculated using a maximum weighting method, which has 46 GtC of biomass of bryophytes, in contrast to 4.0 GtC in the average scenario. This result is thus not directly comparable, and we have removed it.

- 10094, line 22-28: The discussion of peatland and non-peatland fractions and PFT fractional cover seems out of place, since the rest of the manuscript only discusses single-point simulations. Was this sub-grid-scale heterogeneity actually included in the simulations? If so, what basis was used to determine peatland fractions, and fractional PFT cover?

Sub-grid scale heterogeneity was not included in the simulations reported in this paper. The section in question describes how the peatland model will be implemented in future coupled climate model runs. We have revised the wording to make this clearer.

- 10096, line 15: It would be helpful to have the units for w_m here.

We have added the units, which are kg water per kg dry mass

- 10098, Equation 7: θ_m does not seem to be defined anywhere. Is this the same as w_m?

We have added the definition: θ_m represents m^3 water per m^3 moss.

- 10098, line 20: I think the 4.6 factor should have units of μmol $m^{-2}s^{-1}$ per W m^{-2}

We thank the reviewer for pointing this out, and have made the correction.

- 10099, line 7-11: Were fractional PFT coverages included in these simulations? How were they parameterized based on the limited land-cover data from sites? Peatlands typically have open, patchy vegetation. Did the model incorporate this heterogeneity? Were multiple overlapping PFTs used for each site, or just one?

The model has three possible peatland PFTs parameterized. As noted in section 3.2, the FLUXNET database was used to assign values to the areal coverage of the PFTs for each site. We have added a line in Table 4 showing the total fractional vegetation coverage.

- 10101, line 1: What is the model time step?

The time step is 15-30 min for the calculations associated with CLASS and daily for those associated with CTEM. We have clarified this in section 2 of the manuscript.

- Equations 13 and 14: What is the justification for the 0.3 m cutoff? It seems fairly arbitrary. The text says these equations are from Frolking et al (2001), but the table says the parameters are from the McGill Wetland Model.

See our response in the "Model equations" section above. We have added the Frolking et al. (2001) reference to the table title.

- 10101, line 13: There is no equation for C_{hum}. Is it just a constant rate, or a fraction of decomposition?

The humification rate (C_{hum}) is an assumed fraction of decomposition which varies by PFT. The values of the coefficient are provided in Table 2 (variable "humicfac"). We have added this explanation to the text.

- 10105, line 8-17: Were the parameter changes applied before or after spinup? If they were only applied to the spun-up model, than any significant changes that would have accumulated over 100 years would be ignored. These could be important in an earth system modeling context.

The parameters were changed prior to each spinup.

- 10106, line 11-13: Hummock-hollow topography is very typical of bogs. Did this affect any other study sites? I think it's worth discussing this issue in more depth, with respect to all of the sites and how these topographical variations could affect the model. See Dimitrov et al (2010), Baird et al (2009), Loisel and Yu (2013), etc for some good discussions of issues related to microtopography.

We neglected the effects of hummock-hollow topography because the model has been developed for global simulations, and on global scales there is no good information on how to parameterize this. Wu et al. (2013) found that for the McGill Wetland Model, microtopography was not very important for upscaling the net carbon exchange. In the global peatland model by Wania et al. (2013), hummocks and hollows were included but were arbitrarily assigned a distribution of 50%-50%. We decided that considering the lack of information on fractional coverage of hummocks and hollows globally, their inclusion was not warranted in our model.

- Section 4.2, 4.3: All of these evaluations used daily averages, correct? It might help to state this explicitly at the top of the section.

These evaluations are based on daily averages or daily totals. We have clarified this in the manuscript.

10108, line 23: NEP in the model is calculated by subtracting ER from GPP. In eddy co-variance measurements, NEP is the measured quantity, while ER and GPP are derived from NEP (and therefore may contain additional errors).

We have added the following to the beginning of section 4.3:

In eddy-covariance measurements, as noted in section 3.1 above, GPP and ER are obtained by partitioning the observed NEP on the basis of empirically derived relationships. In the case of modelled carbon fluxes, on the other hand, NEP is calculated by subtracting ER from GPP, therefore the error in the NEP simulations accumulates the errors in GPP and ER. Bearing in mind these caveats …

10109, line 2: "Model errors for the extreme values at these two sites" implies that the eddy covariance values are "truth". Eddy covariance is an inherently noisy measurement because it relies on atmospheric turbulence. Furthermore, large spikes could be due to inadequate screening for poor meteorological conditions. I wouldn't place too much confidence that these big outliers in eddy covariance fluxes are actually real ecological fluxes. This is where it's important to check what kind of screening was done on the flux measurements.

We have reworded the sentence as follows: "The discrepancy with the modelled values, contributing to the low r^2 values for these two sites, might be due either to weaknesses in the model or to inadequate screening of the eddy covariance measurements."

10110, line 5-7: If this site were included in the Figures 7-9, readers could see what was going on much more easily.

This site was not included because since the high NEP is largely a product of the tree cover, it clouds the interpretation of the peatland model performance, and is therefore not as informative in this regard as the other sites.

10111: I think a bit more explanation of the Taylor diagrams would be helpful here. I don't think they're really common enough to forego a sentence or two about how to read them.

We have added the following explanation:

Taylor diagrams provide a graphical summary of how closely modelled data match observed data (Taylor, 2001). The radial spokes represent the level of correlation and the x and y axes show the standard deviation. The standard deviation of the observations is plotted on the x axis, and the RMSE of the modelled values is indicated by the concentric contours around this point. Since we have eight pairs of modelled and observed points for each diagram, we normalized the data by dividing each of the standard deviations and the RMSEs by the standard deviation of the observations associated with each point, so that all the observation points fall at 1 on the x axis.

Section 4.5: I think these results would be stronger if readers could see a bit more than just r^2 and RMSE. Changes in modeled values between runs, or changes in mean bias, would be useful additions to this section.

We have added plots of cumulative NEP to the analysis, as shown above.

Figure 1: There is no key for a lot of the notation in this figure. The soil layers are also a bit confusing. The model seems to calculate peat depth prognostically, but this diagram implies that there are fixed depths for fibric, hemic, and sapric layers. That doesn't appear to be the case in the actual model equations.

We have added the following sentences to the figure caption: "The symbols C, T and θ represent carbon, temperature and soil water content respectively. The subscripts L, S, R, H, and D represent leaf, stem, root, fresh litter and old litter respectively." As explained in section 2.1 of the manuscript, the first nine peat layers have thicknesses of 10 cm and the tenth, whose thickness can vary with time, contains the remainder of the peat depth.

Figure 5: What is going on with the "observed" fluxes in UK-Amo QE in 2006? Those do not look like trustworthy measurements, and if they were included in the evaluation it casts doubt on whether the resulting statistics are meaningful. It's probably worth checking with the PI if there was some equipment problem in that year. Also, why are only 4 of the 8 sites shown?

The large scatter in the observed UK-Amo QE flux in 2006 is mentioned in the second paragraph of section 4.2 as being probably due at least partly to instrumental errors. We chose to show two representative fens and two representative bogs in order to allow the figures to be legible and the presentation focused.

Figure 7-9: Why these six sites and not all 8?

For the same reason as above. For full comparisons, all the sites are included in figures 15 to 17 as well as in tables 5 to 7.

Review 2 (Dr. Nigel Roulet)

In this paper the authors combine a newer version of CLASS with a newly developed peatland carbon model based on the structure CTEM. This paper is an interesting and useful addition to the literature but I believe the authors need to do more to substantiate the models usefulness. Their work represents part of a movement by some global modelling groups to incorporate peatlands into the global models. The reason this is important is because peatlands represent the highest carbon density ecosystems in the world so while they cover a relatively small fraction of the land (4 to 6%) they contain up to 25% of the world's terrestrial biogenic carbon. Simulating the sensitivity of their carbon stores to climate and land-use change is important for future projections of global carbon cycling. Since the carbon dynamics of peatlands is so tightly coupled to surface hydrology it is reasonable to ask if climate change will have a significant impact on their carbon function in the future. The only way to address this question is through modelling and that modelling requires a reasonable representation of peatland ecosystems at an appropriate level for incorporation in global ecosystem models. The authors present the details on the development of such a model and then provide an evaluation of their model output for six different peatlands: three bogs and three fens.

I think the authors have done a reasonable job but I do have some constructive criticisms of their manuscripts as it current stands. My main concern is the authors provide little in explanation for why their models produces the results it did. The evaluation of the model against measurements is useful but it is very limited. They compare model out against observations but do not go into detail of why the model is successful in some cases and not very successful in others. They presentation of their results is very limited and not overly useful at time. Better visual presentation of their results (see suggestions below) and the inclusion of some sensitivity analyses would help demonstrate to the community the utility of the model they have developed. Several things stand out as being quite unusual that I think the modelling community, and certainly the peatland carbon modelling community will find unusual – for example the apparent lack of the influence of initial conditions and the apparent lack of sensitivity to peatland wetness on the carbon exchanges. These are quite at odds with the empirical observations from numerous long-term measurement sites (some of these sites are included in this manuscript). The simulation of wtd seems quite poor but it does not seem to really matter in the end? The authors should do some more analysis to better assess where the uncertainties in the simulated results are coming from (see suggestions below). All models are far from perfect but hopefully they are useful. To determine the usefulness readers have to understand why the model does what it does and why it does not do what it was expected to do.

We thank Dr. Roulet for his comments and his constructive criticism, and we endeavour to address his concerns below.

Page 1 Ln 36 This depends on the peatland type. Mineral peatlands with Ca concentration much above 2 mg/l there becomes less bryophytes and more sedges. Roughly this is the difference between bogs and fens.

We have re-worded the sentence to read "bryophytes or sedges".

Page 2 Ln 7-10 Yes but Wu and Roulet showed bogs are quite resilient and fens are not. Christensen et al and Ise et al. worked on poor fens. The conclusion from the literature you cite is that ombrogenic peatlands (bogs) may have sufficient resilience to maintain their sink function in climate change but fens, which rely on additional external inputs of water, may not. This is the crux of the problem in simulating the sensitivity of peatlands to climate change. We break forests into different functional types. Similarly peatlands should not be seen as one type of ecosystem. My guess is that that C store in peatlands is roughly 50 - 60% in bogs and 40 - 50% fens.

As noted above in our response to the first reviewer, we have added some sentences in the introduction outlining the differences between fens and bogs. We have also included the following sentence: "Wu and Roulet (2014) showed that fens, which rely on external inputs of water, may be particularly sensitive to changes in surface hydrology."

Page 2 Ln 17 I believe was should be were

We believe that it should be "was", referring back to "poor representation".

Page 2 Ln 28-34 Unlike the other three models discussed in the sentence HPM it us not process based but it a phenomenological model. It is a one year time scale model and is not of the same temporal scale as the process based models.

True. We have deleted the reference to HPM.

Page 6 Ln 23 It may be a more theoretically sound representation but "better" needs to be justified by evidence.

We have changed "better" to "more detailed".

Page 9 Ln 4- 16 What did you do for the spin up of the peat profiles of each peatland? You discuss the sensitivity of two of the initial parameters derived from the spin up at the end of the results but this is an important issue to discuss up front. Later on you show that it might not matter that the decomposition rates with depth are generalized and the presence or absence of moss is not that important (not sure I understand this) but the hydraulic properties of the profile are important to the simulation of the water table (wtd). Later on you show that you have marginal success in simulated the wtds but it might not matter that much for GEP, ER, or NEP. However, if this model will be extended to do methane this will be critical. At the very least the authors should be explicit here on the decomposition coefficients or base respiration they assign to each layer to capture the drop in intrinsic OM quality. They also should show explicitly the hydraulic parameters for each layer so the readers can determine if the characteristic differences between fen peat and big peat are in the model parameter set or are not in the model parameter set. The authors do not address this issues until the end of the paper and it should be clear from the beginning.

Spin-up is discussed in section 3.2. The purpose of the spin-up was only to determine the C content in the vegetation pools; we have reworded the second paragraph to make this more clear. The decomposition rate coefficients and the moss depth were assigned for fens and bogs based on values in the literature, not on spin-up. The soil hydraulic parameters and decomposition parameters are listed in Tables 1 and 3.

Page 9 Ln 15-16 Does this assumes the relationship between C and density is the same across all peatlands. Is this true? The density - depth relationship and depth - age relationship can be quite different among individual peatlands and quite different between bogs and fens. The model appears to have an ombrotrophic bog set up? Is this used for all the simulations?

Yes, we used one C-density relation for all the peatlands. It is true that density-depth-age relationships may differ substantially among peatlands, but this information is not available on a global scale, which is where our model will be applied.

Page 10 Ln 1 – 14 You use Taylor plots in your evaluation but do not mention this here?

We did not think it necessary, as Taylor diagrams include the r and RMSE.

Page 10 Ln 16 A general comment on the presentation of the times series in the result sections. Time series are useful but they are difficult to sue to isolate if the uncertainty in the model result is random (ok assuming they cancel) versus systematic (which may or may not be OK). Scatter plots of simulated versus observed around a 1:1 line would reveal if there are some systematic errors - for wtd and LE there appears to be some systematic errors in the growing season. For NEE, GEP and respiration, it appears that for some peatlands the top and bottom 10% are systematically missed and in other sites both the GEP and ER are grossly under-estimated but because NEP is the difference in these two numbers the NEP does not look that bad. Using these plots does not necessarily negate the utility of the model but it helps the reader assess if the model is suitable or not for the task it is being developed for – the assessment of peatland carbon dynamics in changing climate conditions. For example St. Hilaire et al. (2010) showed that MWM truncated high GEPs and ERs but these represented less than 10% of the total exchanges so it did not matter for the overall annual exchange. Where this truncation may have implications for climate simulations is if there is a systematic shift into those conditions that are more favourable to greater GEP and/or ER. St, Hilaire et al explicitly show this so the reader is fully aware of the issues. In these models it is the accumulation of small systematic uncertainties that can give erroneous results over the long-term.

We have added scatterplot versions of Figures 7, 8 and 9 (GPP, ER and NEP), and inserted the following paragraph in section 4.3:

Figures 11-13 show the daily modelled versus observed GPP, ER and NEP in scatterplot form. Although the model performs reasonably well, with r^2 values averaging over 0.7 for both GPP and ER, a general tendency can be seen for the modelled GPP to be biased low at high and low values, and high at medium values. The bias in the very low values may be spurious, given the relatively large errors associated with eddy covariance measurements of small fluxes; also, the occasional negative observed values of GPP may be indicative of erroneous partitioning of the measured NEP between GPP and ER. At FI-Lom, FI-Kaa and UK-Amo, the high model bias at low observed values may be related to early leaf-out and/or delayed leaf drop. The biases at medium values are possibly related to the use of the "big-leaf" assumption in CLASS-CTEM, which neglects sunlit and shaded canopy fractional areas, and may have a dampening effect on photosynthesis. Low biases at high values may be related to water stress caused by a low water table, as seen in Figure 4 for RU-Fyo and FI-Lom. In the case of ER, the modelled values do not show systematic biases except for RU-Fyo and UK-Amo, which were difficult to model as noted above. Given the fact that a major focus of this study was the incorporation of respiration for organic soils and mosses into CLASS-CTEM, this is encouraging.

Page 10 Ln 18 On Figure 3 the value of 0.25 cm should be 0.25 m. This result is interesting. The authors are not aware but there are two papers (one in press and one in review at Ecohydrology) that show that the wtd changes over time across the hummock - hollow at MB move in unison. This means if you know a wtd at a single point and you know where that point is with respects to the difference in hummock – hollow elevations then you can estimate of the wtds across MB. So the authors' explanation is plausible though I am surprised the model offset is the same height of the height of the hummocks above the hollows. This raises the question why the same problem did not arise for Fajemyran. It has micro-topography, maybe even greater, than MB?

This is an interesting point. We are not certain, but perhaps the water table was measured in a hollow at Fajemyran? Our thanks for pointing out the error in the Figure 3 caption, which we have corrected.

Page 10 Ln 30 – 35 The Wtds for the fens is poor in all three sites. They are generally between 0.1 to 0.3 m off. Part of this maybe the parameter set up is for bogs not fens. In terms of carbon function this has a much larger implication for fens than bogs - see Wu and Roulet 2014. Did you try any of the fen simulations by adding in extra water emulate additional water through groundwater seepage? We know fens receive some addition water from either surface inflows and/or groundwater seepage. What you do not know is how much extra water. My gut feeling, from visiting a few of these sites, is the extra water is quite small for AB, maybe about 5 to 10% for Degero, and probably more for Lom. You compare in Fig. 5 measured and simulated Et and it looks like Et is overestimated at most sites, hence I assume this is the reason for the problems with the wtds? It's important to a better handle on where the problems are with the wtd estimates because wtd is a critical variable to the NECB. It's even more important if you intend to eventually use this model to get at methane.

These are good points. We have not attempted to introduce groundwater seepage because on global climate model grid scales, unless a tiling approach is implemented this is impossible to parametrize. We do have a student working on groundwater modelling within CLASS, but this is only anticipated as being applicable at regional climate model scales. When our peatland model is implemented with CLASS in the Canadian Regional Climate Model we will definitely be interested in revisiting this groundwater question.

Page 11 Ln 4-6 As suggested in the general comment above scatter plots will reveal if there are consistent biases in the simulated turbulent fluxes.

Page 11 Ln 29 Again scatters plots of GEP and ER around a 1:1 line and this will illustrate the biases in the model relative to the size of the flux. It also illustrates the range of GEP and ER the model does well and where it does not do well. This is important because NEP is the difference of two much bigger numbers and it may do NEP reasonable well but for the wrong reasons. An alternative way to illustrate the uncertainty is to analysis the residuals of the regressions between observed and simulated and see if there are patterns. If the errors are random there should not be any pattern to the residuals but if the residuals show a pattern this suggests structural issues with the model.

As noted above, we have added scatterplots of GPP, ER and NEP.

Page 11 Ln 33-36 It is interesting that the model does well on Kaa given that an appa mire - i.e. it contains a lot of open water in the form of pools in the measurement footprint . Pools tend to be large sources of CO2 with no mechanism for the uptake of CO2 (see work by Hamilton et al. 1994 and recent work by Pelletier et al (2014). This suggests that the model gets the ’right’ answer without accounting for the spatial variability. This is a little disconcerting.

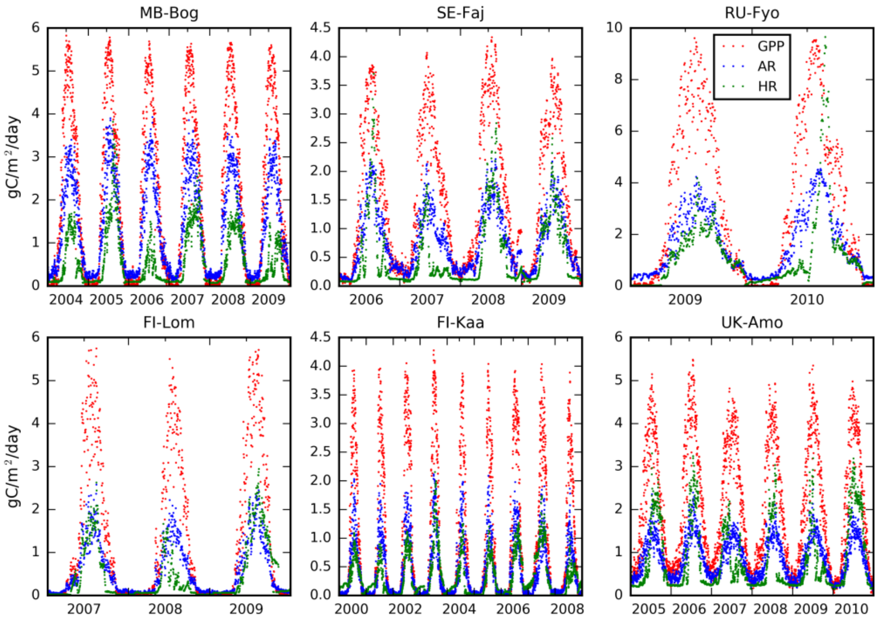
We would argue that this does not necessarily imply that the model is getting the right answer for the wrong reasons. It is possible that at Kaa the impact of the open water pools is relatively limited.

Page 11 35-38 I also find this result reason for concern. In one case, RU, there is a huge mass of old carbon that sustains a larger than simulated ER and in the other case, UK, there is a relatively tiny mass of C that produces the same over-estimate. This does not really make sense to me unless the respiration below 1 m depth is insignificant.

This is indeed the case. Generally respiration decreases with depth in soils, which is one of the factors that allow the buildup of peat in these ecosystems. Changes to heterotrophic respiration with depth in soils includes changes in oxygen transport (e.g. diminishing vascular tissues) and bulk oxygen availability, soil microbial community changes, mineral sorption, and more broadly temperature and moisture changes. (Note that the actual peat depths are UK-Amo with 10 m of peat while RU-Fyo has around 1 m.)

In both cases the errors in ER are offset by a grossly overestimated GEP. I can understand why there is little difference in GEP if the conditions are general the same at the peat surface. This section needs some more thinking – how much of the ER comes from autotrophic respiration?

We have included new plots, reproduced below, that display GPP, AR, and HR for comparison of their relative magnitudes.



How associated in AR to GEP – if one is over estimated (GEP) does this push AR up?

Not necessarily. AR is intricately linked to GPP but GEP includes HR, which is not directly tied to the production side.

If HR is a very small component of total ER then is does not matter that there is a small or large mass of peat. Throughout the paper the authors tease the readers with interesting results that are often confounding but then provide little explanation of why the results come about. You have no idea why the observations are what they are, but you are simulating the carbon dynamics in your model so you can tell the reader where the ER is coming from, what makes it up, and why GEP is large enough to offset it. It is in these explanation that you come up with from how the different components of the model interact that will convince a reader your model is reasonable or not. The same is true for the results in the energy balance and wtds. You report your results but tell us from playing with the model why you get the results you do.

As can be seen in the new AR/GPP/HR plots, the HR is commonly the smallest component at each site. In looking at the sites mentioned (RU-Fyo and UK-Amo), the RU-Fyo site shows a peak GPP of ~10 gC/m2/d, AR of ~4 gC/m2/d and HR generally ~75% of the AR value with some exceptions. The UK-Amo site shows a different pattern with the AR being approximately 30% of the GPP and the HR peak value being typically larger than the AR flux (ca. 1.5 x). Thus the UK-Amo site shows proportionally higher HR, reflecting the impact of the larger peat mass while the RU-Fyo site has proportionally lower HR with its relatively shallow peat mass.

Page 12 Ln 9 See comment above (Page 11 Ln 33-36) on the presences of pools.

See response above.

Page 12 Ln 20-21 What does it mean when the simulations averaged over a month look much better than the short-term comparisons? It means that errors cancel out, which may be fine or may not be. If the reason for the lower agreement at the higher time resolution is one of timing and over some averaging period of several days the problems go away then it's fine. But if the problems are at certain periods of time and these periods maybe more frequent in climate change scenarios you wish to use the model to simulate then this could be a problem. Given the apparent variance in agreement across the various peatlands the authors would gain a better understanding of the models behaviour by doing some sensitivity analysis on the initial conditions and key parameters. This will also tell the authors if they are compounding errors with poor wtds influencing the C dynamics. Sensitivity analysis on a model like the one the authors present takes a lot of work and time but it reveals a lot of good information that readers want to know. I do not like referring authors to my own work but I think the papers of Wu and Roulet (2012) and others on the development and evaluation of MWM illustrate the value that the scatter plots serve and what a through sensitivity analysis can show. The sensitivity analysis in Wu and Roulet (2012) took a good month to run but it demonstrates what might happen if temperature and wtd change over time. Wu et al. (2013) and St. Hilaire et al. (2010) are also papers where this detailed sensitivity analysis revealed some explanations for the behaviour of the model.

We agree that the sensitivity of the model to temperature and precipitation/hydrology changes in a changing climate is an important thing to investigate, but we feel that it is beyond the scope of this paper. Rather than undertaking such an analysis on the basis of these few sites, we believe that it would be better addressed in the context of GCM climate change scenario outputs, and should therefore be the subject of a follow-up paper. We would plan to undertake some additional parameter sensitivity tests at the same time.

Page 12 Ln 32 I do not believe these are not annual C budgets but the annual cumulative net ecosystem production. It is very important you get this terminology correct (see Chapin et al. 2006) to avoid confusion down the road. You do not simulate DOC export or methane exchange and in peatlands these are very important components of the annual C budgets. The net ecosystem carbon budgets from MB (Roulet et al. 2007) and Degero Stor (Nilsson et al. 2008) show that these two exports can offset the annual NEP by 20 to 40%.

We changed title 4.4 to "Annual net ecosystem production".

Page 13 Ln 31 What does it mean when the GEP, ER, and NEP cluster and appear to follow the observations much better than the energy balance terms? Does this mean the C fluxes in peatlands are constrained to the point that they are relatively insensitive to changes in environmental conditions? This is way the sensitivity analysis is so important. It impossible to know why the results are what they are without this further analysis. Mimicking three to five years of measurements is important but having the model reproduce changes in response to changes in the environmental conditions is also important for the intended use of the model.

The apparent improved skill of the model in capturing the C fluxes over the energy balance terms is not overly surprising. The main determinants of variability for the C fluxes (through GPP, AR, and HR) are 1) soil water availability, 2) incoming solar radiation, 3) atmospheric carbon dioxide concentrations, and 4) temperature of the air and soils. In peatlands, water availability for plant productivity is usually not limiting. As well the carbon dioxide atmospheric concentrations, air temperatures and incoming solar radiation are reasonably well constrained thus the predominant controls on the variability of the C fluxes are likely the soil temperatures and moisture state. Conversely the energy balance terms will be heavily influenced by the position of the water table (at the surface vs. at depth), the vegetation cover and roughness length, and albedo of the land surface. The major influences of the energy balance terms are more variable and also more difficult to accurately simulate than the major terms of the C flux terms thus it is reasonable to anticipate that the C fluxes would be simulated more skillfully.

Integrating peatlands into the coupled Canadian Land Surface Scheme (CLASS) v3.6 and the Canadian Terrestrial Ecosystem Model (CTEM) v2.0

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Abstract

Peatlands, which contain large carbon stocks that must be accounted for in the global carbon budget, are poorly represented in many earth system models. We integrated peatlands into the coupled Canadian Land Surface Scheme (CLASS) and the Canadian Terrestrial Ecosystem Model (CTEM), which together simulate the fluxes of water, energy and CO_2 at the land surface –atmosphere boundary in the family of Canadian Earth System Models (CanESMs). New components and algorithms were added to represent the unique features of peatlands, such as their characteristic ground floor vegetation (mosses), the slow decomposition of carbon in the water-logged soils and the interaction between the water, energy and carbon cycles. This paper presents the modifications introduced into the CLASS-CTEM modelling framework together with site-level evaluations of the model performance for simulated water, energy and carbon fluxes at eight different peatland sites. The simulated daily gross primary production and ecosystem respiration are well correlated with observations, with values of the Pearson correlation coefficient higher than 0.8 and 0.75 respectively. The simulated mean annual net ecosystem production at the eight test sites is 87 g C m^{-2} yr^{-1}, which is 22 g C m^{-2} yr^{-1} higher than the observed annual mean. The general peatland model compares well with other site-level and regional-level models for peatlands, and is able to represent bogs and fens under a range of climatic and geographical conditions.

1. Introduction

Peatlands represent about 20% of the global soil carbon (C) pool and have played a critical role in regulating the global climate since the onset of the Holocene (Yu et al. 2013). Peatlands have accumulated more than 600 Gt C over the Holocene and serve as a long-term C sink at a rate higher than 5 Gt C per century on average (Yu et al. 2010). Over 90% of the world's peatlands are located in the northern hemisphere (Yu et al., 2010) in large areas such as the Hudson Bay Lowlands, the west Siberian Lowlands and the FennoSoviet Lowlands, where gross primary production (GPP) is comparatively low (e.g. Yebra et al., 2015). The inhibited decomposition in waterlogged organic soil persistently sequesters C in peatlands, despite the relatively low primary production.

Peatlands are usually characterized by a ground layer of bryophytes or sedges covering 80-100% of the surface ~~on non-mineral peatlands~~ (Vitt, 2014). Bryophytes, especially *Sphagnum* mosses, are nonvascular land plants that are able to effectively capture and store water and nutrients (Turetsky, 2003). Globally, bryophytes and lichens are widely present, especially over tundra, boreal forest floor and desert, and are estimated to account for a net C uptake of 0.34 ~~to 3.3~~ Gt C yr^{-1} ~~(~~on average (Porada et al., 2013), out of 5.0 (±0.9) Gt C yr^{-1} global net C uptake by land and oceans between 1960 and 2010 (Ballantyne et al., 2012). Peatlands can be classified as either fens or bogs. Bogs are dependent upon precipitation for water and nutrients while fens receive additional contributions from ground and surface waters (Rydin and Jeglum, 2006). The different sources of nutrients between bogs and fens leads to differences in their physical state including hydrology, soil and water chemistry, vegetation, and nutrient availability. These differences can lead to differences in the fluxes of carbon from these fens vs. bogs, e.g. fen methane emissions are more sensitive to vegetation type but less sensitive to temperature than bogs (Turetsky et al. 2014). Fens generally produce the most methane with water tables at or above the peat surface, while bogs produce the most methane with the water table below the peat surface (Turetsky et al. 2014).

Peatlands are particularly vulnerable to C loss under climate change. The IPCC Fifth Assessment Report (AR5) projected a large increase of temperature and a risk of lower soil moisture (Christensen et al., 2013, Seneviratne et al., 2010) in the boreal region. Warmer temperatures and drought can both stimulate the decomposition of peat and further enhance climate change through increased CO_2 and CH_4 emissions (Davidson and Janssens et al., 2006; Tarnocai, 2006; Ise et al., 2008; Dorrepaal et al., 2009; Wu and Roulet, 2014). However, the increasing atmospheric CO_2 concentration and temperature may also promote increased primary production and shifts in vegetation ecozones, compensating for the additional C loss from soil respiration (Camill and Clark, 2000; Ward et al. 2013; Wang et al. 2015). Wu and Roulet (2014) showed that fens, which rely on external inputs of water, may be particularly sensitive to changes in surface hydrology. Overall, large uncertainties prevail in the future carbon budget of peatlands and its feedback to climate change (McGuire et al. 2009).

Earth system models (ESMs) simulate the global C cycle and feedbacks to climate and are used to make future climate projections. Poor representation of processes related to the C cycle in peatlands and organic soil types was identified as one of the key reasons for inaccuracies in simulated soil organic mass and heterotrophic respiratory fluxes in the ESMs used in CMIP5 (Todd-Brown et al. 2013). Recognizing the importance of representing organic soils in the high latitudes, progress has been made recently to integrate peatlands, wetlands and permafrost into coupled global climate-C models. For example, several versions of the Lund-Potsdam-Jena (LPJ) model, a global dynamic vegetation model, have incorporated wetlands or peatlands to simulate global methane emissions (Wania et al. 2009a, 2009b), the spatial expansion and C sequestration of peatlands (Spahni et al., 2012) and wetlands (Kleinen et al. 2012; Schuldt et al., 2013) during the Holocene, and the water and energy cycles in permafrost (Ekici et al, 2014). The simulation of the global spatial distribution of wetlands and permafrost and the long-term C sequestration of peatlands improved the simulations of soil temperature and water content (e.g. Wania et al., 2009a). However, the models were not evaluated on fine temporal and spatial scales because they were designed for capturing the long-term C accumulation. On the other hand, several peatland models have been developed and evaluated for individual sites. For example, the McGill Wetland Model (MWM) simulates the C exchange in Degerö Stormyr and the Mer Bleue bog (St-Hilaire et al., 2010); the peatland version of the GUESS-ROMUL model simulates the variation of net ecosystem production (NEP) with water table position in a fen (Yorova et al., 2007); ~~the Holocene Peatland Model (HPM) simulates net primary production,~~

~~decomposition, water balance and peat accumulation (Frolking et al., 2010)~~ and the PEATBOG model simulates C and N cycles in peatlands, specifically the Mer Bleue bog (Wu et al., 2013). These models have been shown to reproduce well the processes occurring in the peatlands that they were designed for. However, conclusions drawn from these studies about the global implications of peatlands on climate change are often obtained from scaling up the results of the site-level sensitivity analyses and have high uncertainties.

The coupled Canadian Land Surface Scheme (CLASS) (Verseghy, 2012) and the Canadian Terrestrial Ecosystem Model (CTEM) (Melton and Arora, 2014) constitute the land surface component of the family of Canadian Earth System Models (CanESMs). The objective of this study is to introduce peatlands into the latest coupled system of CLASS version 3.6 and CTEM version 2.0 (Melton and Arora, 2015). In this paper we present the functional and structural modifications made to the CLASS-CTEM modelling framework and the explicit site-level evaluation of the energy, water and C balances in varied peatlands that are located in typical northern peatland regions: North America, Eurasia and Siberia.

2. Model Description

CLASS was first developed in the late 1980s for inclusion in the Canadian Global Climate Model (GCM) (Verseghy, 1991; Verseghy et al., 1993), and has been under continuous development since then. It simulates the energy and water balances of the components of the land surface, mainly the temperatures and liquid and frozen water contents of the vegetation, snow and soil for four sub-areas of each grid cell (bare soil, vegetation covered ground, snow covered ground and vegetation over snow), at a timestep of 15-30 minutes. The model has been parameterized for mineral, organic or mixed soil types (Letts et al., 2000). The organic soil parameterization significantly improved the simulations of soil water and energy balances in peatlands and other organic soils (Comer et al. 2000; Bellisario et al. 2010).

CTEM simulates the terrestrial ecosystem C cycle for nine plant functional types (PFTs) and soil through photosynthesis, autotrophic and heterotrophic respiration based on parameterizations developed by Arora (2003) and Arora and Boer (2005). CTEM's treatment of soil moisture and soil carbon pools showed comparatively high correlations with the biome soil pool and turnover time among ESMs (Todd-Brown et al. 2013). These processes determine the flow of carbon in and out of model's three live vegetation components of leaves, stems and roots and two dead carbon pools of litter and soil organic matter. CTEM version 1.2 and above have an improved ability to capture the regional heterogeneity in land cover using a mosaic approach (Melton and Arora, 2014), which matches the similar capability in CLASS. When coupled to CLASS, the structural attributes of vegetation such as the leaf area index (LAI), root depth, and vegetation height that are calculated in CTEM are passed to CLASS and used in its calculations of the energy and water balance. The photosynthesis in CTEM directly controls the stomatal activity and the associated stomatal resistance of the PFTs and thus affects the energy and water exchanges at the surface in CLASS. Photosynthesis and leaf respiration are modelled at the CLASS~~a~~ time step of 15-30 minutes, whereas the rest of terrestrial ecosystem processes are modelled at a daily time step.

To account for the eco-hydrological and biogeochemical interactions among vegetation, atmosphere and soil in peatlands, the following modifications were made to the coupled CLASS3.6-CTEM2.0 modelling framework:

1. The top soil layer was characterized as a moss layer with a higher heat and hydraulic capacity than a mineral soil layer. The moss layer buffers the exchange of energy and water at the soil surface and regulates the soil temperature and moisture (Turetsky et al., 2012).

2. Three peatland vascular PFTs (evergreen shrubs, deciduous shrubs and sedges) as well as mosses were added to the existing 9 CTEM PFTs. These peatland-specific PFTs are adapted to cold climate and inundated soil with optimized plant structure (shoot/root ratio, rooting depth), growth strategy and metabolic acclimations to light, water and temperature.

3. We considered the soil inundation stress on microbial respiration in the litter C pool. The original CTEM assumed that litter respiration was not affected by oxygen deficit as a result of flooding, since litter was always assumed to have access to air. This assumption does not hold for peatlands where high water table positions occur routinely.

4. To provide the framework for future runs coupled to the global earth system model, ~~W~~we separated the soil C balance and heterotrophic respiration (HR) calculations for peatland and non-peatland fractions for each grid cell in the global model. Over the non-peatland fraction, we use~~d~~ the original CTEM approach that aggregates~~d~~ the HR from each PFT weighted by the fractional cover. Over the peatland fraction the soil C pool and decomposition are controlled by the water table position, following the two-compartment approach used in the MWM (St-Hilaire et al., 2010).

2.1 Soil layers

The water table depth (WTD) in natural peatlands fluctuates seasonally from above the soil surface to the top of the permanently saturated soil layer, which is often referred to as the boundary between *acrotelm* and *catotelm*. The boundary is usually estimated to be 30 cm below the soil surface in wetlands (National Wetland Working Group, 1997), and has been widely used as the bottom of the first soil layer in two-layer soil decomposition models (e.g. Granberg et al., 1999; Yorova et al., 2007; Spahni et al., 2013). To capture the effect of the fluctuating water table on the transfer of water and energy within the soil, we used a multi-layer configuration rather than the standard three-layer configuration of the soil layers in CLASS. We assigned nine organic soil layers, each 10 cm thick, at the top of the soil profile and a 10th soil layer from 90 cm down to the bottom of the organic soil (Figure 1). Moss was treated as the top first soil layer and the substrate below the 10th soil layer was considered as bedrock. Mineral soil was not included.

2.2 A moss layer as the first soil layer

The standard configuration of soil layers in CLASS consists of 3 layers with thickness of 0.10m, 0.25m, and 3.75m. Organic soil in CLASS was parameterized by Letts et al. (2000) as fibric, hemic and sapric peat in the three soil layers respectively, representing fresh, moderately decomposed and highly decomposed organic matter. Tests of CLASS on peatlands revealed improved performance in the energy simulations for fens and bogs with this organic soil parameterization. However, the model overestimated energy and water fluxes at bog surfaces during dry periods due to the neglect of the moss cover (Comer et al., 2000).

To take into account the interaction amongst the moss and the soil layers and the overlying atmosphere for energy and water transfer, we added a new soil layer 0.10 m thick above the fibric organic soil to represent living and dead peatland bryophytes, such as *Sphagnum* mosses and true mosses (Bryopsida). The physical characteristics of mosses differ from those of either the shoots or the roots of vascular plants (Rice et al., 2008). In particular, mosses can hold more than 30 grams of water per gram of biomass (Robroek et al., 2009). More than 90% of the moss leaf volume is occupied by the water-holding hyaline cells (Rice et al., 2008), which retain water even when the water table depth declines to 1- 10 m below the surface (Hayward and Clymo, 1982).

The parameter values of the moss layer for water and energy properties were derived from a number of recent experiments measuring the hydraulic properties of mosses (Price et al., 2008; Price and Whittington, 2010; McCarter and Price, 2012) (Table 1). Living mosses range from 2 - 3 to over 5 cm in height (Rice et al., 2008) and have lower values of dry bulk density and field capacity than fibric peat (Price et al., 2008). Compared to fibric peat, the saturated hydraulic conductivity of living moss is higher by orders of magnitude (Price et al., 2008) and the thermal conductivity is more affected by the water content (O'Donnell et al., 2009). To fully account for the effect of mosses, we set the depth of the living moss ($z\cancel{d}_m$) within the top soil (i.e. moss) layer to 3 cm for fens and 4 cm for bogs, and interpolated its water content w_m (kg water per kg dry mass$^{\cancel{-1}}$) from the water content of the overall layer $\theta_{l,1}$ (m^3 water per m^3 soil) ~~-~~and the depth of the living moss:

$$w_m = \frac{z\cancel{d}_m \theta_{l,1} \rho_w}{B_m} \qquad \textbf{Eqn. 1}$$

where the dry moss biomass (B_m) is converted from moss C (C_m) using the standard conversion factor of 0.46 kg C per kg dry biomass, $\theta_{l,1}$ (m^3 m^{-3}) is the liquid water content of the top soil layer, and ρ_w is the density of water (1000 kg m^{-3}). The maximum and minimum moss water contents were estimated from a number of observed moss water contents (e.g. Flanagan and Williams, 1998; Robroek et al., 2009). In CLASS, evaporation at the soil surface is controlled by a soil evaporation efficiency coefficient β (Verseghy, 2012). This parameter is calculated from the liquid water content and the field capacity of the first soil layer following Lee and Pielke (1992). For peatlands, β was assumed to be regulated by the relative moisture of the living moss rather than the ratio of relative liquid water content of the first soil layer:

$$\beta = 0.25[1 - \cos\left(\frac{w_m - w_{m,min}}{w_m - w_{m,max}}\right)]^2 \qquad \textbf{Eqn. 2}$$

where w_m, $w_{m,max}$, $w_{m,min}$ are the water content and the maximum and minimum water contents of the living moss in kg water per kg dry moss.

2.3 Primary production of mosses

Mosses are an important contributor to the primary production and the C sequestration in peatlands, owing to the low decomposability of the moss tissue. *Sphagnum* in peatlands grows at 20 – 1600 g biomass m^{-2} yr^{-1} and accounts for about 50% of the total peat volume (Turetsky, 2003). We have modified

CTEM to include a moss C pool and moss litter pool along with the related C fluxes, i.e. photosynthesis, autotrophic respiration, heterotrophic respiration and humification. The net photosynthesis of moss (G_m) is calculated from the gross photosynthesis ($G_{0,m}$) and dark respiration ($R_{d,m}$).

$$G_m = G_{0,m} - R_{d,m} \qquad \textbf{Eqn. 3}$$

The moss photosynthesis and dark respiration are calculated using the Farquhar (1985) biochemical approach following the MWM (St-Hilaire et al., 2010) and CTEM (Melton and Arora, 2015), with modifications for integration with CLASS-CTEM and moss phenology. The leaf-level gross photosynthesis rate $G_{0,m}$ (µmol CO_2 m^{-2} s^{-1}) is obtained as the minimum of the transportation limited photosynthesis rates (J_s) and the first root of the quadratic solution of the light-limited rate (J_e) and the Rubisco limited rate (J_c). A logistic factor (ς) is added with values 0 or 1 to introduce a seasonal control of moss photosynthesis. In the MWM, spring photosynthesis starts when the snow depth is below 0.05 m and the soil temperature at 5 cm depth goes above 0.5 °C (Moore et al., 2006). Since in our case CLASS sets the minimum depth for melting, discontinuous snow to 0.10 m, this limits the spring photosynthesis to starting only once the snow is completely melted.

$$G_{0,m} = \varsigma\, min(J_s, \frac{(J_c+J_e)\pm\sqrt{(J_c+J_e)^2-4(J_c+J_e)}}{2}) \qquad \textbf{Eqn. 4}$$

The dark respiration in mosses ($R_{d,m}$) is calculated as a function of the base dark respiration rate ($R_{d,m,0}$) which has a value of 1.1 µmol m^{-2} s^{-1} (Adkinson and Humphreys, 2011) scaled by the moss moisture ($f_{m,,rd}$) and soil temperature functions ($f_{T,rd}$). The moss moisture function is based on the volumetric water content of the moss, θ_m (m^3 water per m^3 moss). The MWM models the relation between water content in mosses and dark respiration with optimal water content at 5.8 g water per g dry weight, following the approach in Frolking (et al., 1996). We modified the relation for water content above the optimal water content, based on a recent discovery of a weak linear positive relation between the dark respiration rate and the water content above the optimal water content during the late summer and fall (Adkinson and Humphreys, 2011)

$$\mathrm{R}_{d,m} = \mathrm{R}_{d,m,0} f_{m,rd} f_{T,rd} \qquad \textbf{Eqn. 5}$$

$$f_{T,rd} = (3.22 - (0.046 * \mathrm{T}_{moss})^{(\mathrm{T}_{moss}-25/10)} \qquad \textbf{Eqn. 6}$$

$$f_{m,rd} = \begin{cases} 0, & \theta_m < 0.4 \\ 0.35{\theta_m}^{2/3} - 0.14, & 0.4 \leq \theta_\mathrm{m} < 5.8 \\ 0.01\theta_m + 0.942, & 5.8 < \theta_\mathrm{m} \end{cases} \qquad \textbf{Eqn. 7}$$

Photosynthetic photon flux density (PPFD) is measured by the photosynthetically active radiation (PAR), which is defined as the solar radiation between 0.4 to 0.7 µmol that can be used by plants via photosynthesis. In the coupled CLASS-CTEM system, the PAR received by the moss (PAR_m, unit µmol protons m^{-2} s^{-1}) is converted from the visible short-wave radiation reaching the ground (K_{*g}, unit W m^{-2}) in CLASS by a factor of 4.6 µmol m^{-2} s^{-1} per W m^{-2} (McCree, 1972). K_{*g} is a function of the incoming shortwave radiation ($K\downarrow$, unit: W m^{-2}), the surface albedo (α_g), and the canopy transmissivity (τ_c):

$$\mathrm{K}_{*g} = K\downarrow\ \tau_c(1-\alpha_g) \qquad \textbf{Eqn. 8}$$

The energy uptake by the moss layer is thus a function of the total incoming short-wave radiation, the aggregated leaf area index (LAI) of the PFTs present, the snow depth, the fractional vegetation cover and the soil water content (Verseghy, 2012). In peatland C models that do not consider vegetation dynamics, the transmissivity of the vegetation canopy is usually assumed to be constant (e.g. St-Hilaire et al., 2010). Compared with such models, CLASS enables a ~~better~~more detailed representation of light incident on the moss surface since it includes partitioning of direct/diffuse and visible/near-IR radiation, PFT-specific transmissivities, and time-varying LAI and fractional PFT coverages (Verseghy et al., 2012).

2.4 Peatland-specific PFTs

CLASS normally categorizes the global vegetation into four broad PFTs that differ in their structure and intra-annual development cycles: needleleaf trees (NDL), broadleaf trees (BDL), crops and grasses. CTEM further subdivides each PFT in CLASS into PFTs that vary in their phenology, physiology and their C assimilation rates: evergreen NDL, deciduous NDL, evergreen BDL, deciduous cold BDL, deciduous dry BDL, C3 crops, C4 crops, C3 grasses and C4 grasses. The evergreen broadleaf PFTs and C3 grasses have been parameterized primarily for tropical and temperate vegetation types that are not representative of peatland plants. Therefore, we introduced three~~3~~ new PFTs for peatlands: evergreen shrubs, deciduous shrubs and sedges. Evergreen shrubs, for example the ericaceous shrubs, are the common dominant vascular plants in bogs and poor fens while deciduous shrubs, such as the betulaceous shrubs often dominate rich fens. Both shrubs are categorized as broadleaf trees in CLASS morphologically, but their phenological and physiological characteristics are more similar to those of needleleaf trees. The shrub tundra ecosystem is situated adjacent to needleleaf forest in the northern hemisphere (Kaplan et al., 2003) and they share similar responses to climate in ESMs (e.g. Bonan et al., 2002). Table 2 lists the key parameters for the peatland PFTs used in this model. (The photosynthesis and autotrophic respiration of vascular PFTs are modeled the same as the original CTEM.)

2.5 Heterotrophic respiration

Over the non-peatland fraction, heterotrophic respiration (HR) is calculated as the sum of the respiration from litter and soil carbon pools as in the original version of CTEM (Arora, 2003). The soil C pool over the non-peatland areas is assumed to be exponentially distributed with depth (Arora, 2003). In peatlands a large amount of humic soil is generally located in the permanently saturated zone and the bulk density increases with soil depth (Loisel and Garneau, 2010). Thus the assumption of exponentially decreasing distribution of C content with increasing soil depth is not valid in peatlands. We used a quadratic equation to calculate the distribution of soil C content over depth based on an empirically determined bulk density profile (Frolking et al., 2001).

HR over the peatland fraction of a grid cell is modelled using a two-pool approach with a flexible boundary between the pools that depends on the depth of the water table:

$$\begin{cases} R_o = C_{SOM,o} k_o f_{T,o} \\ R_a = C_{SOM,a} k_a f_{T,a} f_{anoxic} \end{cases} \qquad \textbf{Eqn. 9}$$

where *o* and *a* denote the oxic and anoxic portions of the soil C pool, respectively. The respiration rate *R* (unit: μmol C m^{-2} s^{-1}) is obtained from the respiration rate coefficient~~constant~~ *k* (μmol C kg C^{-1} s^{-1}), the temperature functions f_T, the soil C mass C_{SOM} (kg) and a scaling factor f_{anoxic} after ~~which is set to 0.025~~ ~~(~~Frolking et al.~~,~~ (2010) and Frolking et al. (2001), which represents~~ing~~ the inhibition of microbial respiration under anoxic conditions. The value of this parameter is uncertain, varying in those two papers between 0.001, 0.025 and 0.1. Based on calibration runs using two of the datasets described below, MB-Bog and AB-Fen, we adopted a value of 0.025. Q_{10} is calculated using a hyperbolic tan function of the soil temperatures (T_s) of the oxic and anoxic zones (Melton and Arora, 2015), which are in turn functions of water table depth (Eqn. 10). The Q_{10} values of the anoxic and the oxic zones of the soil are indicated as $Q_{10,a}$ and $Q_{10,o}$. The values of k, f_T and C_{SOM} are updated along with the water table depth (z_{wt}, unit: m, positive downward) and the peat depth (~~d_p~~z_p, unit: m) at each CTEM time step. The equations for k and C_{SOM} are derived from Figure 2 in Frolking et al. (2001), and parameterized differently for fens and bogs (Table 3):

$$\begin{cases} f_{T,o} = Q_{10,o}{}^{(\int_{0\cancel{1}}^{z_{wt}} T_j - 15)/10} \\ f_{T,a} = Q_{10,a}{}^{(\int_{z_{wt}}^{z\cancel{d}_p} T_j - 15)/10} \end{cases} \qquad \textbf{Eqn. 10}$$

$$Q_{10} = 1.44 + 0.56\tanh[0.075(46.0 - T_s)] \qquad \textbf{Eqn. 11}$$

$$\begin{cases} T_{s,o} = \int_0^{z_{wt}} T_j \,/(z_{wt}) \\ T_{s,a} = \int_{z_{wt}}^{z\cancel{d}_p} T_j \,/(\cancel{d}z_p - z_{wt}) \end{cases} \qquad \textbf{Eqn. 12}$$

$$k_o = \begin{cases} 0, & z_{wt} < 0 \\ k_1\left(1 - e^{k_2 z_{wt}}\right) + k_3 z_{wt}, & 0.3 > z_{wt} \geq 0 \\ k_4 e^{k_5 z_{wt}} + k_6 z_{wt} + k_7, & z_{wt} \geq 0.3 \end{cases} \qquad \textbf{Eqn. 13}$$

$$k_a = \begin{cases} k_4 e^{k_5 z\cancel{d}_p} + 10 k_6 z\cancel{d}_p + k_7, & z_{wt} < 0 \\ \left|k_1 e^{k_2 z_{wt}} - k_4 e^{k_5 z\cancel{d}_P} - k_3 z_{wt} + k_8\right|, & 0.3 > z_{wt} \geq 0 \\ k_4\left(e^{k_5 z\cancel{d}_P} - e^{k_5 z_{wt}}\right) + k_6\left(z\cancel{d}_P - z_{wt}\right), & z_{wt} \geq 0.3 \end{cases} \qquad \textbf{Eqn. 14}$$

$$C_{SOM,o} = 0.487 * (k_9 {z_{wt}}^2 + k_{10} z_{wt}) \qquad \textbf{Eqn. 15}$$

$$C_{SOM,a} = C_{som} - C_{SOM,o} \qquad \textbf{Eqn. 16}$$

where 0.487 is a parameter that converts from soil mass to soil C content. The variation of k_o and k_a with water table depth for bogs and fens is shown in Figure 2. It will be noted that there is a sharp transition in decomposition rate at a depth of 0.3 m, reflecting the work of Frolking (2001). As noted in section 2.1 above, this value is widely accepted as a representative estimate of the depth dividing the acrotelm and catotelm. In reality, of course, this depth will vary among peatlands. When our peatland model is implemented in climate mode, it is planned that spinup tests will be run to assess the spatial variability of this depth, and adjustments will be made to equations 13 and 14 if necessary.

As only organic soil is considered in peatlands, the peat soil C is updated from the humification (C_{hum}, kg C m^{-2} day^{-1}) and soil respiration from the oxic (R_o in kg C m^{-2} day^{-1}) and anoxic (R_a in kg C m^{-2} day^{-1}) components during the time step:

$$\frac{dC_{som}}{dt} = C_{hum} - R_o - R_a \qquad \textbf{Eqn. 17}$$

C_{hum} is calculated as a PFT-dependent fraction of the decomposition rate. Values of this coefficient are shown in Table 2 (variable “humicfac”). At the end of each time step, the peat depth (i.e. the depth of the organic soil) ~~d_p~~ z_p is updated from the updated peat C mass (C_{SOM} in kg) by solving the quadratic equation:

$$z\cancel{d}_p = \frac{-k_{10}+\sqrt{k_{10}+\frac{4k_9C_{som}}{0.487}}}{2k_9} \qquad \textbf{Eqn. 18}$$

The water table depth z_{wt} is deduced by searching for a soil layer below which the soil is saturated and above which the soil moisture is at or below the retention capacity with respect to gravitational drainage. Within this soil layer j, z_{wt} is calculated as:

$$z_{wt} = z_{b,j} - \Delta z\left[\frac{\theta_{l,j}+\theta_{i,j}-\theta_{ret,j}}{\theta_{p,j}-\theta_{ret,j}}\right] \qquad \textbf{Eqn. 19}$$

where Δz is the thickness of soil layer (unit: m), θ_l and θ_i are the liquid and frozen water contents (unit, m^3 m^{-3}), θ_{ret} and θ_p are the water retention capacity and the porosity, and $z_{b,}$ (unit: m) is the bottom depth of the soil layer.

3. Evaluation methods and data

3.1 Site locations

The model was applied at eight peatlands sites to assess its performance in simulating the water, energy and C fluxes. ~~Data were obtained from the FLUXNET database (http://fluxnet.ornl.gov/).~~ The peatlands selected consist of four bogs and four fens sites (Figure~~.~~ 3~~2~~). The bogs are the Auchecorth Moss (UK-Amo), 18 km south of Edinburgh, Scotland; the Fajemry Bog (SE-Faj), in the south of Sweden; the Fyodorovskoye Bog (RU-Fyo), about 340 km north-west of Moscow, Russia; and the Mer Bleue Bog (MB-Bog), about 20km away from Ottawa, Canada. The fens are the Kaamanen Wetland (FI-Kaa), close to Inari in Finland; the Lompolojänkkä northern boreal fen (FI-Lom), in northern Finland; the Degerö Stormyr (SE-Deg) near Uppsala, Sweden; and the Alberta Western Peatland treed fen (AB-Fen), north of Edmonton. The characteristics of the 8 peatlands represented nutrient gradients from ombrotrophic to minerotrophic, elevations between 65 and 581 meters above sea level, mean annual precipitation (MAP) ranging from 473 to 1155 mm per year, mean annual temperature (MAT) between -1.4 and 10.0 degrees C and maximum leaf area index (LAI) ranging from 0.7 to 3.5 (Table 4).

Data were obtained from the FLUXNET database (http://fluxnet.ornl.gov/). For each site and for each downloaded variable, the highest available data level was used. The meteorological drivers for the model were obtained from level 4 (gap-filled and quality-controlled) data, except for the wind speed, which was obtained from level 3 and surface pressure from level 2 data. Carbon fluxes were obtained from level 4 daily average data when available. The observed GPP and NEP in the FLUXNET database were derived from the observed NEP and the relations between NEP, temperature and photosynthetically active radiation (PAR). The remaining fluxes were averaged from half hourly level 2 and level 3 data.

In the model evaluation, it must be borne in mind that eddy covariance measurements of turbulent fluxes of energy, water and carbon are subject to inherent uncertainties and errors related to atmospheric conditions such a low turbulence and wind direction, or to equipment malfunction. For this reason we selected a relatively large number of test sites with multi-year datasets, and focused on long-term averages for the validation. We also included in the evaluation variables such as water table depth, soil temperature and snow depth, which are not dependent on turbulent flux measurements.

3.2 Model initialization and spin up

For each site, the FLUXNET database was used to assign values to background variables such as latitude, longitude, peat depth, areal coverage of the three peatland PFTs, and their roughness lengths, visible and near-infrared albedos and canopy mass. Other CLASS- and CTEM-related vegetation parameters were assigned their standard values, as listed in Table 2. The parameter values for evergreen shrubs, deciduous shrubs and sedge mostly reflected those used for evergreen needleleaf trees, deciduous needleleaf trees and C3 grasses in CTEM, respectively. Exceptions were made for some parameters that determine the length or shape and turnover of the stem and root of the PFT and its tolerance to coldness and dryness (Table 2).

Model C pools in vegetation were spun up from initial conditions by repeatedly cycling through the inputs for approximately 100 years until the annual mean C pools ~~in vegetation~~ in consecutive years differed by less than 5%. The initial soil C mass was calculated from the observation-based estimations of peat depth based on an empirically obtained relation between the soil depth and soil mass (Eqn. 15).

3.3 Observational data sets

The model was forced with half-hourly measured meteorological data: downwelling shortwave radiation, downwelling longwave radiation, precipitation, atmospheric pressure, air temperature (T_a), specific humidity, and wind speed. The measurement heights for the latter three were obtained from the FLUXNET metadata. Datasets ranged in length from 2 to 9 years. The parameters used for model evaluation include water table depth (z_{WT}), snow depth, soil temperature (T_s), latent heat flux (QE), sensible heat flux (QH), GPP, ER and NEP. Energy and C fluxes were measured every 30 minutes using the eddy-covariance (EC) technique. The required downwelling longwave radiation (LW) was available only at MB-Bog, AB-Fen, SE-Deg and FI-Lom. For the remaining 4 sites, LW was estimated following the methods of Crawford and Duchon (1998):

$$LW \downarrow = [c_f + (1 - c_f)\varepsilon_c]\sigma {T_a}^4 \qquad \textbf{Eqn. 20}$$

where σ is the Stefan–Boltzmann constant and c_f is the cloud fraction term ranging between 0 and 1. c_f is estimated as the ratio between the incoming shortwave radiation and the clear-sky solar radiation, which in turn is a function of the locational character of the site, i.e. latitude, longitude, altitude and time zone. ε_c is the clear sky emissivity and is estimated from the vapor pressure (e_0) following Ångström (1918):

$$\varepsilon_c = 0.83 - 0.18 * 10^{-0.067e_0} \qquad \textbf{Eqn. 21}$$

Water table depths were available for 3 bogs (RU-Fyo, SE-Faj and MB-Bog) and 3 fens (AB-Fen, FI-Lom, SE-Deg) sites and snow depths were available for MB-Bog and AB-Fen only. Soil temperatures were available at 1, 5, 10, 20, 40, 80, 150 and 250 cm below the soil surface at the MB-Bog and at 2, 5, 10, 20, 50, and 100 cm below the soil surface at AB-Fen. For the other 6 sites, the soil temperature was only measured at 5 cm below the surface.

3.4 Evaluation methods

The model was evaluated against observation-based daily sensible and latent heat fluxes at the soil surface, soil water content, water table and snow depth, soil temperature at various depths and the daily, monthly and annual C fluxes (GPP, ER, NEP). The root mean square error (RMSE) and linear regression coefficient (r^2) were primarily used for evaluation. Statistical analyses were conducted using the free software package R version 3.1.1 (R Core Team, 2014).

Since the ultimate goal is to apply the model globally in an ESM, further experiments were done to investigate the importance of modelling fens and bogs separately. In the version of the model described above, bogs and fens are distinguished primarily through the parameterization of the control of water table depth on soil decomposition (Table 3). Also, the depth of the living moss (d_m) is set to 4.0 cm for bogs and 3.0 cm for fens. In a first test, the parameters for soil decomposition (Table 3) for bogs were used for the fen sites and those for the fens were used for the bog sites. In a second test, the living moss layer was set to a set to a single fixed value of 3.5 cm for both bogs and fens. The resulting differences in the surface fluxes and the soil temperatures were then evaluated.

4. Results and Discussion

4.1 Water budget terms

Figure 4~~3~~ illustrates the simulated daily WTD compared with observations at the six sites where WTD was observed. The model successfully simulated the seasonal dynamics and the zone of fluctuation of the water table in the first two bogs, except for the extremely deep water table observed in RU-Fyo in 2010. Although ponded water is simulated in the model, the simulated WTD did not include the depth of pond above the soil surface, which appears in the observations as a negative value, for example up to -0.14 m in the SE-Faj bog during the winter. The simulated WTD of the FI-Lom fen agreed well with the observations after the spring of the second simulated year (2008). The modeled WTD was calculated as the uppermost surface of the liquid water present in the soil, and thus did not account for the potential occurrence of liquid water below the surface frozen soil layer. As a result, the simulated WTD stayed close to the soil surface over the winter when the soil was frozen. The errors in MB-Bog were consistent over time, which was likely a result of the difference between the observed and modeled peat surfaces. The difference in height between hummocks and hollows at the MB-Bog is about 0.25 m (Lafleur et al., 2005) and the bottom of the fibric peat lies at 0.35 m and 0.10 m below the peat surface for hummock and hollow, respectively (Dimitrov et al., 2010). The parameterized MB-Bog, with 0.10m of fibric peat, is therefore closer to a hollow (Table 1). Correcting the modeled WTD by 0.25 m led to a high agreement with the observed WTD in MB-Bog (Figure 4~~. 3~~). For AB-Fen, the model overestimated the inter-annual fluctuation and did not reproduce the trend of increasing WTD seen in the observations, which was likely associated with the change in vegetation cover. It has been observed that the AB-Fen site is currently changing from a rich fen to a poor fen and is now in a phase of rapid tree establishment and increase in LAI and NEP (Flanagan and Syed, 2011).

The model reproduced the annual variation of snow depth quite well for the bog and fen sites where observations were available (Figure 5~~. 4~~). The errors for the MB bog may be associated with uncertainties in the observed data stemming from the combination of a continuous record from one spot with sporadic snow depth data from other locations on the bog surface (Moore et al, 2006).

4.2 Energy budget terms

The model performed similarly well on the daily average latent heat (QE) and sensible heat (QH) fluxes for multi-year simulations (Table 5, Figure~~.~~ 6~~5~~). The RMSEs ranged from 23.0 to 37.7 W m^{-2} (QH) and 27.3 to 79.7 W m^{-2} (QE) for bogs and from 19.6 to 41.5 W m^{-2} (QH) and 15.8 to 31.5 W m^{-2} (QE) for fens. When organic soils were first introduced into CLASS by Comer et al. (2000), RMSEs ranged from 16.9 to 47.7 W m^{-2} (QH) and 23.1 to 65.6 W m^{-2} (QE) for fens and 67.4 to 182.5 W m^{-2} (QH) and 78.1 to 153.8 W m^{-2} (QE) for bogs. Our new model shows a consistent improvement in the energy flux simulations, especially for bogs, where the surface moss cover plays an essential role in regulating the thermal and hydraulic conductivities (Turetsky et al., 2012).

The mean r^2 coefficient between the simulated and observed daily average QH was 0.47 and the highest r^2 was 0.89 for the AB-Fen site. The poorest agreement in QH occurred in the FI-Kaa fen and the UK-Amo bog. The error in FI-Kaa peaked in the winters of 2002 and 2007 when the snow depth exceeded 0.8 m (not shown). Turbulent fluxes over deep, cold snow packs are notoriously difficult to model accurately (Bazile et al., 2013). In the case of QE, the mean r^2 for the 8 sites is 0.52, and rises to 0.60 if the outlier UK-Amo is disregarded. The large bias of QH and QE at UK-Amo is thought to be partially attributable to instrumental errors, given the scattered data cloud of the observed QE in 2006 (not shown).

The simulated daily average soil temperature at 5 cm depth across the eight sites agreed well with the observations, with r^2 values between 0.77 and 0.98. The comparatively low value found for UK-Amo is perhaps linked to the errors in QE noted above. The RMSE ranged from 1.7 to 4.7 °C with a mean of 3.1 °C. This is larger than the RMSE range of 0.7 to 2.3 °C found for LPJ-WHy v1.2 by Wania et al. (2009a), yet is encouraging considering that the simulation periods for our sites ranged from 2 to 9 years compared to the 1 year simulation with LPJ-WHy, and that we included eight sites in our evaluation compared with two peatland sites for LPJ-WHy. Our model was able to capture the seasonal variation in soil temperature at different depths down to the bedrock. Figure 7~~6~~ compares the modeled soil temperatures against the observations at 5cm, 40cm, 80cm, and 250 cm depths for the Mer Bleue bog, where good-quality data are available for soil T at various depths.

4.3 Carbon fluxes

In eddy-covariance measurements, as noted in section 3.1 above, GPP and ER are obtained by partitioning the observed NEP on the basis of empirically derived relationships. In the case of modelled carbon fluxes, on the other hand, NEP is calculated by subtracting ER from GPP, therefore the error~~bias~~ in the NEP simulations accumulates~~compared with observations accumulates from~~ the errors~~biases~~ in GPP and ER. Bearing in mind these caveats, ~~E~~examination of the modelled daily GPP, ER and NEP suggests~~demonstrates~~ that the model is capable of capturing seasonal dynamics and climate-driven events consistently in various types of peatlands. ~~(~~Figures 8-10 show the daily average fluxes in time series form.~~. 7, 8, 9).~~ The RMSE (Table 6) is between 0.43 and 0.67 g C m^{-2} day^{-1} for GPP and ER for the three sites in Scandinavia and Canada (FI-Kaa, MB-Bog, and SE-Faj, ~~)~~ two bogs and a fen) that have high-quality observed data and are not undergoing vegetation shifts. Larger biases of GPP and ER occurred in the blanket bog (UK-Amo) and the Russian ombrotrophic bog (RU-Fyo), the peat depths of which were very deep and relatively shallow respectively – up to 10 m in UK-Amo and 1 m in RU-Fyo (Table 4). Variations in the historical climate have led to variations in the peat accumulation rates over the Holocene and the vertical stratification of the peat and hence the decomposition rates and decomposability of the peat, which becomes important for deeper, older peat deposits. The Russian bog may be an outlier because warm climate conditions persisted until about 5000 B.P. in Northern Siberia and about 1000 years later in most other areas (Yu et al., 2009). The RU-Fyo bog experienced a period of low GPP due to an abrupt decrease of air temperature in the early fall of 2010, which was well reproduced by the model. The starting and ending periods of photosynthesis in the spring and fall were accurately simulated except for the coldest peatland, FI-Lom, where the length of the growing season was slightly overestimated. Short periods of overestimation of soil temperature at 5 cm existed during that period, by up to 5°C, which may have caused the errors in GPP; Moore et al. (2012) noted a high correlation between soil temperature and the initiation of photosynthesis in the spring.

~~NEP is calculated by subtracting ER from GPP, therefore the bias in the NEP simulations compared with observations accumulates from the biases in GPP and ER.~~ The RMSE of the daily NEP simulations (Table 6) ranges from 0.486 to 1.65 gC m^{-2} day^{-1}. The lowest biases were for the SE-Faj bog and the two poor fens (SE-Deg and FI-Kaa) that had little vegetation cover, with the maximum LAI below 1.0 m^2 m^{-2}. Values of r^2 greater than about 0.3 were observed at six sites. At the two others, SE-Faj and UK-Amo, the observed NEP varied widely, ranging from -1.8 to 2.2 g C m^{-2} day $^{-1}$ and from -3.9 to 4.8 g C m^{-2} day $^{-1}$ respectively. The discrepancy with the modelled values, contributing~~Model errors for the extremes values at these two sites may have contributed~~ to the~~ir~~ low r^2 values for these two sites, might be due either to weaknesses in the model or to inadequate screening of the eddy covariance measurements. NEP was overestimated at the beginning and the end of the growing season for FI-Lom due to the overestimation of GPP for that period as discussed above. These results may be compared to an evaluation of the MWM using the SE-Deg dataset that was conducted by Wu et al. (2013). For daily NEP they obtained an RMSE of 0.49, similar to ours, but a higher r^2 of 0.52. It should be noted that the MWM was driven by observed WTD and soil temperature, while in our simulations these were allowed to evolve freely, so our comparable result is gratifying.

Figures 11-13 show the daily modelled versus observed GPP, ER and NEP in scatterplot form. Although the model performs reasonably well, with r^2 values averaging over 0.7 for both GPP and ER, a general tendency can be seen for the modelled GPP to be biased low at high and low values, and high at medium values. The bias in the very low values may be spurious, given the relatively large errors associated with eddy covariance measurements of small fluxes; also, the occasional negative observed values of GPP may be indicative of erroneous partitioning of the measured NEP between GPP and ER. At FI-Lom, FI-Kaa and UK-Amo, the high model bias at low observed values may be related to early leaf-out and/or delayed leaf drop. The biases at medium values are possibly related to the use of the “big-leaf” assumption in CLASS-CTEM, which neglects sunlit and shaded canopy fractional areas, and may have a dampening effect on photosynthesis. Low biases at high values may be related to water stress caused by a low water table, as seen in Figure 4 for RU-Fyo and FI-Lom. In the case of ER, the modelled values do not show systematic biases except for RU-Fyo and UK-Amo, which were difficult to model as noted above. Given the fact that a major focus of this study was the incorporation of respiration for organic soils and mosses into CLASS-CTEM, this is encouraging.

Since NEP is the residual of two large terms, GPP and ER, in Figure 14 we investigate the relationship between the modelled GPP, autotrophic respiration (AR) and heterotrophic respiration (HR). Across most sites, simulated AR is approximately 40 - 50 % of GPP with a relatively consistent relationship between the two. In CLASS-CTEM, autotrophic respiration is sensitive to temperature, the maximum catalytic capacity of Rubsico, and the vertical profile of radiation along the depth of the canopy (Melton and Arora, 2016). GPP is also sensitive to these same factors and thus tends to respond similarly. HR is much more variable than AR and GPP and also shows greater variability between sites. FI-Kaa is relatively consistent in simulated HR while sites such as SE-Faj and FI-Lom have markedly variable HR fluxes. HR in CLASS-CTEM is sensitive to soil matric potential, soil temperature and detrital carbon stocks (Melton and Arora, 2016). The strongest control on the HR variability at these sites appears to be the soil matric potential. The CLASS-CTEM HR parameterization has a maximal rate at a soil matric potential intermediate between wet and dry soils (absolute soil matric potential between 0.04 and 0.06 MPa; see Figure 1 in Melton et al. 2015). The primary assumption of the HR parameterization is that soil moisture constrains HR when soils are very dry due to limited microbial respiration. As soil become very wet, HR also drops to reflect diminished oxygen supply to microbes. The sites with the high variability of HR tend to reflect soil moisture conditions during the growing season with soil matric potentials fluctuating between the zone of optimal HR production and shutdown due to overly moist soils. For example, in 2007, SE-Faj had high variability of HR with the water table rising from 12 cm to only a few centimetres below the soil surface (indicating saturated soil conditions) resulting in a large shutdown of the HR flux, while 2008 was a drier year with a water table more consistently about 20 cm below the surface and much less variable HR fluxes simulated.

The simulated accumulated monthly NEP from March to November agreed well with the observations in the four bogs and four fens. The outliers for bogs were the overestimations in MB-Bog in October and November due to the underestimation of GPP (Figure~~.~~ 8~~7~~). The NEP in RU-Fyo in one August was underestimated owing to the underestimated GPP, which in turn was a result of the underestimated LAI and rooting depth temperature in the summer. Figure 15~~0~~, showing plots of NEP averaged for each month of the year at each site, demonstrates on the whole larger scatter for the bogs than the fens, with the scatter increasing through the summer and fall. The overall value of r^2 was 0.59 for bogs and 0.58 for fens; both values are higher than or similar to those obtained in evaluations of other peatland C models. For example, the r^2 value of the monthly NEP for LPJ-WHy was reported to be 0.35 for four peatlands, with three of the sites overlapping those used in this study: SE-Deg, FI-Kaa and MB-Bog (Wania et al., 2009b). The Finland peatland model simulated the NEP in FI-Kaa with r^2 of 0.80 for the same time period tested for our model (Gong et al., 2013), but only the one site was used in the evaluation.

4.4 ~~Annual Carbon budget~~Annual net ecosystem production

The simulated mean annual NEP values with their standard deviations generally fall within the range of the standard deviations of the observations (Figure 16~~. 11~~), between 9 g C m^{-2} yr^{-1} in the rich fen (FI-Lom) and 73 g C m^{-2} yr^{-1} in the productive bog (RU-Fyo) (Table 7). The only site with large bias in annual NEP was AB-Fen. Observation-based estimations of NEP in this fen were extremely high, totalling 176 g C from May to October, in comparison with other sites (Syed et al., 2006). This treed fen had a high peat density and LAI and large variation in the WTD, which, accompanied by high spring temperatures, resulted in high ecosystem photosynthesis capacity and production (Adkinson et al., 2010). Considering nutrient factors and the site-specific peat density could potentially capture the large NEP at this site. The observed annual NEP for the eight sites varied greatly overall, between -17 and 187 C m^{-2} yr^{-1}, while the simulated NEP showed slightly less variation, ranging from 13 to 157 g C m^{-2} yr^{-1}. The simulated mean annual NEP across the sites was 87 g C m^{-2} yr^{-1} and was 22 g C m^{-2} yr^{-1} higher than the mean observed NEP. In contrast the LPJ-WHy model simulated most of the annual NEP between -5 – 0 gC m^{-2} yr^{-1}, lower than their observed median of 40 g C m^{-2} yr^{-1} (Wania et al., 2009b). As noted above, variations in the depth and age of the peat at the eight sites reflected fluctuations in past climate, leading to site-specific soil properties that were not always captured by the standardized values used in the model. Peatlands in different geographical locations also reflected the effects of local conditions: for example, the blanket bog UK-Amo in a maritime climate accumulated 101 g C m^{-2} yr $^{-1}$ in 2007 (Dinsmore et al., 2010) while the dry MB-Bog was estimated to be a source of 13.8 g C m^{-2} yr $^{-1}$ (Roulet et al., 2007). The modeled NEP bias tended towards underestimation for the treed fen (AB-fen) and the productive ombrotrophic bog (MB-Bog), and towards overestimation for the remaining sites .

The model errors in GPP were smaller than the standard deviation of the observations, except for the atypical sites (AB-Fen, RU-Fyo) and the sites that had only a few years of data (FI-Lom, SE-Faj) (Table 7). The bias of the simulated ER did not exceed the error bars except for in the RU-Fyo bog, for which a thin peat depth of 1 meter was used to initialize the simulation (Table 4). The simulated WTD was consistently shallower in the summer than the observations (Figure 4~~. 3~~), which slowed down the soil respiration in the model and contributed to the discrepancies in ER. The observed WTD showed an abrupt decrease in the summer of 2010 without pulses of large ER being observed during that period (Figure 9~~. 8~~), indicating uncertainties in the WTD observations. Another reason for the errors in ER was the underestimation in soil T. For example, the simulated soil T at 5 cm depth was higher in the summers with RMSE of 4.6 °C in RU-Fyo (Table 5). The site is particularly shallow and homogeneous, thus the standardized living moss layer of 4 cm for bogs was probably too large, leading to an overestimation of the thermal insulation effect from the moss layers and hence less seasonal variation in soil temperature and ER.

An overview of the model's performance is illustrated via a series of Taylor diagrams (Figure 17~~. 12~~). Taylor diagrams provide a graphical summary of how closely modelled data match observed data (Taylor, 2001). The radial spokes represent the level of correlation and the x and y axes show the standard deviation. The standard deviation of the observations is plotted on the x axis, and the RMSE of the modelled values is indicated by the concentric contours around this point. Since we have eight pairs of modelled and observed points for each diagram, we normalized the data by dividing each of the standard deviations and the RMSEs by the standard deviation of the observations associated with each point, so that all the observation points fall at 1 on the x axis. The outliers are the vegetated treed fen (AB-Fen), the maritime blanket bog UK-Amo and the extremely shallow peatland RU-Fyo. The model simulations consistently agreed quite well with the observations except at these sites for some evaluated parameters. The Pearson *r* was above 0.90 for the soil temperature at 5 cm and above 0.50 and 0.60 for the sensible and latent heat fluxes, except for those at UK-Amo. The modeled daily GPP and ER were highly correlated with the observations, with Pearson *r* values between 0.80 and 0.95 for GPP, and between 0.70~~5~~ and 0.96 for ER. The simulated daily NEP accumulated the errors in GPP and ER and was somewhat less well correlated with the observations, with Pearson *r* values between 0.4 and 0.72.

4.5 The necessity of distinguishing fens and bogs

The original version of our peatland model (referred to as “*CONTROL*” hereafter) as described above distinguishes bogs and fens through the controls of water table depth on soil decomposition and the depth of the living moss. The parameters for the water table depth regulation of soil decomposition were derived from the empirical relations in the MWM (Eqn. 13, 14). Our first test, “*K-SWAP*”, involved swapping the values of the decomposition parameters (Table 3) between the bog and fen sites. As shown in Figure 18~~. 13~~, the differences between the test and control runs are generally very small~~minimal~~. The relative differences in the simulated values of the fluxes and temperatures between *K-SWAP* and *CONTROL* ranged from -1.6 % to +5.1 % for RMSE and from -23 % and +6 % for r^2. The relative differences in RMSE and r^2 for GPP, QH, QE and Ts5 were smaller than ±1 %. The largest differences in r^2 between *K-SWAP* and *CONTROL* were for NEP at SE-Faj and UK-Amo, which had significantly lower r^2 values than the other sites. The long-term effect on the overall carbon balance, as reflected in the cumulative NEP, is shown for six of the sites in Figure 19. (AB-Fen and RU-Fyo are omitted, since the differences in those two cases were imperceptible for both sensitivity tests.) The cumulative differences were everywhere less than 15%. The results of *K-SWAP* indicate that parameterizing fens and bogs differently for the regulation of water table depth on soil decomposition does not make a large~~makes little~~ difference in the simulation.

The second test, “*D-MOSS*”, retained the settings in *K-SWAP* and changed additionally the depth of the living moss in both bogs and fens to 3.5 cm. The RMSE and r^2 of *D-MOSS* show site-specific differences compared to *CONTROL* (Figure~~.~~ 18~~3~~). The relative differences between *D-MOSS* and *CONTROL* in RMSE and r^2 were in the range of – 5 % to +7 % and -15 % to +13 %, respectively. The mean differences for all sites and all evaluated variables were less than 5% for both RMSE and r^2. For GPP, ER and the soil temperature at 5 cm depth, the r^2 in *D-MOSS* was similar to that of *CONTROL*. For QE, the r^2 in *D-MOSS* was higher than the control for all the fens and one unusual bog (UK-Amo), but not for the other three bogs. Compared to *CONTROL*, the r^2 of NEP was higher in *D-MOSS* for five sites by up to 7 % and less than 2 % lower in the other sites, except for UK-Amo where r^2 was also low in *CONTROL*. Turning to the long-term carbon balance as shown by the cumulative NEP in Figure 19, it is evident that the depth of the living moss has more of an effect on the simulation than the decomposition parameters. The difference is largest for FI-Kaa at 29%, and then SE-Faj and SE-Deg at 23%. However, the effect of the moss depth~~ of living moss~~ seems to be more~~-~~ site-specific than related to the differences between bogs and~~ versus~~ fens ~~difference~~.

Since as noted in section 2.5 above, there was some uncertainty about what value to assign to the anoxic respiration scaling factor f_{anoxic}, a third test was performed to assess the sensitivity of the simulation to this parameter. Frolking et al. (2010) assigned it a value of 0.001, and Frolking et al. (2001) set it to 0.025 for bogs and 0.1 for fens. For our simulations, based on the results of calibration runs we chose a constant value of 0.025 for all of the sites. Since according to Frolking et al. (2001) this value is more representative of bogs, we ran tests for the four fen sites with f_{anoxic} set first to 0.1 and then to 0.001. The effect of the changes on the cumulative ER is shown in Figure 20. It can be seen that the maximum cumulative difference is only about 9% (for f_{anoxic} = 0.1 at SE-Deg), and in the other cases the differences are much smaller. This suggests that we are not incurring any serious errors by using a single value for f_{anoxic}.

Based on the results of ~~T~~the three~~two~~ tests described above, we conclude ~~suggest~~ that when our model is applied at climate time and space scales, ~~when applying the model, it is not necessary to distinguish~~as a first-order approximation it will not be necessary to distinguish between fens and bogs through the use of different model parametrizations and coefficients. ~~, in contrast to the MWM and its soil decomposition component the Peatland Decomposition Model (PDM) (Frolking et al., 2001), which were developed for the detailed modelling of specific sites. Therefore, when the present model is implemented within CLASS-CTEM on regional and global scales, one general type of peatland may be simulated with no differentiation between bogs and fens~~It will only be necessary to map the locations of peatlands, and whether a given peatland behaves like a bog or a fen will evolve out of the climate forcings, which will determine the vegetation cover and the hydrological characteristics of the peatland in question. ~~.~~This will considerably simplify the global implementation of the model, since global datasets mapping the locations of fens vs. bogs are not available.

5. Conclusions

We have presented here an extension of the CLASS-CTEM model, enabling it to simulate the water, energy and C cycles of peatlands. The model simulations of the daily C fluxes are of comparable accuracy to those performed by other models that were developed for a particular site or an area, for example the Finland regional peatland model (Gong et al., 2013) for the FI-Lom site and the MWM for the MB-Bog and SE-Deg sites (Wu et al., 2013). Compared with models that simulate global peatland C fluxes such as LPJ-WHy (Wania et al., 2009a, b) and CLIMBER2-LPJ (Kleinen et al., 2012), our model performs well and covers the ranges in the observations (Yu et al., 2010). The variations in climatic conditions and in the C stocks contained by peatlands in nature are difficult to capture completely by the general peatland model here. The model errors were larger for sites with unusual soil properties or vegetation cover. Long-term decline of water table depth can also shift the vegetation in peatlands from mosses and grasses to shrubs and trees (Flanagan and Syed, 2011; Munir et al., 2014; Talbot et al. 2010). Taking into account such effects could improve the performance of the model (Sulman et al., 2012). Also, other forms of C besides CO_2, such as methane (CH_4) and dissolved organic C, are as yet missing from the C budget in the model and need to be included in order to fully simulate the net C budget of peatland ecosystems. At the moment, approaches to modelling CH_4 emissions from peatlands or wetlands diverge widely and further work is needed in areas such as more accurate land surface classification, more realistic emissions from non-inundated wetlands (where water table depth regulates the emissions) and peat soils from high latitudes (Bohn et al., 2015). This study has tested the model's performance on northern peatlands only; further tests are needed to validate the model on the remaining 10% of peatlands (Yu et al., 2011) that are located in the tropical region and southern hemisphere.

The coupled CLASS-CTEM models serve as the land surface component for the family of Canadian Earth System Models (CanESMs). Despite some limitations in simulating unusual peatlands, the extended version that we have presented here shows an overall good skill in simulating the water and energy dynamics and the daily and annual C fluxes in peatlands. Contrary to models designed for specific sites such as the MWM, the peatland model presented here need not distinguish between bogs and fens, which constitutes a distinct advantage for application in an ESM at the global scale.

Code Availability

Fortran code for the CLASS-CTEM modelling framework is available on request and upon agreeing to Environment Canada's licensing agreement available at http://collaboration.cmc.ec.gc.ca/science/rpn.comm/license.html. Please contact the third author, Dr. Joe Melton (joe.melton@canada.ca) to obtain model code.

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Figures

Figure 1. Schematic diagram of the peatland CLASS-CTEM model with 12 PFTs and 10 soil layers. The symbols C, T and θ represent carbon, temperature and soil water content respectively. The subscripts L, S, R, H, and D represent leaf, stem, root, fresh litter and old litter respectively.

Figure 2. Variation of respiration rate coefficients k_o and k_a with water table depth.

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Figure 4~~3~~. Simulated and observed daily average water table depth (m) in three bogs (MB-Bog, RU-Fyo, SE-Faj) and three fens (AB-Fen, FI-Lom, SE-Deg).

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Figure 12. Scatterplots of simulated vs. observed daily ER (gC m^{-2} d^{-1}) in bogs and fens.

Figure 13. Scatterplots of simulated vs. observed daily NEP (gC m^{-2} d^{-1}) in bogs and fens.

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Table 1. Physical properties of organic soil types

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Table 7. Summary of observed (obs.) and modeled (mod.) mean annual GPP, ER and NEP of the 8 sites with standard deviation shown in brackets; units are g C m^{-2} yr^{-1}.

Tables

Table 1. Physical properties of organic soil types

Soil Type	Soil depth (cm)	Pore Volume (m^3 m^{-3})	Retention capacity (m^3 m^{-3})	Residual water content (m^3 m^{-3})	Clapp and Hornberger parameter "b"	Saturated Hydraulic conductivity (m s^{-1})	Soil moisture Suction at saturation (m)	Heat Capacity (J m^{-3} K^{-1})
Moss	0 – 10	[1]0.980	[2]0.200	[3]0.010	2.3	[4]$0.183*10^{-2}$	[5]0.0103	[5]$2.5*10^6$
Fibric	10 – 20	0.935	0.275	0.040	2.7	$0.280*10^{-3}$	0.0103	$2.5*10^6$
Hemic	20 – 50	0.880	0.625	0.150	6.1	$0.200*10^{-5}$	0.0102	$2.5*10^6$
Sapric	> 60	0.830	0.705	0.220	12.0	$0.100*10^{-6}$	0.0101	$2.5*10^6$

[1]O'Donnell et al., 2009; [2]Price and Whittington, 2010; [3]McCarter and Price, 2012; [4]Price et al., 2008; [5]Berlinger et al., 2001.

Table 2. Descriptions of vegetation characteristics for the four peatland PFTs. A dash (−) indicates the parameter is inapplicable to that PFT.

Parameter name	Description	Unit	Moss	Evergreen shrubs	Deciduous shrubs	Sedge	References
abar	Parameter determining root distribution	−	−	8.50	9.50	9.50	1
avertmas	Average root biomass for estimating rooting profile	Kg C m^{-2}	−	1.50	1.20	0.20	1
bsratelt	Litter respiration rate at 15 °C	Kg C kg C^{-1} $year^{-1}$	−	0.4453	0.5986	0.5260	2
bsratesc	Soil C respiration rates at 15 °C	Kg C kg C^{-1} yr^{-1}	−	0.0208	0.0208	0.0100	2
bsrtroot	Base respiration rates at 15 °C for root	Kg C kg C^{-1} $year^{-1}$	−	0.5000	0.2850	0.1000	2
bsrtstem	Base respiration rates at 15 °C for stem	Kg C kg C^{-1} $year^{-1}$	−	0.0700	0.0335	−	2

cdlsrtmx	Maximum loss rate for cold stress	Day^{-1}	–	0.10	0.30	0.15	2
drlsrtmx	Maximum loss rate for drought stress	Day^{-1}	–	0.006	0.005	0.020	2
humicfac	Humification factor used for transferring C from litter into soil C pool	–	–	0.42	0.42	0.42	2
kn	Canopy light/nitrogen extinction coefficient	–	–	0.50	0.50	0.46	2
laimax	Maximum leaf area index	m^2	–	4.0	3.0	4.0	2
laimin	Minimum leaf area index	m^2	–	1.0	1.0	0.01	2
lfespany	Leaf life span	year	–	5.0	0.4	1.0	3
lwrthrsh	Lower temperature threshold for cold stress related leaf loss rate	°C	–	-50.0	-5.0	0.1	2
mxrtdpth	Maximum rooting depth	m	–	1.00	1.00	1.00	1
rmlcoeff	Leaf maintenance respiration coefficient	–	–	0.025	0.020	0.015	2
rmlmoss25	Base dark respiration rate in mosses	µmol CO$_2$ m^{-2} s^{-1}	1.1	–	–	–	4
rootlife	Turnover time scale for root	year	–	11.50	12.00	2.00	2, 5
rtsrmin	Minimum root/shoot ratio	–	–	0.16	0.16	0.30	2, 6
stemlife	Turnover time scale for stem	year	–	65	75	–	2
Tlow	Lower temperature limits for photosynthesis	°C	0.5	-2.0	-2.0	-1.0	2, 7, 8
Tup	Upper temperature limits for photosynthesis	°C	–	34.0	34.0	40.0	2
Vmax	Maximum photosynthesis rate	µmol CO$_2$ m^{-2} s^{-1}	[10]6.5, 14	60	50	40	4, 9

[1]calibrated based on proper rooting depth; [2]adapted from the parameters for evergreen, deciduous needleleaf and C3 grasses; [3]Lamberty et al. (2007); [4]Williams and Flanagan (1998); [5]modified for shrubs so that the root turnover time follows trees > shrubs > grasses; [6]calibrated based on Murphy et al. (2009) for the minimum root/shoot ratio of sedge to be lower than grasses; [7]Moore et al. (2006); [8]Tanja et al. (2003); [9]Assumed based on literature (Givinish, 2002; Reich, 1998) so that Vmax values are higher in evergreens than in deciduous and are in line with the values for trees; [10] V_{max} of mosses is 14 in the summer and 6.5 in the remaining time (Williams and Flanagan, 1998).

Table 3. Soil decomposition parameters for bog and fen (reformulated from the McGill Wetland Model, based on- Frolking et al. (2001))

	k_1 (µmol C kg C^{-1} s^{-1})	k_2 (m^{-1})	k_3 (µmol C kg C^{-1} s^{-1})	k_4 (µmol C kg C^{-1} s^{-1})	k_5 (m^{-1})	k_6 (m^{-1})	k_7 (µmol C kg C^{-1} s^{-1})	k_8 (µmol C kg C^{-1} s^{-1})	k_9 (m^{-2})	k_{10} (m^{-1})
Bog	0.009	-20.0	0.015	-0.183	-18.0	0.003	0.0134	0.0044	4.057	72.067
Fen	0.010	-40.0	0.015	-1.120	-25.0	0.000	0.0151	-0.0052		

Table 4. Descriptions of the test sites

Site	**Bog**				**Fen**			
	MB-Bog	SE-Faj	RU-Fyo	UK-Amo	AB-Fen	FI-Kaa	FI-Lom	SE-Deg
Site name	Mer Bleue bog	Fäjemyr bog	Fyodorovskoye bog	Auchencorth Moss	Alberta treed fen	Kaamanen fen	Lompolojänkkä fen	Degerö fen
Latitude (°)	45.41	56.27	56.46	55.79	54.47	69.14	68.00	64.18
Longitude (°)	-75.52	13.55	32.92	-3.24	-113.32	27.30	24.21	19.55
Elevation (m)	65	150	273	265	581	155	269	270
[1]Climate	Dfb	Cfb	Dfb	Cfb	Dfb	Dfc	Dfc	Dfc
[2]Land Cover	Permanent Wetlands	Permanent Wetlands	Woody	Grasslands	Mixed Forests	Woody Savannas	Woody Savannas	Grasslands

Dominant vegetation	Shrub	Evergreen Needle-leaf Forest	Evergreen Needle-leaf trees	Grass	Ever-green Needle-leaf Trees	Grass	Evergreen Needle-leaf	Evergreen Needle-leaf Trees
Vegetation coverage	0.50	0.20	0.70	0.25	1.00	0.15	0.50	0.15
Max. LAI ($m^{-2}m^{-2}$)	3.0	1.0	3.5	1.9	2.6	0.7	1.3	0.9
MAP (mm)	943	700	711	1155	504	474	484	523
MAT (°C)	6.0	6.2	3.9	10.0	2.1	-1.1	-1.4	1.2
Peat depth (m)	0.3 – 6	4 – 5	1.0	< 0.5 – > 10	2.0	0.3 – 1.4	2 – 3	3 – 8
Peatland type	Ombrotro-phic Bog	Ombrotro-phic Bog	Ombrotro-phic Bog	Blanket Bog	Treed fen	Poor Fen	Aapa mire	Poor fen
Data period	2004-2009	2006-2009	2009-2010	2005-2010	2003-2009	2000-2007	2007-2009	2002-2006
References	10, 11, 19	16, 19	12	17, 18, 19	3, 4, 5, 19	6, 7, 19	8, 9, 19	13, 14, 15, 19

[1] Climate types are classified using the Köppen-Geiger Climate Classification (KCGG) (Kottek et al., 2006). Dfb = Snow fully humid warm summer; Dfc = Snow fully humid cool summer; Cfb = Warm temperature fully humid with warm summer.

[2] Land cover is classified using the International Geosphere Biosphere Programme (IGBP) Land Cover Classification.

[3]Syed et al. (2006); [4]Adkinson et al. (2011); [5]Flanagan and Syed (2011); [6]Aurela et al. (1998); [7]Maanavilja et al. (2011); [8]Aurela et al. (2009); [9]Drew et al. (2010); [10]Moore et al. (2002); [11]Bubier et al. (2006); [12]http://www.eol.ucar.edu/projects/ceop/dm/insitu/sites/neespi/Fyodorovskoye/wetspruce/; [13]Sagerfors et al. (2008); [14]Laine et al. (2011); [15]Peichi et al. (2014); [16]Lund et al. (2007); [17]Dinsmore et al. (2010); [18]Leith et al. (2014); [19] http://fluxnet.ornl.gov

Table 5. Summary of statistics of model performance with respect to daily average latent heat flux (QH), sensible heat flux (QE) and soil T at 5cm (Ts5). * indicates unrealistic values observed for the site.

Site		Bog				Fen				Mean
		MB-Bog	SE-Faj	RU-Fyo	UK-Amo	AB-Fen	FI-Kaa	FI-Lom	SE-Deg	
QH (W m^{-2})	r^2	0.65	0.50	0.41	0.22	0.89	0.25	0.42	0.39	0.47
	RMSE	23.0	27.3	37.7	31.0	41.5	36.7	25.4	19.6	30.3
QE (W m^{-2})	r^2	0.89	0.56	0.51	0.01*	0.82	0.35	0.49	0.54	0.52
	RMSE	27.3	33.5	33.3	79.7	15.8	31.5	28.3	23.9	34.1
Ts5 (°C)	r^2	0.98	0.87	0.88	0.77	0.91	0.85	0.90	0.79	0.87
	RMSE	1.7	2.6	4.6	2.3	4.7	2.9	2.1	3.86	3.1

Table 6. Summary of statistics of model performance with respect to GPP, ER and NEP (g C m^{-2} day^{-1})

Site		Bog				Fen				Mean
		MB-Bog	SE-Faj	RU-Fyo	UK-Amo	AB-Fen	FI-Kaa	FI-Lom	SE-Deg	
Daily GPP (gC m^{-2} d^{-1})	r^2	0.90	0.80	0.81	0.63	0.95	0.78	0.76	0.65	0.79
	RMSE	0.669	0.606	2.36	1.44	1.45	0.601	1.07	0.84	1.13
Daily ER (gC m^{-2} d^{-1})	r^2	0.91	0.84	0.61	0.56	0.93	0.73	0.80	0.54	0.74
	RMSE	0.524	0.456	2.90	1.12	0.867	0.431	0.543	0.615	0.93
Daily NEP (gC m^{-2} d^{-1})	r^2	0.45	0.21	0.30	0.17	0.72	0.28	0.35	0.41	0.36
	RMSE	0.724	0.539	1.65	0.936	1.01	0.624	1.00	0.486	0.87

Table 7. Summary of observed (obs.) and modeled (mod.) mean annual GPP, ER and NEP of the 8 sites with standard deviation shown in brackets; units are g C m^{-2} yr^{-1}.

Site	Bog				Fen				Mean
	MB-Bog	SE-Faj	RU-Fyo	UK-Amo	AB-Fen	FI-Kaa	FI-Lom	SE-Deg	
GPP obs.	714(±45)	472(±3)	1502(±251)	789(±189)	864 (±172)	289 (±39)	418(±52)	383(±24)	679
GPP mod.	734(±15)	573(±49)	1135(±4)	752(±37)	594 (±72)	327 (±33)	489(±39)	300(±71)	613
ER obs.	612(±29)	536(±102)	1545(±119)	706(±212)	678 (±160)	270 (±40)	380(±59)	295(±36)	628
ER mod.	690(±89)	426(±55)	1000(±86)	594(±46)	581 (±88)	270 (±46)	372(±96)	224(±76)	520
NEP obs.	103(±25)	25(±34)	-17(±73)	87(±48)	187 (±37)	17 (±29)	57(±9)	58(±6)	65
NEP mod.	44(±78)	97(±77)	135(±91)	157(±43)	13 (63)	57 (±22)	117(±57)	77(±5)	87

Figure 1. Schematic diagram of the peatland CLASS-CTEM model with 12 PFTs and 10 soil layers. The symbols C, T and θ represent carbon, temperature and soil water content respectively. The subscripts L, S, R, H, and D represent leaf, stem, root, fresh litter and old litter respectively.

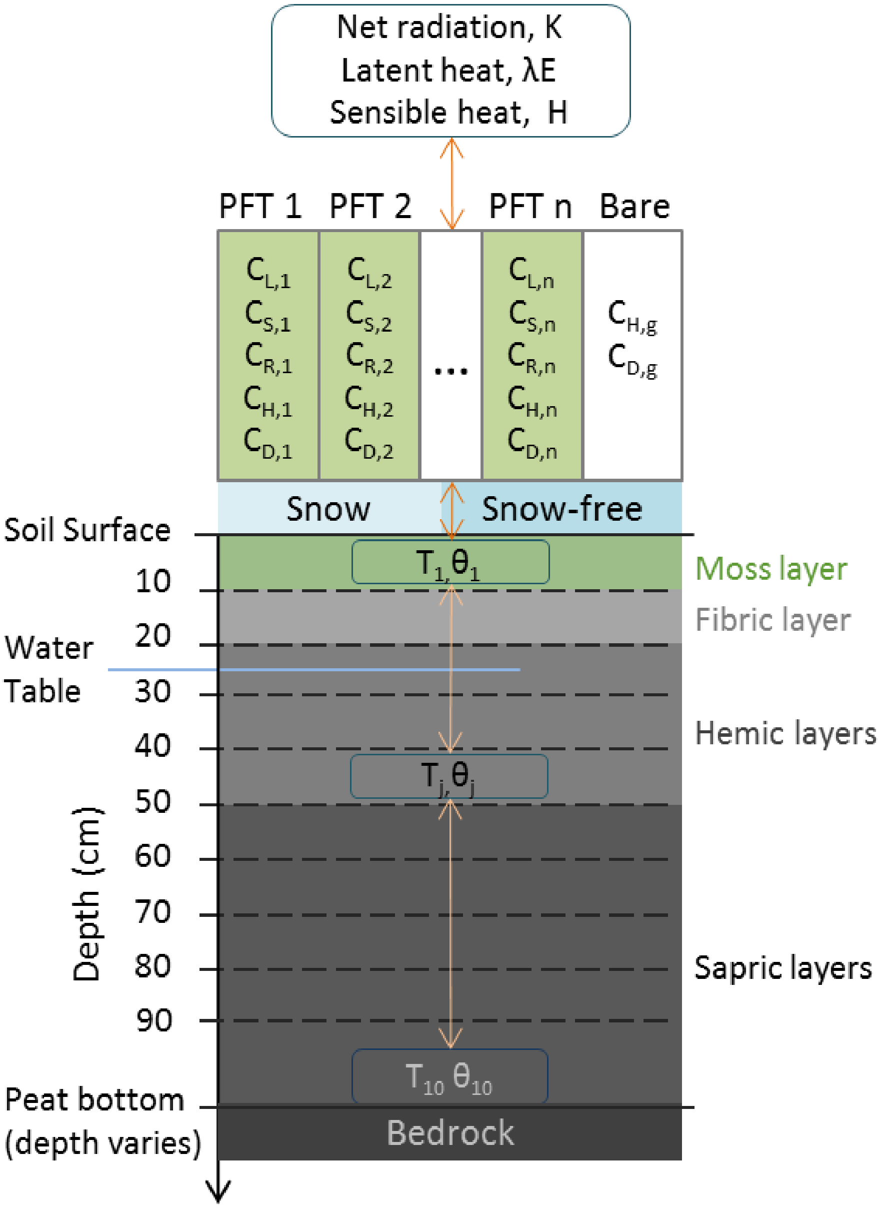


Figure 2. Variation of respiration rate coefficients k_o and k_a with water table depth.

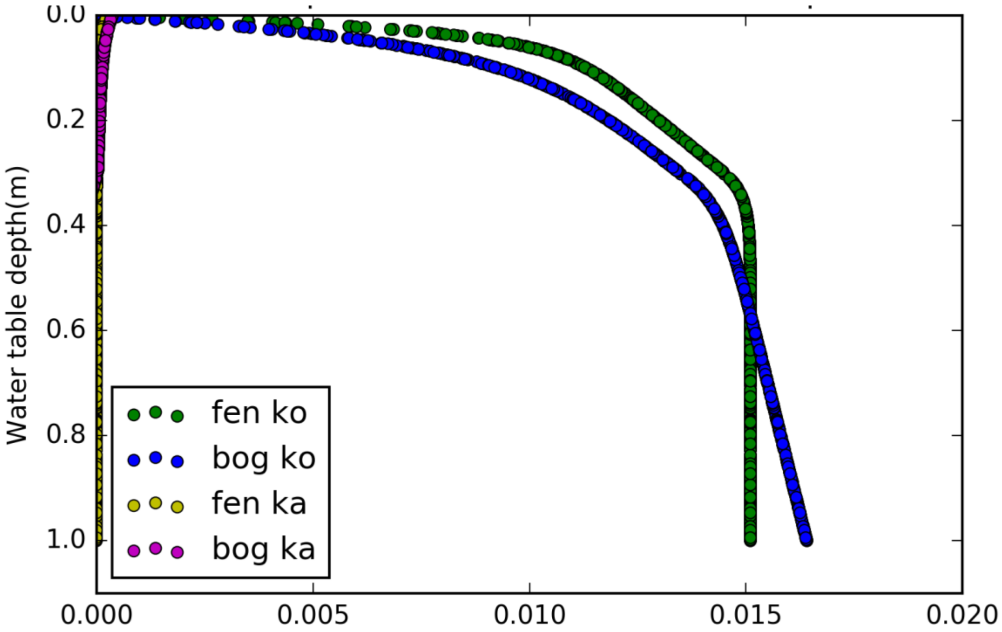


Figure 3~~2~~. Locations of the test peatlands; closed circles indicate bogs and triangles indicate fens.

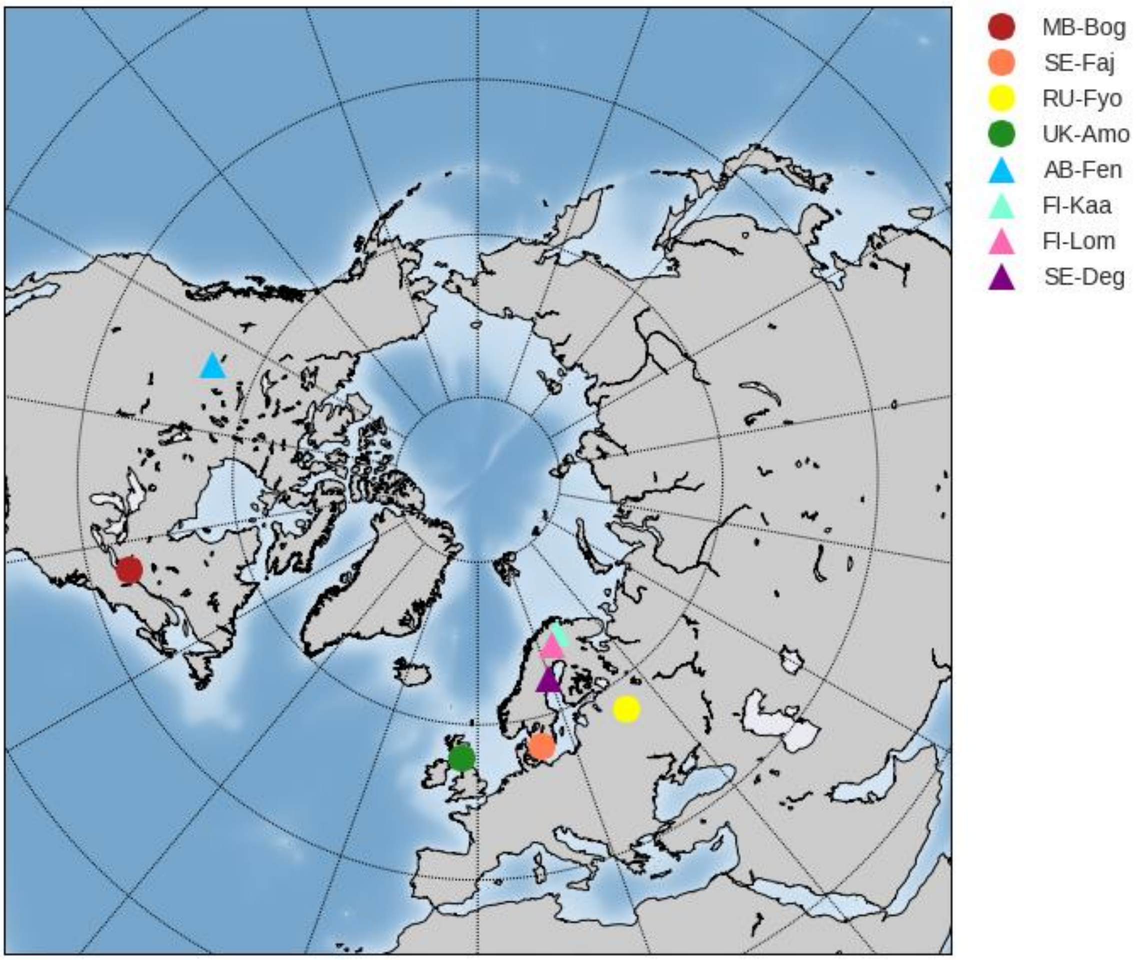


Figure 4~~3~~. Simulated and observed daily average water table depth (m) in three bogs (MB-Bog, RU-Fyo, SE-Faj) and three fens (AB-Fen, FI-Lom, SE-Deg).

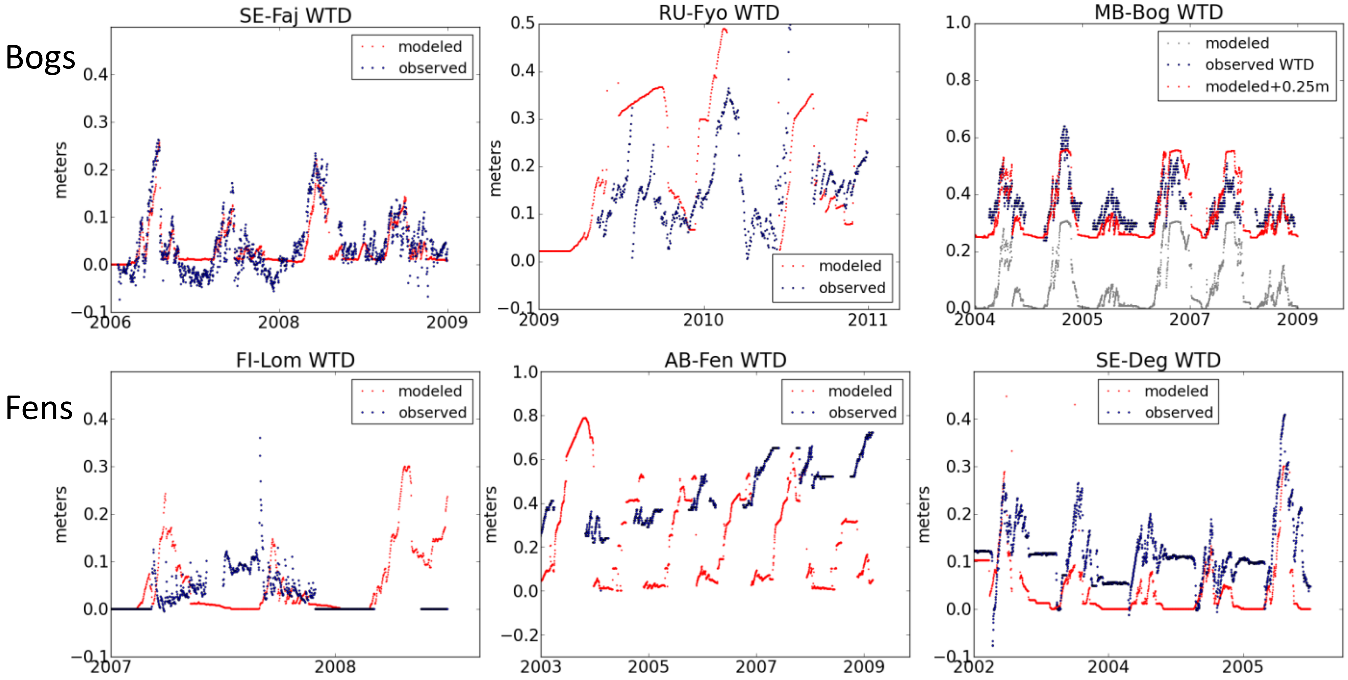


Figure 5~~4~~. Simulated and observed daily average snow depth (m) in the MB-Bog and the AB-Fen.

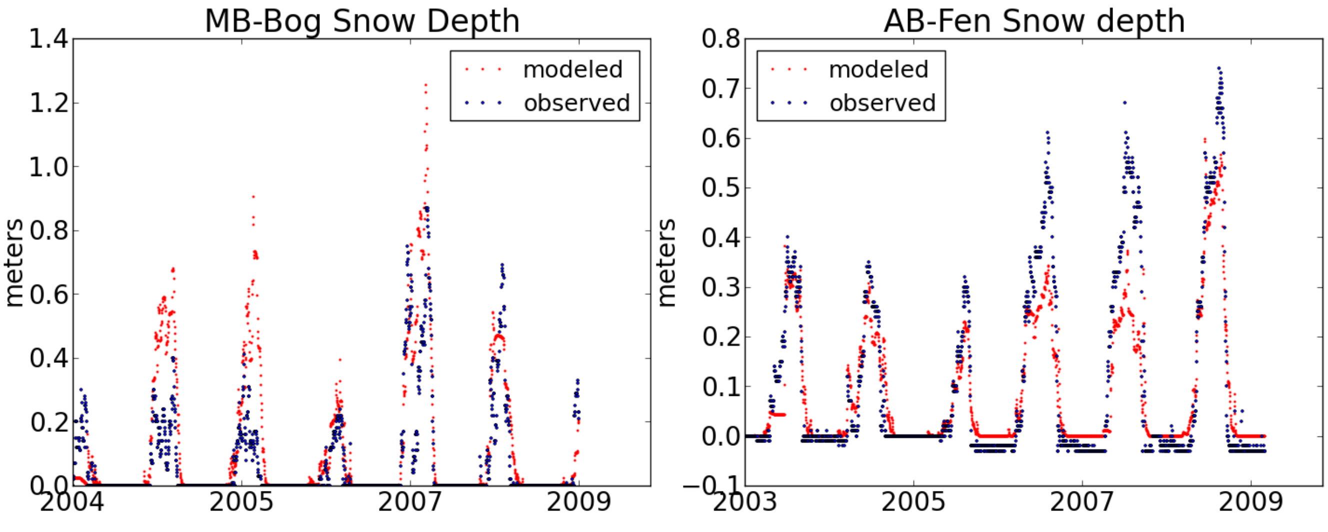


Figure 6~~5~~. Simulated and observed daily average latent heat flux QE (W m^{-2}) and sensible heat flux QH (W m^{-2}) in two bogs (MB-Bog and UK-Amo) and two fens (FI-Lom and SE-Deg).

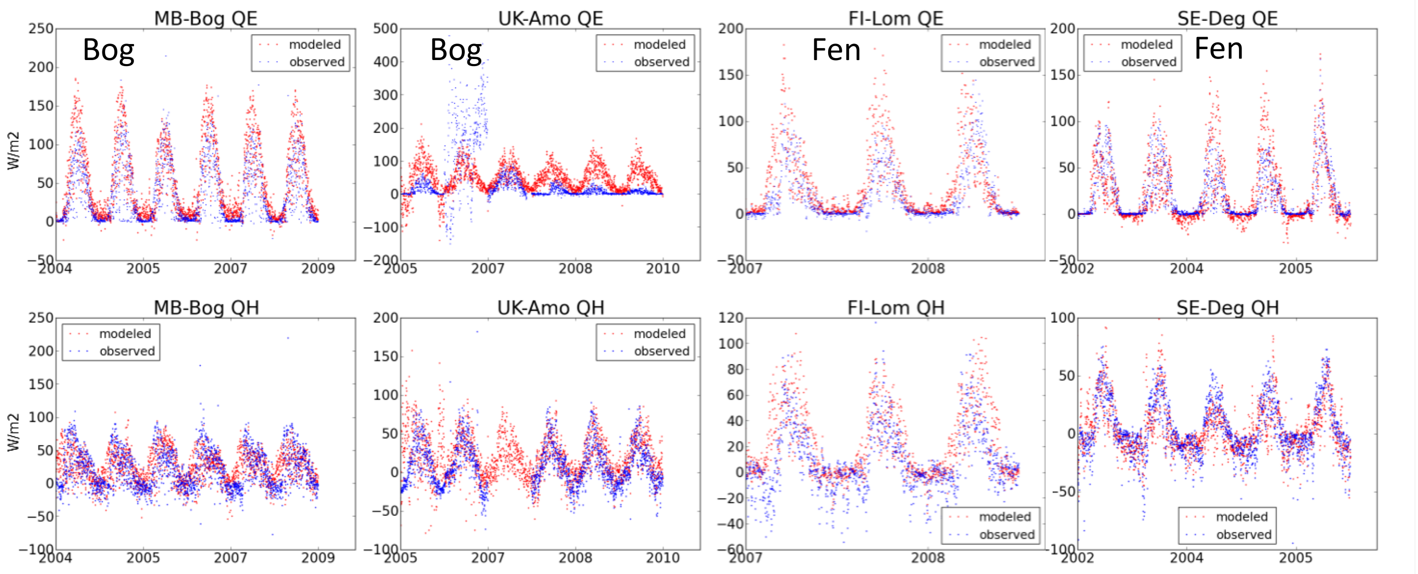


Figure 7~~6~~. Simulated and observed daily mean soil temperature T_s (°C) at 5cm, 40cm, 80cm and 250 cm at the Mer Bleue Bog. Note that the simulated temperatures at 40 and 80 cm are interpolated from the simulated soil layer temperatures above and below these depths. The deepest measurement corresponds approximately to the midpoint of the lowest soil layer.

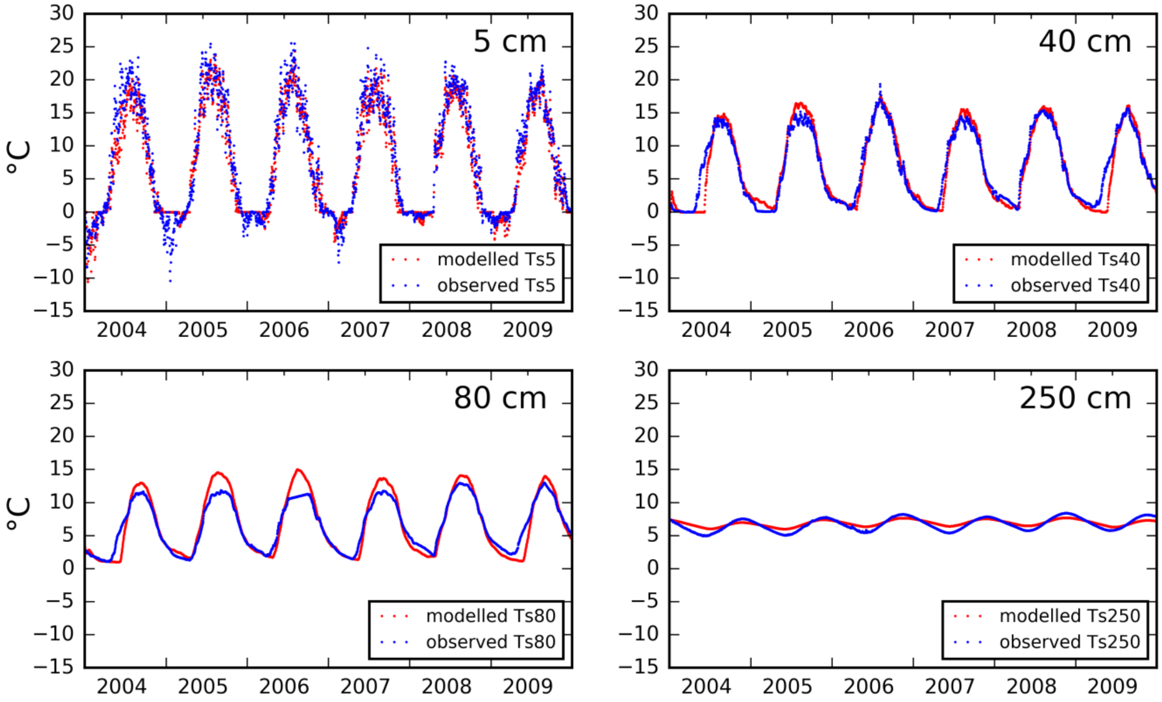


Figure 8~~7~~. Simulated and observed daily GPP (gC m^{-2} d^{-1}) in bogs and fens.

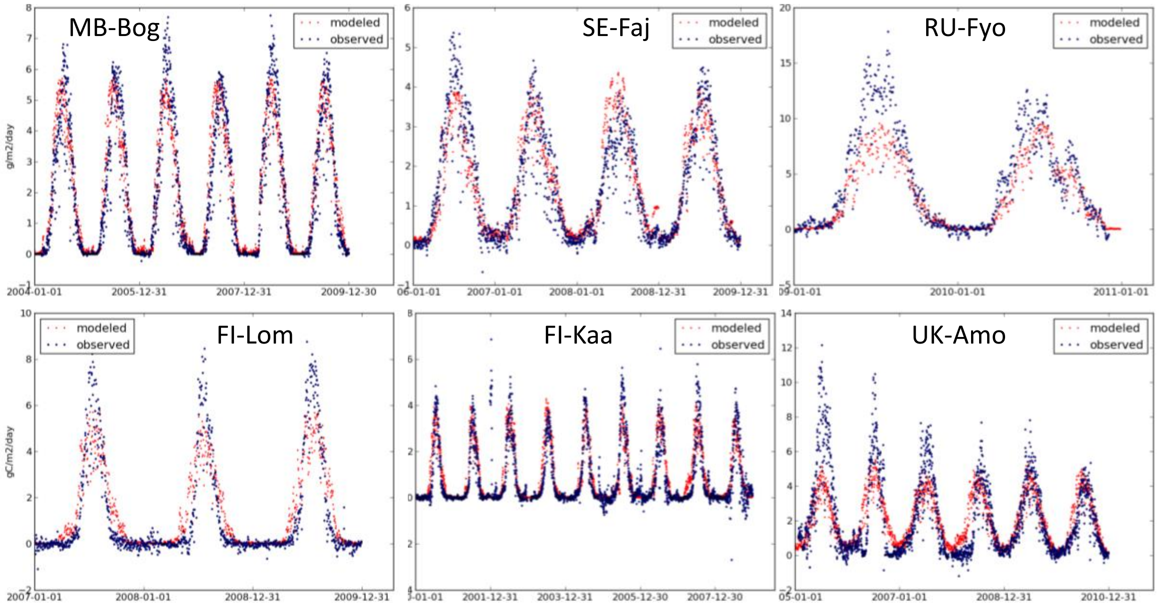


Figure 9~~8~~. Simulated and observed daily ER (gC m^{-2} d^{-1}) in bogs and fens.

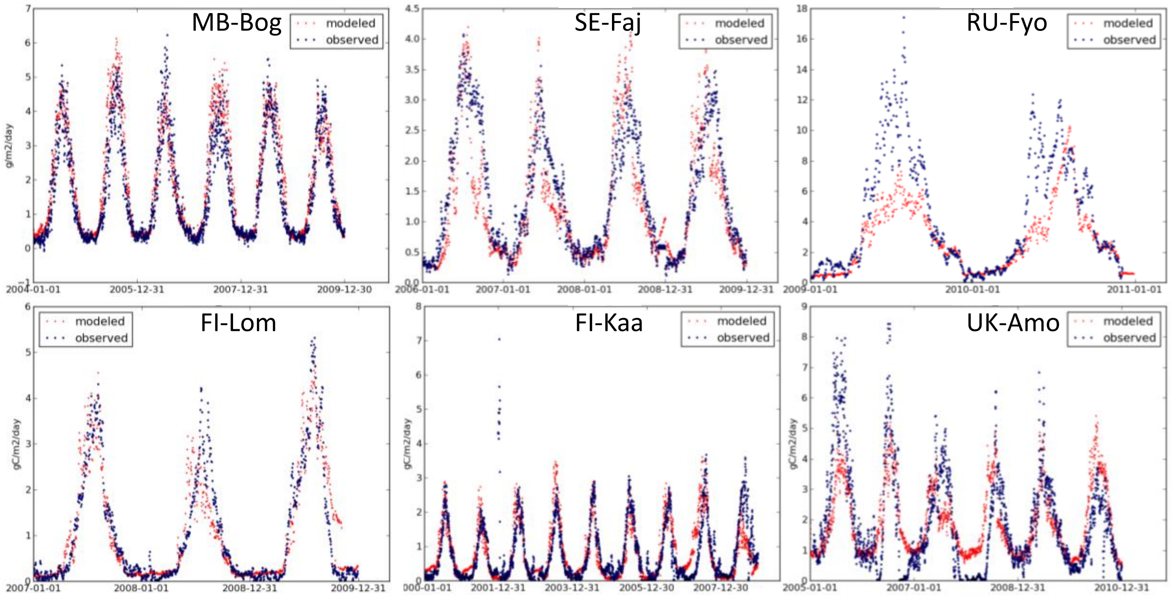
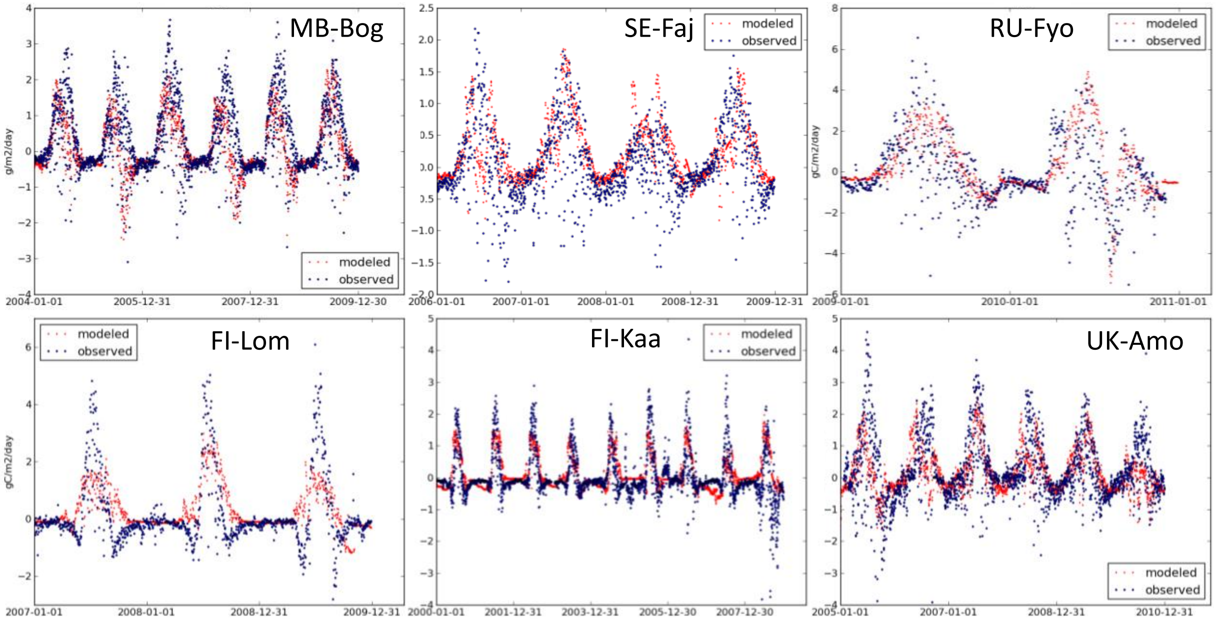


Figure 10~~9~~. Simulated and observed daily NEP (gC m^{-2} d^{-1}) in bogs and fens.



~~F~~Figure 11. Scatterplots of simulated vs. observed daily GPP (gC m^{-2} d^{-1}) in bogs and fens.

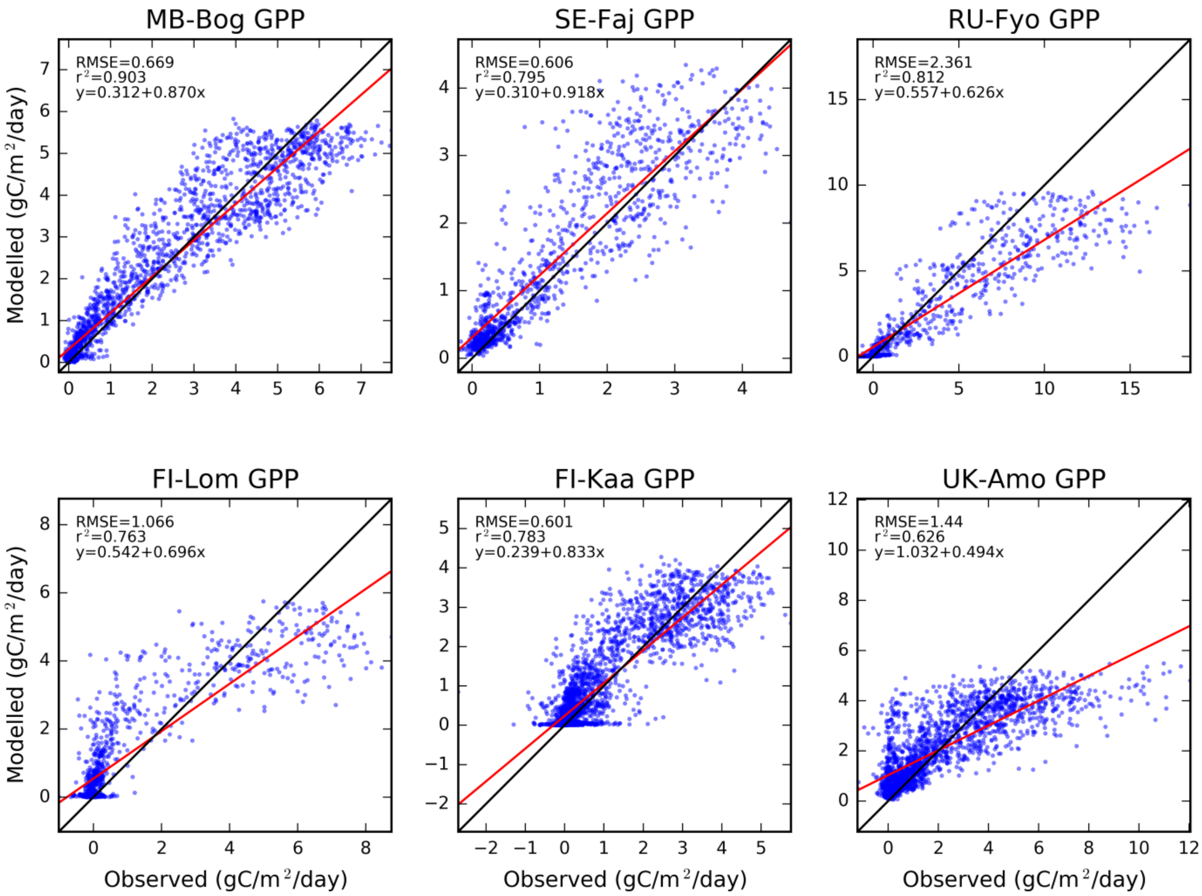


Figure 12. Scatterplots of simulated vs. observed daily ER (gC m^{-2} d^{-1}) in bogs and fens.

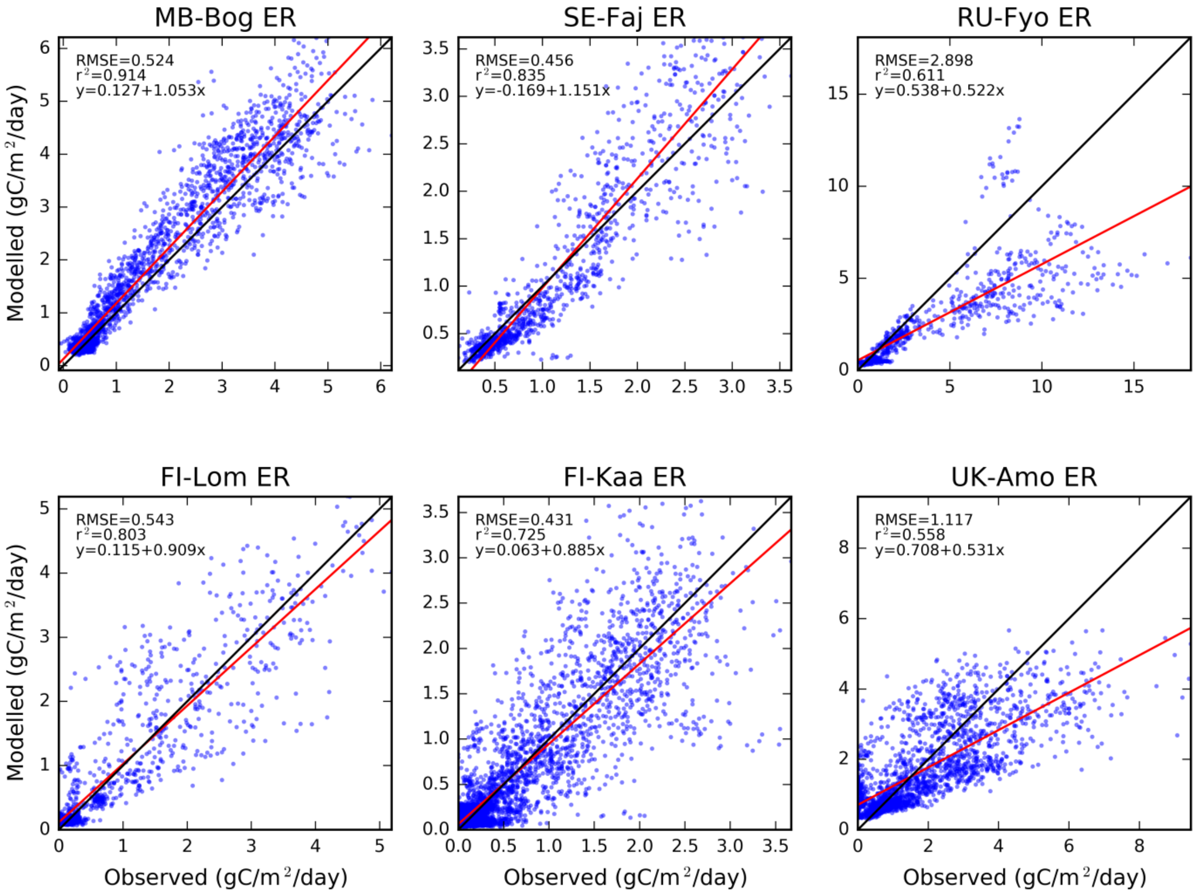


Figure 13. Scatterplots of simulated vs. observed daily NEP (gC m^{-2} d^{-1}) in bogs and fens.

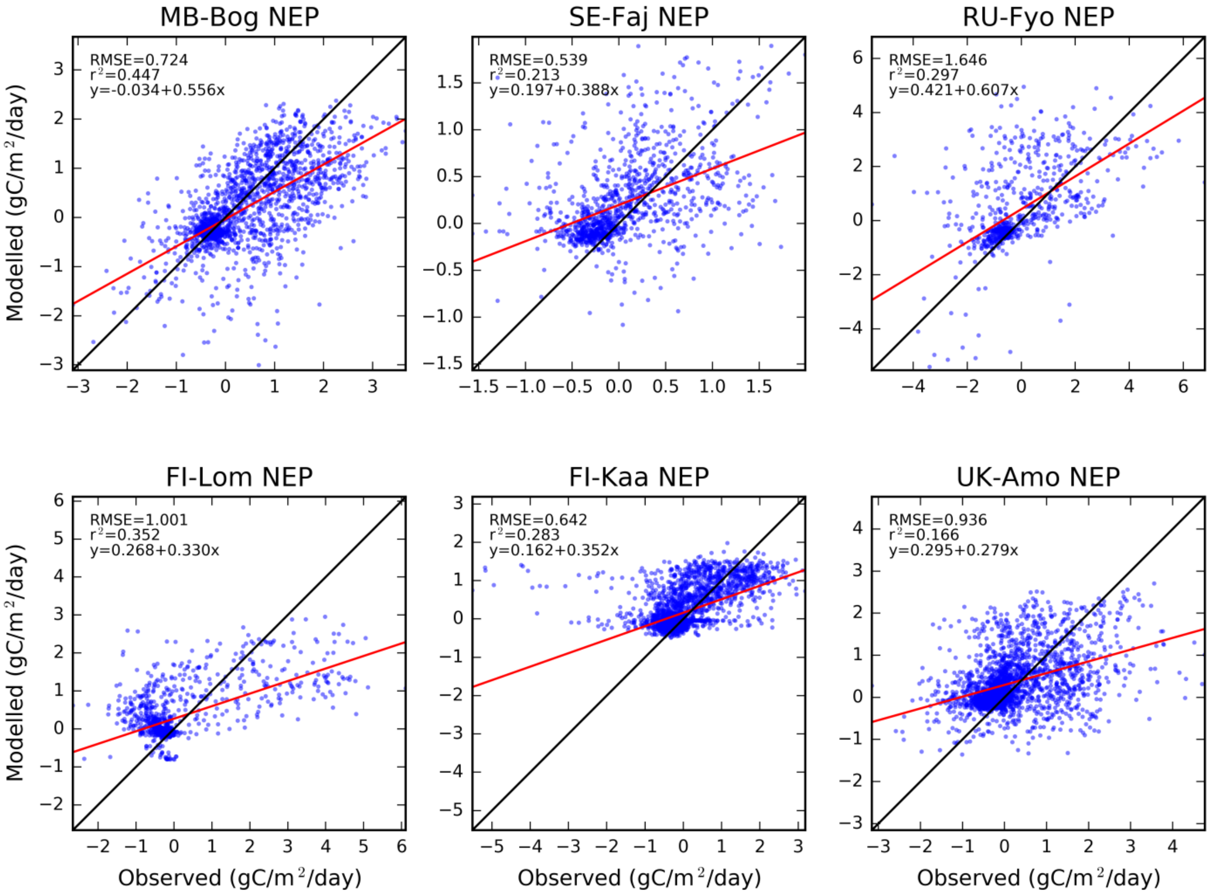


Figure 14. Simulated GPP, autotrophic respiration (AR) and heterotrophic respiration (HR) (gC m^{-2} d^{-1}) for bogs and fens.

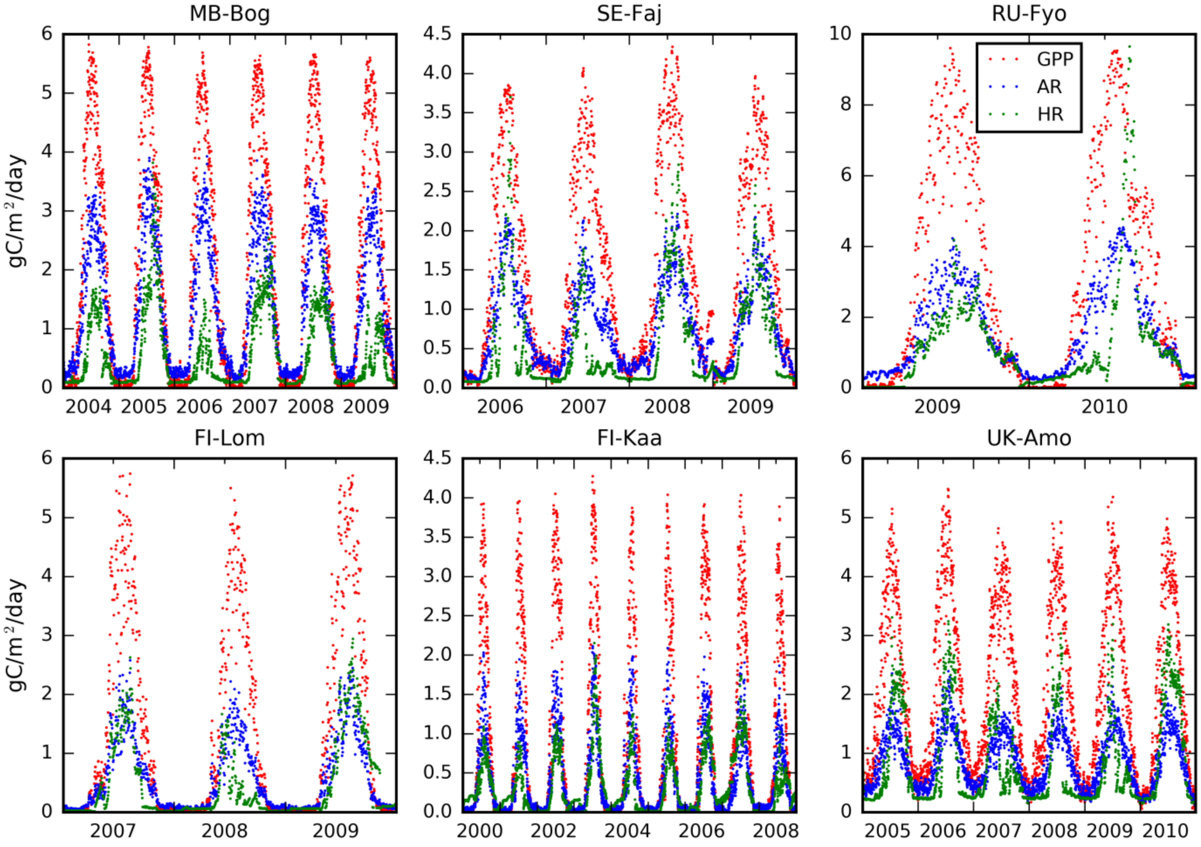


Figure 15~~0~~. Scatter plots of simulated and observed monthly mean NEP (gC m^{-2} month^{-1}) in bogs and fens. The sites are represented by different symbols and NEP for each of the 12 months is colour-coded. The black line represents the best fit of the modelled NEP and the observed NEP.

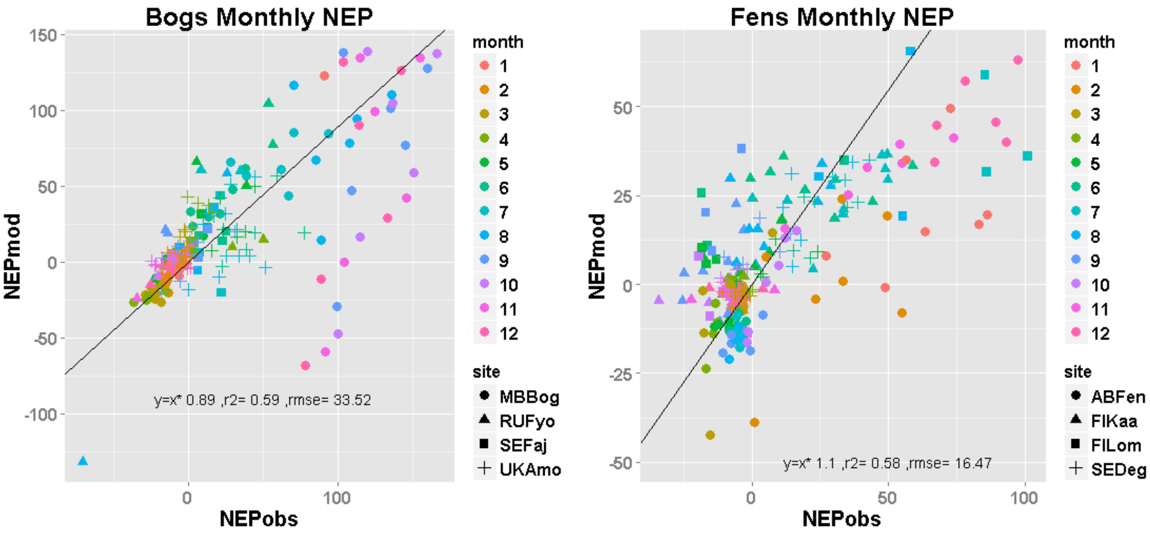


Figure 16~~1~~. Observed and simulated annual GPP, ER and NEP (g C m^{-2} yr^{-1}) for the eight sites (error bars show the standard deviations); red bars are modeled fluxes and blue bars are observed fluxes.

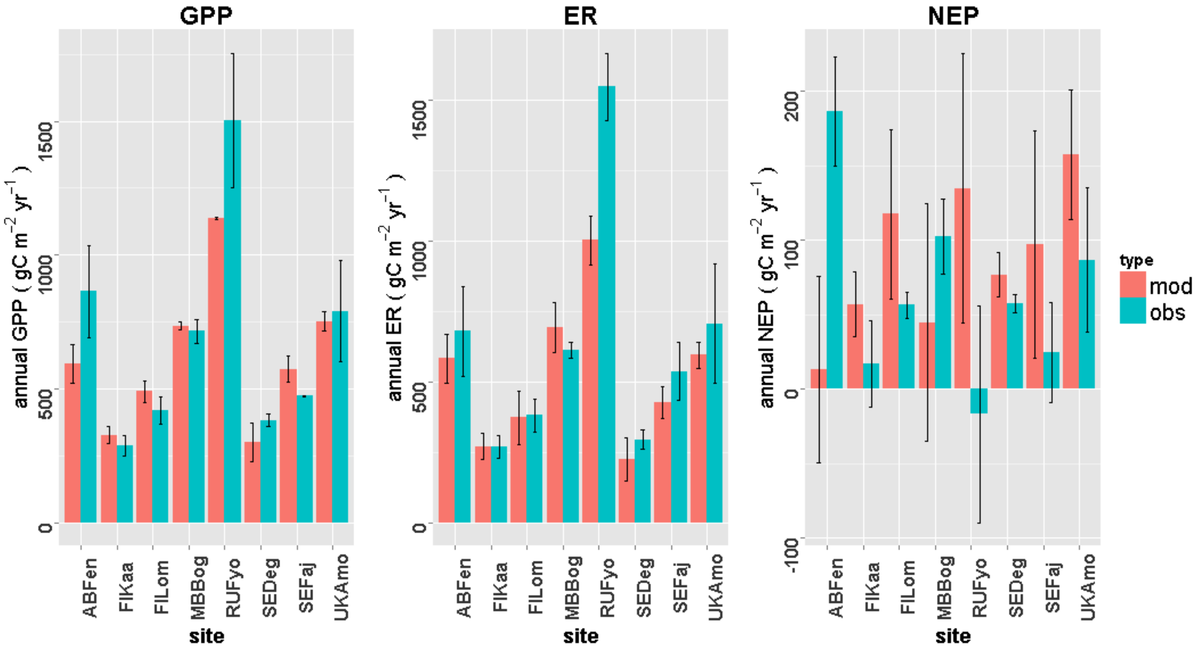


Figure 17~~2~~. Taylor diagrams of model performance on average sensible heat flux (QH), latent heat flux (QE), soil temperature at 5 cm depth, and daily average GPP, ER and NEP (gC m^{-2} d^{-1}) in bogs and fens.

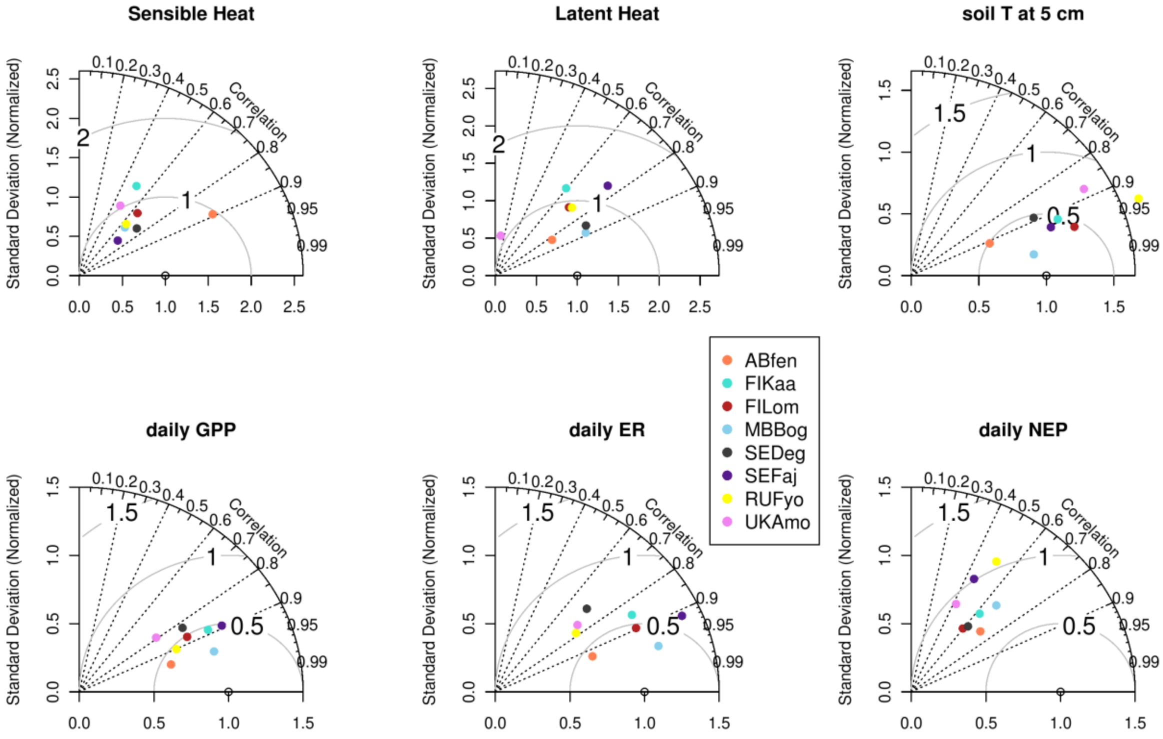


Figure 18~~3~~. Comparisons of RMSE and r^2 of the simulated latent heat flux (QE), sensible heat flux (QH), soil temperature at 5 cm depth (Ts5), GPP, ER and NEP against the original simulations for the two tests described in section 4.5.

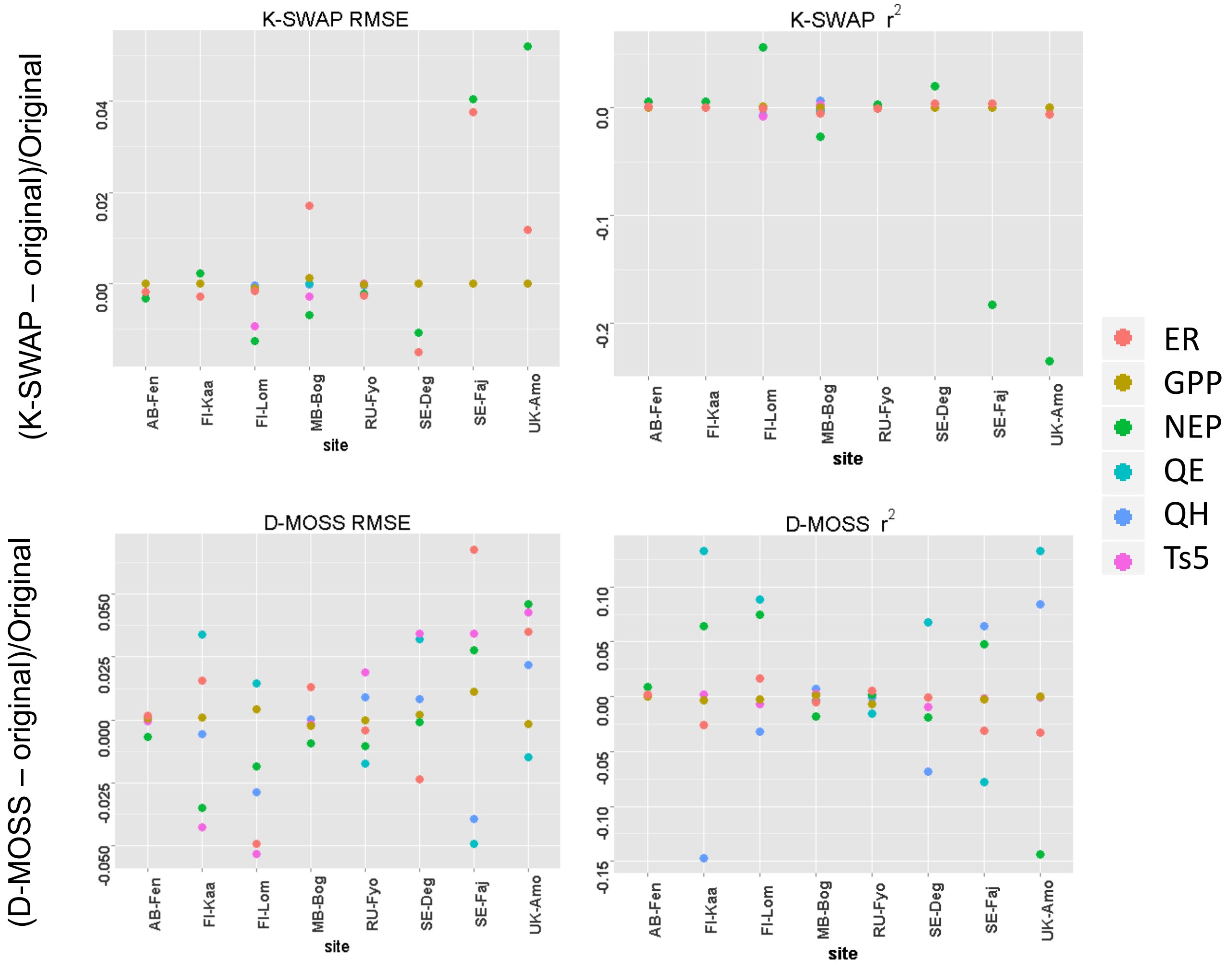


Figure 19. Cumulative NEP for bog and fen sites over the test periods, for the control runs and the two sensitivity tests K-SWAP and D-MOSS.

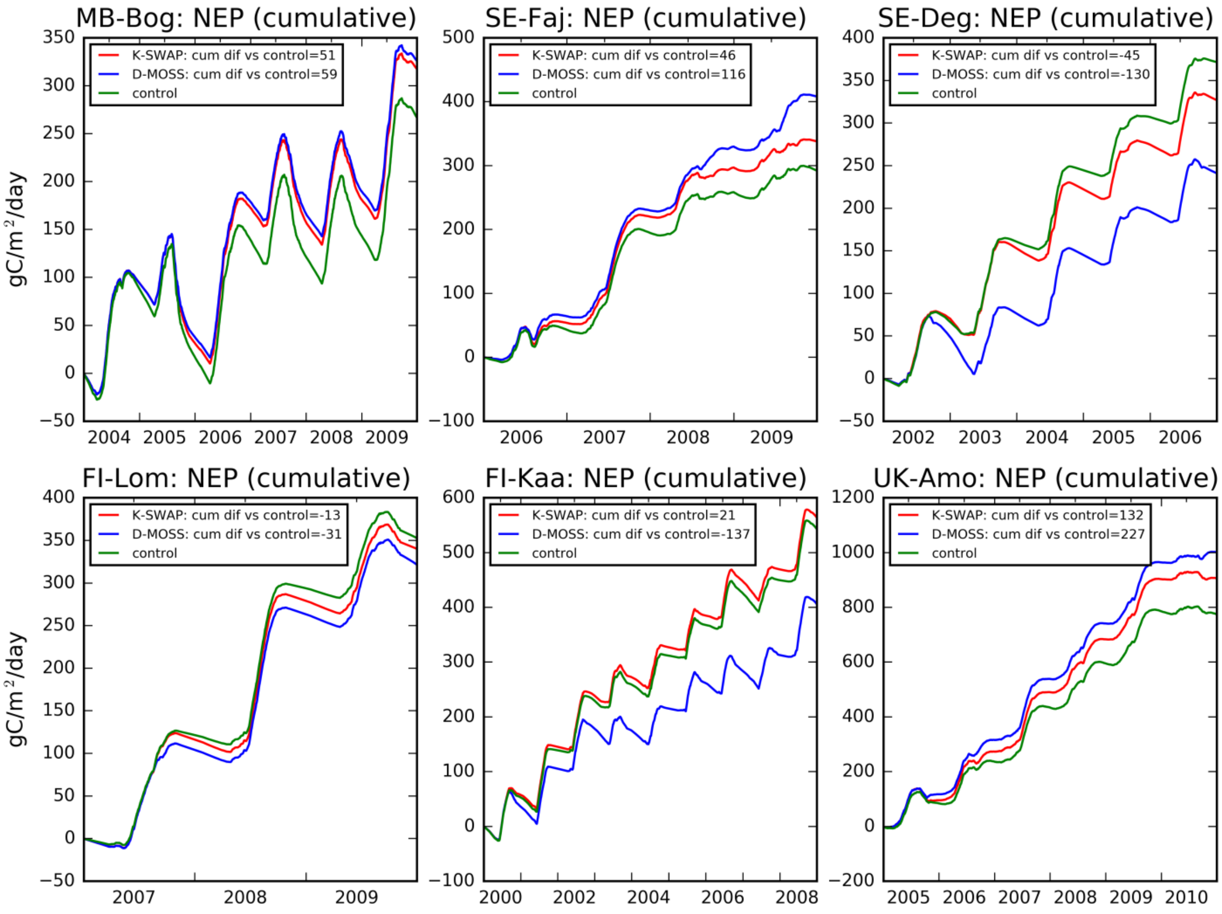


Figure 20. Effect of varying f_{anoxic} on the ER flux for the four fen sites. The control run was with f_{anoxic} set to 0.025.