Response to Referee #1 (Dr. Kleinen)

We would like to thank Dr. Kleinen for his thoughtful and constructive review. Our responses to all of the referee's comments (italicized) are presented below.

In their manuscript, the authors present a model study of soil carbon accumulation in Alaska over the last 15000 years with a special focus on peat carbon accumulation. Overall, the manuscript is quite interesting and suitable for publication in biogeosciences. However, a number of minor issues remain before it is ready for publication.

We made all edits and changes following the referee's comments and suggestions. We detailed our responses below.

Figure 2 shows the vegetation distribution used to drive the model for 5 time slices. However, results are presented in Figs. 7 and 9 for 6 time slices. This is confusing for the reader. At the very least it needs to be clearly marked in the figure caption. The symbols used in Fig. 2 to show peat basal dates are also very difficult to make out. Maybe it is possible for the authors to make this Figure clearer.

We have five vegetation distribution maps for five time slices. In Fig. 2, we present those five maps. We present six maps of carbon density distribution in Figs. 7 and 8. The reason is that during 5 ka-1900 AD, there was climate change affecting carbon accumulation rates, although the vegetation map remains the same during 9ka-1900 AD. Yes, it is indeed confusing for readers. Thus, in this revision, we made the explanation in the captions of Figs 2, 7, and 8 to clarify this. Also, we have made all panels in Fig. 2 clearer and changed the symbol size.

Figure 7: Figure caption is unclear. How can you show cumulative SOC density? This would imply only the very last time in the time interval is shown. I assume you actually mean the mean SOC density.

Correct. For non-peatland soils, we wanted to show the mean carbon density during each time slice. We have made the caption clearer to readers and change the "cumulative" to "average".

Figure 12: Caption also unclear. I assume the late 20th century distribution is shown? Figure caption shows 15ka to 2000AD, implying a mean value over this time frame.

The maps of total SOC density in Alaska are the sums of SOC during all periods, from 15ka, which is the beginning of the simulation, to the late 20th, which is the end. This is the cumulative carbon density. We have changed the caption of panel (d) to "area-weighted total (peatland plus non-peatland) SOC density from 15 ka to 2000 AD, and added "total" in the descriptions of other panels.

Since a large part of the results hinges on the modelled changes in peatland area, it is essential that a description of how area changes are determined is provided. Currently it is only stated that area is prescribed from Matthews & Fung, implying no change is possible.

Page 15, line 339 – page 16, line 349: how were peatland area changes determined? Completely unclear (see comment #4)

The change of peatland area is determined by the basal ages of the peatland. And from the distribution of the basal ages in Fig. 2, we link some vegetation types during each time slice to the ages. For example, during 15-11ka, the peatland area is determined based on the alpine tundra. However, within each pixel, we assume the inundated area represents the peatland area and other area represents non-peatland. The inundation area information is from the modern inundation map and does not change. The number of pixels that have peatland vegetation is changing through time determined by the basal age distribution. The percentage of peatland area within each pixel is unchanging. We have made the description clearer in the Method section. We added the peatland expansion into Results& Discussion section to better describe the link between basal ages and the peatland area change. We also added the drawbacks of such assumption.

Page 4, lines 94-95: the Spahni et al. Model has actually been evaluated with respect to the variables listed – see Wania et al. Publications on the LPJ-Why model on which Spahni is based.

Thanks for pointing out our wrong statement here. We checked the relevant references and corrected our statement.

Page 5, line 97: Why do you cite Kleinen et al. 2010? They do not use a processbased peatland model, but rather prescribed peat accumulation. I assume you actually meant to cite Kleinen et al. 2012?

We have cited Kleinen et al. (2012) instead.

Page 7 and 8, lines 159-166: The aboveground vegetation in your calibration site is significantly different from the Mer Bleu site you use for belowground calibration. In addition the climatic situation at the two sites is significantly different. Therefore is seems quite a stretch to argue that belowground processes are basically the same. Please provide more justification for this assumption.

Assuming the belowground carbon in Mer Bleu is the same as that in APEXCON could be wrong. In this revision, we added another site (Suurisuo mire complex) in southern Finland, which is a sedge fen dominated by *Carex rostrate.* We compared the ratios of belowground biomass over total biomass at both sites and applied 70% to APEX site and then estimated the belowground biomass. We added the description in the text and cited the reference in this revision.

Page 8, line 173: Please correct date for late Holocene time frame

We have corrected the date from “9 ka-1900AD” to “5ka-1900 AD”.

Page 9, lines 194-195: The Shuttle Radar Topography Mission (SRTM) only covered latitudes 56S-60N. Therefore there is NO SRTM data for Alaska. You obviously used some other source for topography data – please provide correct reference.

We directly used the data from He et al. (2014). We cited Zhuang et al. (2007) paper instead.

Page 9, lines 197-203: Downscaling / bias correction is unclear. From the text one gets the impression, that ECBILT fields and CRU data may be significantly different for 20th century. However, my reading of the original publications is that bias correction minimised that difference. Please clarify this – it would strongly strengthen the text.

Yes, the climate data were bias-corrected to minimize the difference between ECBILT and CRU. We made the clarification on this.

Page 12, line 256: References to Figures 2 and 3 mixed up, please correct.

We have made the change.

Page 13, lines 279-289: Study sites unclear. Please provide table of site locations.

Below is the table of descriptions of those sites. We cited Wang et al. (2016) in this revision

Sites used for comparison of carbon accumulation rates between simulation and observation [*Jones and Yu,* 2010]

Site name	Location	Peatland type	Latitude	Longitude	Dating method	No. of dates	Basal age (cal yr BP)	Time-weighted Holocene accumulation rates (g C m^{-2} yr^{-1})
Kenai Gasfield	Alaska, USA	fen	60º27'N	151º14'W	AMS	12	11,408	13.1
No Name Creek	Alaska, USA	fen	60º38'N	151º04'W	AMS	11	11,526	12.3
Horsetrail fen	Alaska, USA	rich fen	60º25'N	150º54'W	AMS	10	13,614	10. 7

Swanson fen	Alaska, USA	poor fen	60º47'N	150º49'W	AMS	9	14,225	5.7

Page 14, lines 314-316 and table 4: table 4 only lists uncertainty ranges for peatland vegetation. How were uncertainty ranges for upland vegetation derived? Certainly not from the ranges in table 4. Please clarify. Page 15, lines 333-334 – see comment #13.

Thankfully, the authors have used a spellchecker, so there are very few typos. However, there are numerous places in the text, where grammar needs checking: Temporal forms are not always consistent, and some sentences are missing single words or larger parts. Therefore CAREFUL COPY-EDITING is highly important.

The uncertainties of the upland vegetation are from the uncertainties of parameters in previous study (Tang and Zhuang, 2008; 2009). We used the prior ranges of the parameters based on those studies. We added this statement in the text in this revision. Following the referee's recommendation, we have carefully checked the whole text in terms of language.

Response to Referee #2 (Dr. Tupek)

We would like to thank Dr. Tupek for his thoughtful and constructive review, as well as his detailed comments. Our responses to all of the referee's comments are provided as below.

Authors tested SOC simulations from the modified version of their Terrestrial Ecosystem Model (TEM) for peatlands (P-TEM) for Alaska region for time periods defined by climatic characteristics (solar radiation, temperature, and precipitation levels) and vegetation distribution during last 15 000 years. The model was applied for peatlands and non-peatlands (mineral soil forests). Simulated C distributions, NPP, and peat depths were presented for Alaska at fine scale spatial resolution (maps) and summarized for vegetation types. This can be an interesting study if presented carefully

Thanks for the constructive comments. Following your comments, we made all edits and changes as detailed below. **The Method, Result, and Discussion sections were totally revised. We also had revisions with respect to grammar and typos in the Abstract, Introduction and Conclusions sections. However, those revisions were not marked. Please see the final manuscript without tracks for a better vision.**

The advances of the model include hydrology, soil thermal, C and N dynamics modules. This looks promising however, the model code is not publicly available and need to be asked from authors. No software details were given. I'd like to see the code and run an example simulation in R to understand the model structure. Description of NPP simulation by the model is missing. Description of Carbon and Nitrogen dynamics of CNDM module is also missing. Add descriptions for clarity. Results largely depended on the adopted distribution of vegetation types. Authors mentioned that distribution of vegetation types and their changes overdriven C accumulation over climate, but also noted that climate had probably driven distribution of vegetation types. Individual parameter values are not listed. It would be interesting to see the changes of key parameters between vegetation types in relation to their prevailing climate.

Response: The descriptions of P-TEM including modules of STM, HM, CNDM, and MDM were less listed in this manuscript indeed. The main reason is that we have described the model framework, specific parameters and the parameterization processes, along with the comparison between simulation and observation regarding soil moisture, methane emissions, water-table depth, and carbon and nitrogen dynamics in our previous study. Specifically, please find the paper "**Quantifying Peat Carbon Accumulation in Alaska Using a Process-Based Biogeochemistry Model"** for details (***Wang, S., Q. Zhuang, Z. Yu, S. Bridgham, and J. K. Keller (2016), Quantifying peat carbon accumulation in Alaska using a process-based biogeochemistry model, J. Geophys. Res. Biogeosci., 121, doi:10.1002/2016JG003452.***).

The above paper was under review by JGR-Biogeosciences at that time we submitted this regional study to Biogeoscience. Now the paper was published, therefore we believe there is no reason to repeat those model details. We have cited this newly published paper in the text in this revision.

Our model source codes are written in C/C++, not in R. The model has a number of sub-models, thus its source code is rather lengthy. We appreciate your interests in the model, we are open to collaborate by using the model to do research so that we have sufficient time to understand the code.

Description of observations of peat depths that were used for model validation is not sufficient. Some description is in section 2.5 but it is not clear and the points on the maps in Fig. 2 are barely visible. Describe clearly.

Response: The peat depths for model validation are from Hugelius et al. (2014). We used the basal ages to determine the process of peatland expansion from Gorham et al. (2012). We added our findings of the linkage between basal ages and vegetation distribution in the Result& Discussion section (sec. 3.3) and discussed the related uncertainties. We also changed the symbol size in Fig. 2 to make the figure of the basal age distribution much clearer to readers.

Structure of the paper is unclear. Reorder the ideas, avoid using repetitions.

Response: Thanks for the comments. In this revision, we re-ordered the ideas mainly in Result and Discussion sections and made the structure more logical to readers. We also combined the Result and Discussion sections to avoid repetitions. We shortened the Sec. 3.1, 3.2 and added the text describing peat expansion and vegetation changes in Sec. 3.3.

Methods are presented in results. Results are presented in discussion. For example lines 369-370 in results describe how peat depth was calculated for the first time. Discussion Section 4.3 presents too many numbers without deeper insights on reason behind differences between other studies. At the end of discussion a scatterplot Fig. 14 between observed and modeled peat depths is presented for the 1st time. The Fig. 14 shows that without exceptional agreement of 3 largest values the rest of the scatter is just a gunshot indicating poor performance of the model in most conditions. Authors avoid the explanation. Move results to result section. Present some values in Tables. In discussion interpret the results with a focus on the model and data input.

Response: Thanks for the comments, which helped us significantly improve our presentation of the study. In this revision, we combined the Result and Discussion sections. Also we have shortened some sentences, only providing key points. We have moved the statement of the peat depth calculation into the Method section. In the Result& Discussion section, we added some contents regarding the reasons behind the vegetation changes through time, e.g., the relationships between climate and vegetation distribution. Besides, we added some sentences to discuss the uncertainties of the model and some assumptions in this study. This can represent the reasons behind the differences between model simulation and observation. For the comparison of peat depth, we used the peat sample at each site and directly compared the modeled depth with the observation for that particular pixel. However, as the peat characteristics may differ from site to site, even several kilometers apart, it is very hard for the model to really capture the true peat depth. We added this statement at the end of the discussion. The model is suitable for being applied at regional level and can capture the peat depths features (e.g., the mean values) in a large area as showed similarity of the spatial peat depth distribution between our model and observation (see Hugelius et al. (2014) Figure 3 for observed peat depth distribution).

Interesting results as underestimation in uplands, lack of C loss simulation (Fig. 2), reasons behind vegetation controlling C storage, disagreement with observations, assumption that peatlands will remain C sink are brushed away. The agreement with other studies is OK but not enough for discussion. Describe reasons for agreement/disagreements, give insights on function/performance and reason why to use/trust your model. Although the authors claimed that the PTEM includes CN module, nothing can be learned from reading the paper how this or other modules affect the results. Given the SOC underestimation of uplands and large scatter with peatlands, and large-scale climate estimates, could accounting for differences in nutrient status or reevaluating response of C/N ratio be a key for improved estimation of spatial variability of SOC accumulation of P-TEM or TEM model?

Given the complexity of the biogeochemistry of peatlands, we were not able to address and discuss all processes and mechanisms related to C and N in our simulations. Rather we dedicated our discussion on 1) how the features of vegetation distribution changes over time affect carbon accumulation; 2) how different climates in various paleo-periods affect carbon accumulation rates. We admitted that we have not discussed how N affects C in the model. However, P-TEM is a version that inherited all processes of C and N interactions in an early version of TEM (Zhuang et al., 2003, McGuire et al., 1992), which has been extensively evaluated and applied in numerous applications in northern high latitudes. Here we assume the C and N interactions will also be valid for the peatland ecosystems. In fact, we have started to use C and N data collected from SPRUCE (Brain et al., 2016) experiment to evaluate the N feedbacks to C dynamics. We expect to have a new version of P-TEM to fully account for C and N feedbacks in peatland ecosystems.

Authors claim that recent climate is warmer and wetter in summers and therefore with future warmer-wetter climate peatland carbon sink will continue. Possibility of increased respiration and C loss due to droughts or warmer winters is not mentioned. For the conclusion on future C sink a simulations with climate scenarios would be useful.

Agreed. We have revised our statement regarding future carbon accumulation. We further stated that further study is needed to have a better view on the soil carbon dynamic under future climate scenarios. Given the complexity of peatland dynamics in terms of their areal changes (e.g., expansion and shrinkage, and new peatland formation), we feel analyzing how peatland carbon responds to future climate changes and peatland dynamics is a tremendous work, which is well beyond this study. In addition, the current paper is already very long. Thus, we decided to conduct a full analysis on Arctic peatland carbon responses to future climates in a separate study.

Increase Figs. 2, 3, 4 and their legends size by 50 or 100%

We have increased the legends size and symbol size to make the figures clearer.

Meanwhile, the sequence of some tables and figures has been adjusted to better present the results.

why are panels b, d, f in Fig. 3 scaled by zero? that makes differences to appear smaller increase legend in Fig. 5

We have decreased the axis scale in Fig. 3 to make the difference appear bigger. We also increased the legend in Fig. 5.

increase Fig. 7 and 9, why fig. 9 it has 2 legend bars?

We have increased the size of each panel. We mistakenly put extra color bar in panel (f). We have deleted it.

line 137 "observed water contents drive STM"?, did you mean observed temperatures?

The STM considers soil water content at different depths to simulate the soil temperature. We used the observed soil water content at particular site to drive the STM when parameterizing the model in ***Wang, S., Q. Zhuang, Z. Yu, S. Bridgham, and J. K. Keller (2016), Quantifying peat carbon accumulation in Alaska using a process-based biogeochemistry model, J. Geophys. Res. Biogeosci., 121, doi:10.1002/2016JG003452.***. During the regional simulation, we used the simulated soil water content at different depths directly from HM to drive the STM.

lines 235-238 reformulate for clarity

We have reformulated the sentences.

line 293 correct value of C storage

We have changed this value to 0.8 kg $\mathrm{C}\ \mathrm{m}^{-2}$.

lines 300-302, 309 reformulate for clarity

We have made the reformulation.

line 315 range of what?

The range here is for vegetation carbon storage. We have clarified this.

lines 325 "spots were widely spread" reformulate, "SOC concentration" do you mean SOC storage?

We have reformulated them.

line 326 reformulate "tundra was taking back area" or similar

We have reformulated it.

line 361 Table 4 is not showing parameters

We have changed the statement to "due to uncertainties of observation" and cited the paper which has the parameters listed.

lines 375-377 reformulate for clarity

We have reformulated the section.

lines 420 – 460 reformulate for clarity

We have reformulated the discussion part.

line 424 why if $p < 0.05$ "some certain effects"?

From the result in Wang et al. (2016) that p-value is less than 0.05, we can get the idea that the interaction factor is one of the significant factors. We reorganized this part.

line 428 "positive effect" of temperature? low temp slowed SOC accumulation, that's negative effect

Yes, it should be "negative effect" as the cooler condition during the neoglacier period slowed the carbon accumulation. We reformulated this sentence.

line 437 delete "suggesting the warmest climate during HTM" it comes by definition of HTM

Correct. Repeating the definition of HTM can be awkward. We revised it.

lines 443-448 does not make sense

We deleted this part since it was talking about the uncertainties coming from the climate model (ECBILT) itself, and has already been discussed in He et al. (2014). In this study, we directly used the output of the model.

line 452 what is "stored C in overall in the spatial scale"?

We have reformulated the statement.

line 454 "negative accumulation rate" avoid writing nonsense

We have added "(meaning C loss)" right after this statement.

lines 485 – 545 reformulate whole section, move results into results, check for repetitions, highlight only most important trends and insights, shorten discussion if nothing much relevant to say

We have reformulated the result and discussion.

lines 508-519 OK

References – change into the corresponding format of Biogeosciences

Thanks for pointing this out. We have changed the reference and citation format according to *Biogeosciences* submission requirement The manuscript has never been submitted to other journals before.

Quantifying Soil Carbon Accumulation in Alaskan Terrestrial Ecosystems during the Last 15,000 Years

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Abstract: Northern high latitudes contain large amounts of soil organic carbon (SOC), in which Alaskan terrestrial ecosystems account for a substantial proportion. In this study, the SOC accumulation in Alaskan terrestrial ecosystems over the last 15,000 years was simulated using a process-based biogeochemistry model for both peatland and non-peatland terrestrial ecosystems. Comparable with the previous estimates of 25-70 Pg C in peatland and 13-22 Pg C in non-peatland soils within 1-m depth in Alaska, our model estimated a total SOC of 36-63 Pg C at present, including 27-48 Pg C in peatland soils and 9-15 Pg C in non-peatland soils. Vegetation stored only 2.5-3.7 Pg C in Alaska currently with 0.3-0.6 Pg C in peatlands and 2.2-3.1 Pg C in non-peatlands. The simulated average rate of peat C sequestration was 2.3 Tg C yr^{-1} with a peak value of 5.1 Tg C yr^{-1} during the Holocene Thermal Maximum (HTM) in the early Holocene, four folds higher than the average rate of 1.4 Tg C yr^{-1} over the rest of the Holocene. The SOC accumulation slowed down, or even ceased, during the neoglacial climate cooling after the mid-Holocene, but accumulation increased again in the 20th century. The model-estimated peat depths ranged from 1.1 to 2.7 m, similar to the field-based estimate of 2.29 m for the region. We found that the changes in vegetation types and their distributions due to climate change were the main factors determining the spatial variations of SOC accumulation during different time periods. Warmer summer temperature and stronger radiation seasonality, along with higher precipitation in the HTM and the 20th century might have resulted in the extensive peatland expansion and carbon accumulation, implying that soil C accumulation would continue under future warming conditions.

Keywords: Carbon, Peatlands, Alaska, Modelling, Climate

1. Introduction

Global surface air temperature has been increasing since the middle of the 19th century (Jones and Mogberg, 2003; Manabe and Wetherald, 1980, 1986). Since 1970, the warming trend has accelerated at a rate of 0.35 ℃ per decade in northern high latitudes (Euskirchen et al., 2007; McGuire et al., 2009). It is predicted that the warming will continue in the next 100 years (Arctic Climate Impact Assessment 2005; Intergovernmental Panel on Climate Change (IPCC), 2013, 2014). The land surface in northern high latitudes (>45° N) occupies 22% of the global surface and stores over 40% of the global soil organic carbon (SOC) (McGuire et al., 1995; Melillo et al., 1995; McGuire and Hobbie, 1997). Specifically, the northern high latitudes were estimated to store 200-600 Pg C (1 Pg C = 10^{15} g C) in peatland soils depending on the depth considered (Gorham, 1990, 1991; Yu, 2012), 750 Pg C in non-peatland soils (within 3 m) (Schuur et al., 2008; Tarnocai et al., 2009; Hugelius et al., 2014), and additional 400 Pg C in frozen loess deposits of Siberia (Zimov et al., 2006a). Peatland area is around 40 million hectares in Alaska compared with total 350 million hectares in northern high-latitude regions (Kivinen and Pakarinen, 1981). Alaskan peatlands account for the most vast peatland area in the USA and cover at least 8% of total land area (Bridgham et al., 2006). To date, the regional soil C and its responses to the climate change are still with large uncertainty (McGuire et al., 2009; Loisel et al., 2014).

The warming climate could increase C input to soils as litters through stimulating plant net primary production (NPP) (Loisel et al., 2012). However, it can also decrease the SOC by increasing soil respiration (Yu et al., 2009). Warming can also draw down the water table in peatlands by increasing evapotranspiration, resulting in a higher decomposition rate as the aerobic respiration has a higher rate than anaerobic respiration in general (Hobbie et al., 2000).

SOC accumulates where the rate of soil C input is higher than decomposition. The variation of climate may switch the role of soils between a C sink and a C source (Davidson and Janssens, 2006; Davidson et al., 2000; Jobbagy and Jackson, 2000). Unfortunately, due to the data gaps of field-measurement and uncertainties in estimating regional C stock (Yu, 2012), with limited understanding of both peatlands and non-peatlands and their responses to climate change, there is no consensus on the sink and source activities of these ecosystems (Frolking et al., 2011; Belyea, 2009; McGuire et al., 2009).

To date, both observation and model simulation studies have been applied to understand the long-term peat C accumulation in northern high latitudes. Most field estimations are based on series of peat-core samples (Turunen et al., 2002; Roulet et al., 2007; Yu et al., 2009; Tarnocai et al., 2009). However, those core analyses may not be adequate for estimating the regional C accumulation due to their limited spatial coverage. Model simulations have also been carried out. For instance, Frolking et al. (2010) developed a peatland model considering the effects of plant community, hydrological dynamics and peat properties on SOC accumulation. The simulated results were compared with peat-core data. They further analyzed the contributions of different plant functional types (PFTs) to the peat C accumulation. However, this 1-D model has not been used in large spatial-scale simulations by considering other environmental factors (e.g., temperature, vapor pressure, and radiation). In contrast, Spahni et al. (2013) used a dynamic global vegetation and land surface process model (LPX), based on LPJ (Sitch et al., 2003), imbedded with a peatland module, which considered the nitrogen feedback on plant productivity (Xu-Ri and Prentice, 2008) and plant biogeography, to simulate the SOC accumulation rates of northern peatlands. However, these models have not been evaluated with respect to their simulations of soil moisture, water table depth, methane fluxes, and carbon fluxes presumably due to relatively simple model structures, especially in terms of ecosystem processes (Stocker et al., 2011, 2014; Kleinen et al., 2010). Furthermore, climatic effects on SOC were not fully explained. The Terrestrial Ecosystem Model (TEM) has been applied to study C and nitrogen pools and fluxes in the Arctic (Zhuang et al., 2001, 2002, 2003, 2015; He et al., 2014). However, the model has not been calibrated and evaluated with peat-core C data, and has not been applied to investigate the peatland C dynamics. Building upon these efforts, recently we fully evaluated the peatland version of TEM (P-TEM) including modules of hydrology (HM), soil thermal (STM), C and nitrogen dynamics (CNDM) for both upland and peatland ecosystems (Wang et al., 2016).

Here we used the peatland-core data for various peatland ecosystems to parameterize and test P-TEM (Figure 1). The model was then used to quantify soil C accumulation of both peatland and non-peatland ecosystems across the Alaskan landscape since the last deglaciation. This study is among the first to examine the current peatlands and non-peatlands C distributions and peat depths in various ecosystems at the regional scale.

~~2. Methods~~

~~2.1 Model Description~~

~~In P-TEM, peatland soil organic C (SOC) accumulation is determined by the difference between the net primary production (NPP) and aerobic and anaerobic decompostion. Peatlands accumulate C where NPP is greater than decomposition, resulting in positive net ecosystem production (NEP):~~

$$\cancel{NEP = NPP - R_H - R_{CH_4} - R_{CWM} - R_{CM} - R_{COM}}\ \text{~~(1)~~}$$

~~P-TEM was develoepd based on the Terrestrial Ecosystem Model (TEM) at a monthly step (Zhuang et al., 2003; 2015). It explicitly considers the process of aerobic decomposition (R_H) related to the variability of water table depth; net methane emission after methane oxidation (R_{CH_4}); CO_2 emission due to methane oxidation (R_{CWM}) (Zhuang et al., 2015); CO_2 release accompanied with the methanogenesis (R_{CM}) (Tang et al., 2010; Conrad, 1999); and CO_2 release from other anaerobic processes (R_{COM}, e.g., fermentation, terminal electron acceptor (TEA) reduction) (Keller and Bridgham, 2007; Keller and Takagi, 2013). For upland soils, we only considered the heterotrohic respiration under aerobic condition (Raich, 1991). For detailed model description see Supplement.~~

~~We model peatland soils as a two-layer system for hydrological module (HM) while keeping the three-layer system for upland soils (Zhuang et al., 2002). The soil layers above the lowest water table position are divided into: (1) moss (or litter) organic layer (0-10 cm); and (2) humic organic layer (10-30 cm) (Wang et al., 2016). Based on the total amount of water content within those two unsaturated layers, the actual water table depth (WTD) is estimated. The water content at each 1 cm above the water table can be then determined after solving the water balance equations (Zhuang et al., 2004).~~

~~In the STM module, the soil vertical profile is divided into four layers: (1) snowpack in winter, (2) moss (or litter) organic layer, (3) upper and (4) lower humic organic soil (Wang et al., 2016). Each of these soil layers is characterized with a distinct soil thermal conductivity and heat capacity. We used the observed water contents at the particular sites to drive the STM (Zhuang et al., 2001).~~

~~The methane dynamics module (MDM) (Zhuang et al., 2004) considers the processes of methanogenesis, methanotrophy, and the transportation pathways including: (1) diffusion through the soil profile; (2) plant-aided transportation; and (3) ebullition. The soil temperatures calculated from STM, after interpolation into 1-cm sub-layers, are input to the MDM. The water table depth and soil water content in the unsaturated zone for methane production and emission are obtained from HM, and the net primary production (NPP) is calculated from the CNDM. Soil-water pH is prescribed from observed data and the root distribution determines the redox potential (Zhuang et al., 2004).~~

~~**2.2 Model Parameterization**~~

~~We have parameterized the key parameters of the individual modules including HM, STM, and MDM (Wang et al., 2016). The parameters in CNDM for upland soils and vegetation have been optimized in the previous studies (Zhuang et al 2002, 2003; Tang and Zhuang 2008). The parameters for peatland soils in P-TEM were parameterized using a moderate rich *Sphagnum* spp. open fen (APEXCON) and a *Sphagnum*-black spruce (*Picea mariana*) bog (APEXPER) (Table 3). Both are located in the Alaskan Peatland Experiment site (APEX) study area, where *Picea mariana* is the only tree species above breast height in APEXPER. Three water table position manipulations were established in APEX including a control, a lowered, and a raised water table plots (Chivers et al., 2009; Turetsky et al., 2008; Kane et al., 2010; Churchill et al., 2011). There were also several internal collapse scars that formed with thaw of surface permafrost, including a non-, an old, and a new collapse plots. APEXCON represents the control manipulation and APEXPER represents the non-collapse plot. The annual NPP and aboveground biomass at both sites have been measured in 2009. There were no belowground observations; however, at a Canadian peatland, Mer Bleue, which includes *Sphagnum* spp. dominated bog~~

~~(dominated by shrubs and *Sphagnum*) and pool fen (dominated by sedges and herbs and *Sphagnum*). Assuming the belowground biomass in APEXCON and APEXPER was close to that in Mer Bleue, we used the belowground biomass at Mer Bleue to represent the missing observations at both sites (Table 4). We conducted a set of 100,000 Monte Carlo ensemble simulations for each site-level calibration, and parameters with the highest mode in posterior distribution were selected (Tang and Zhuang, 2008, 2009).~~

~~2.3 Regional Vegetation Data~~

~~The Alaskan C stock was simulated through the Holocene where the vegetation biome maps were reconstructed at four time periods: a time period encompassing a millennial-scale warming event during the last deglaciation known as the BØlling-AllerØd at 15-11 ka (1 ka = 1000 cal yr Before Present), HTM during the early Holocene at 11-10 and 10-9 ka as well as the mid- (9-5 ka) and late- Holocene (9 ka-1900 AD) (He et al., 2014). We used the modern vegetation distribution for the simulation during the period 1900-2000 AD (Figure 2). We assumed that the vegetation distribution remained static within each corresponding time period. Five vegetation types were classified as upland vegetation: boreal deciduous broadleaf forest, boreal evergreen needleleaf and mixed forest, alpine tundra, wet tundra; and barren (Table 1). Mountain ranges and large water bodies were delineated as 'Barren' and data could not be interpolated across them. By using the same vegetation distribution map, we reclassified the upland vegetation into two peatland vegetation types: *Sphagnum* spp. poor fens (SP) generated from tundra ecosystems, and *Sphagnum* spp-black spruce (*Picea mariana*) bog/ peatland (SBP) generated from forest ecosystems (Table 1), both of which dominate the major area of Alaskan peatlands. We used both the upland and peatland vegetation types to simulate the C dynamics in Alaska.~~

~~Upland and peatland distribution for each grid cell was determined using the wetland inundation data extracted from the NASA/ GISS global natural wetland dataset (Matthews and Fung, 1987). The resolution was resampled to 0.5° × 0.5° from 1° × 1°. We postulated that, given the same topography of Alaska during the Holocene, it was reasonable to assume that the wetland distribution can be represented by modern inundation map. The inundation fraction was assumed to be the same within each grid through time and the land grids not covered by expanded peatland yet were assumed as uplands. We calculated the total area of modern Alaskan peatlands to be 302,410 km^2, which was within the range from 132,000 km^2 (Bridgham et al., 2006) to 596,000 km^2 (Kivinen and Pakarinen, 1991). The soil water pH data were extracted from Carter and Scholes (2000), and the elevation data were derived from Shuttle Radar Topography Mission and were resampled to 0.5° × 0.5° spatial resolution.~~

~~2.4 Climate Data~~

~~Climate data were downscaled and bias-corrected from ECBilt-CLIO model output (Timm and Timmermann, 2007; He et al., 2014). Climate fields include monthly precipitation, monthly air temperature, monthly net incoming solar radiation, and monthly vapor pressure (2.5° × 2.5°). We used the same time-dependent forcing atmospheric carbon dioxide concentration data for model input as were used in ECBilt-CLIO transient simulations from the Taylor Dome (Timm and Timmermann, 2007). The historical climate data used for the simulation through the 20th century are monthly CRU2.0 data.~~

~~The mean annual net incoming solar radiation (NIRR) was 78±4.8 W m^{-2} before the HTM (15-11 ka). It showed an increase at the early HTM (11-10 ka), reaching 83.6±4.5 W m^{-2} and continueed to increase to 84±4.7 W m^{-2} at the late HTM (10-9 ka). NIRR decreased after~~

~~the HTM through the entire mid-Holocene (9-5 ka) to a minimum of 79 ± 5 W m^{-2} at the end of the Holocene. It became higher from 1900 to 2000 AD, with annual mean 82 ± 5.1 W m^{-2} (Figure 3b). The mean annual air temperature showed a similar pattern as it rose from -7 ± 1.8 °C to -5 ± 1.6 °C at the early HTM and reached -4.7 ± 1.5 °C at the late HTM, indicating a warmer-than-present climate. There was also a temperature decrease when HTM ended through the rest of the Holocene and the temperature increased again from 1900 AD to -5.8 ± 1.5 °C, presumably due to the global warming (Figure 3d). Total annual precipitation increased from 306 ± 40 mm to 369 ± 25 mm at the end of the HTM, suggesting an overall wet climate. A dryer condition occurred from the mid-Holocene and became driest in the late-Holocene (5 ka-1900 AD) (Figure 3f). The monthly values of NIRR followed the same pattern as annual means, except during the winter. The maximum summer radiation occurred during the late-HTM, leading to the highest radiation seasonality. Large seasonality also appeared in the 20th century, however, lower than that during the HTM (Figure 3a). Temperature seasonality followed the trend of annual temperature. The days of year with temperature above 0 °C increased 10-15 days at the HTM compared with that before the HTM, suggesting a longer growing season (Figure 3c). Precipitations were highest during the summer (July-September) in each time period and lowest during the winter and early spring (December-April). The periods at 15-11ka and in the late-Holocene exhibited less overall, especially summer precipitations than at the HTM. During the 20th century, there was less winter precipitation but it was compensated by a higher summer precipitation compared with the late-Holocene (Figure 3e). The orbital induced maximum seasonality of insolation and the warmest climate during the HTM as described in Huybers et al. (2006) and Yu et al. (2010) corresponded well to the simulated trends of air temperature.~~

~~2.5 Data of Peatland Basal Ages~~

~~We conducted the simulation from 15 to 5 ka for an Alaskan peatland assuming it started to accumulate C since 15 ka. However, assuming that peatlands in all grids had the same basal age (15 ka) could overestimate the total peat SOC accumulation. Therefore we used the observed basal ages of peat samples from Gorham et al. (2012) and categorized them into different time periods (Figure 2). We found that during each period, the spatial distribution of peatland basal ages was similar to that of the vegetation types (e.g., peatland initiation points were mainly located where was dominated by alpine tundra at south, northwestern, and southeastern coast during 15-11 ka). We thus used the vegetation types to estimate the peatland basal ages at regional scales (Table 2).~~

~~2.6 Simulations and Sensitivity Test~~

~~To verify the model ability to simulate the peat C accumulation rates in the past 15,000 years, we conducted a simulation using pixels located on the Kenai Peninsula from 15 to 5 ka after model parameterization. We compared the model simulation results with the peat-core data from four peatlands on the Kenai Peninsula, Alaska (Jones and Yu, 2010; Yu et al., 2010) (see Wang et al. (2016) for detail). The observed data include the peat depth, bulk density of both organic and inorganic matters at 1-cm interval, and age determinations. The simulated C accumulation rates represent the actual ("true") rates at different times in the past. However, the calculated accumulation rates from peat cores are considered as "apparent" accumulation rates, as peat would continue to decompose since the time of formation until present when the measurement was made (Yu, 2012). To facilitate comparison between simulated and observed accumulation rates, we converted the simulated "true" accumulation rates to "apparent" rates,~~

~~following the approach by Spahni et al. (2013). That is, we summed the annual net C accumulation over each 500-year interval and deducted the total amount of C decomposition from that time period, then dividing by 500 years.~~

~~For the study region, we conducted a transient simulation using continuous monthly meteorology data (Figure 2) from 15 ka to 2000 AD. Five maps (Figure 3) were used to represent the vegetation distributions of Alaska and were assumed to be static during each time period (e.g., 15-11 ka, 11-10 ka, 10-9 ka, 9 ka-1900 AD, and 1900-2000 AD). The simulation was firstly conducted assuming all grid cells were taken up by upland vegetation to get the upland soil C spatial distributions during different time periods. We then conducted the second simulation assuming all grid cells were dominated by peatland vegetation by merging upland types into peatland types following Table 1 to obtain the distributions of peat SOC accumulation. We used the inundation fraction map to extract both uplands and peatlands from each grid and estimated the corresponding SOC stocks within each grid, which were then summed up to represent the Alaskan SOC stock.~~

~~We conducted a sensitivity test to evaluate the responses of NPP, SOC decomposition rates (aerobic plus anaerobic respiration), and net SOC balance to the climate variables. Simulations under three scenarios were conducted to test the temperature effect. We used the original forcing data as the standard scenario and the warmer (monthly temperature +5°C) and cooler (−5°C) as other two while keeping the rest forcing data unchanged. Similarly, we used the original forcing data as the standard scenario and the wetter (monthly precipitation +10 mm) and drier (−10 mm) to test the effect from precipitation. To further study if vegetation distribution has stronger effects on SOC sequestration than climate in Alaska, we simply replaced SBP with SP and simultaneously replaced the upland forests with tundra at the beginning of 15 ka. We also~~

~~conducted the simulation under "warmer" and "wetter" conditions described before while keeping the vegetation distribution unchanged.~~

2. Methods

2.1. Overview

To conduct regional simulations of carbon accumulation for both uplands and peatlands, we first parameterized the P-TEM for representative ecosystems in Alaska. Second, we organized the regional vegetation and peatland distribution data, spatial basal age data for all peatland grid cells based on site-level soil core data, and climate data for each period during the Holocene. Finally, we conducted the regional simulations and sensitivity analysis.

2.2 Model Description

In P-TEM (Wang et al., 2016), peatland soil organic C (SOC) accumulation is determined by the difference between NPP and aerobic and anaerobic decompostion. Peatlands accumulate C where NPP is greater than decomposition, resulting in positive net ecosystem production (NEP):

$$NEP = NPP - R_H - R_{CH_4} - R_{CWM} - R_{CM} - R_{COM} \qquad (1)$$

P-TEM was developed based on the Terrestrial Ecosystem Model (TEM) at a monthly step (Zhuang et al., 2003; 2015). It explicitly considers the process of aerobic decomposition (R_H) related to the variability of water-table depth; net methane emission after methane oxidation (R_{CH_4}); CO_2 emission due to methane oxidation (R_{CWM}) (Zhuang et al., 2015); CO_2 release accompanied with the methanogenesis (R_{CM}) (Tang et al., 2010; Conrad, 1999); and CO_2 release from other anaerobic processes (R_{COM}, e.g., fermentation, terminal electron acceptor (TEA) reduction) (Keller and Bridgham, 2007; Keller and Takagi, 2013). For upland soils, we only considered the heterotrohic respiration under aerobic condition (Raich, 1991). For detailed model description see Wang et al. (2016).

We modeled peatland soils as a two-layer system for hydrological module (HM) while keeping the three-layer system for upland soils (Zhuang et al., 2002). The soil layers above the lowest water table position are divided into: (1) moss (or litter) organic layer (0-10 cm); and (2) humic organic layer (10-30 cm) (Wang et al., 2016). Based on the total amount of water content within those two unsaturated layers, the actual water table depth (WTD) is estimated. The water content at each 1 cm above the water table can be then determined after solving the water balance equations (Zhuang et al., 2004).

In the STM module, the soil vertical profile is divided into four layers: (1) snowpack in winter, (2) moss (or litter) organic layer, (3) upper and (4) lower humic organic soil (Wang et al., 2016). Each of these soil layers is characterized with a distinct soil thermal conductivity and heat capacity. We used the observed water content to drive the STM (Zhuang et al., 2001).

The methane dynamics module (MDM) (Zhuang et al., 2004) considers the processes of methanogenesis, methanotrophy, and the transportation pathways including: (1) diffusion through the soil profile; (2) plant-aided transportation; and (3) ebullition. The soil temperatures calculated from STM, after interpolation into 1-cm sub-layers, are input to the MDM. The water-table depth and soil water content in the unsaturated zone for methane production and emission are obtained from HM, and NPP is calculated from the CNDM. Soil-water pH is prescribed from observed data and the root distribution determines the redox potential (Zhuang et al., 2004).

2.3 Model Parameterization

We have parameterized the key parameters of the individual modules including HM, STM, and MDM in Wang et al. (2016). The parameters in CNDM for upland soils and vegetation have been optimized in the previous studies (Zhuang et al 2002, 2003; Tang and Zhuang 2008). Here we parameterized P-TEM for peatland ecosystems using data from a moderate rich *Sphagnum* spp. open fen (APEXCON) and a *Sphagnum*-black spruce (*Picea mariana*) bog (APEXPER) (Table 1). Both are located in the Alaskan Peatland Experiment (APEX) study area, where *Picea mariana* is the only tree species above breast height in APEXPER. Three water table position manipulations were established in APEX including a control, a lowered, and a raised water table plots (Chivers et al., 2009; Turetsky et al., 2008; Kane et al., 2010; Churchill et al., 2011). There were also several internal collapse scars that formed with thaw of surface permafrost, including a non-, an old, and a new collapse plots. APEXCON represents the control manipulation and APEXPER represents the non-collapse plot. The annual NPP and aboveground biomass at both sites have been measured in 2009. There were no belowground observations at APEX, however at a Canadian peatland, Mer Bleue, which includes *Sphagnum* spp. dominated bog (dominated by shrubs and *Sphagnum*) and pool fen (dominated by sedges and herbs and *Sphagnum*). The belowground biomass was also observed at Suurisuo mire complex, southern Finland, a sedge fen site dominated by *Carex rostrate*. We used the ratio (70%) of belowground biomass to total biomass from these two study sites to calculate the missing belowground biomass values at APEXCON and APEXPER (Table 2). We conducted 100,000 Monte Carlo ensemble simulations to calibrate the model for each site using a Bayesian approach and parameter values with the modes in their posterior distributions were selected (Tang and Zhuang, 2008, 2009).

2.4 Regional Model Input Data

The Alaskan C stock was simulated through the Holocene driven with vegetation data reconstructed for four time periods including a time period encompassing a millennial-scale warming event during the last deglaciation known as the BØlling-AllerØd at 15-11 ka (1 ka = 1000 cal yr Before Present), HTM during the early Holocene at 11-10 and 10-9 ka, and the mid- (9-5 ka) and late- Holocene (5 ka-1900 AD) (He et al., 2014). We used the modern vegetation distribution for the simulation during the period 1900-2000 AD (Figure 2). We assumed that the vegetation distribution remained static within each corresponding time period. Upland ecosystems were classified into boreal deciduous broadleaf forest, boreal evergreen needleleaf and mixed forest, alpine tundra, wet tundra; and barren lands (Table 3). By using the same vegetation distribution map, we reclassified the upland ecosystems into two peatland types including *Sphagnum* spp. poor fens (SP) dominated by tundra and *Sphagnum* spp.-black spruce (*Picea mariana*) bog/ peatland (SBP) dominated by forest ecosystems (Table 3).

Upland and peatland ecosystem distribution for each grid cell was determined using the wetland inundation data extracted from the NASA/ GISS global natural wetland dataset (Matthews and Fung, 1987). The resolution was resampled to $0.5° \times 0.5°$ from $1° \times 1°$. Given the same topography of Alaska during the Holocene, we assumed that the wetland distribution kept the same throughout the Holocene. The inundation fraction was assumed to be the same within each grid through time and the land grids not covered by peatland were treated as uplands. We calculated the total area of modern Alaskan peatlands to be 302,410 km^2, which was within the range from 132,000 km^2 (Bridgham et al., 2006) to 596,000 km^2 (Kivinen and Pakarinen, 1991). The soil water pH data were extracted from Carter and Scholes (2000), and the elevation data were derived from Zhuang et al. (2007).

Our regional simulations considered the effects of basal ages on carbon accumulation. To obtain the spatially explicit basal age data for all peatlands grid cells, we first categorized the observed basal ages of peat samples from Gorham et al. (2012) into different time periods (Figure 2). During each period, the spatial distribution of peatland basal ages was correlated with the dominated vegetation types. For instance, peatland initiations during 15-11 ka occurred in the pixels that were dominated by alpine tundra at south, northwestern, and southeastern coast. We thus used the vegetation types to estimate the peatland basal ages for all grid cells at regional scales (Table 4).

Climate data were bias-corrected from ECBilt-CLIO model output (Timm and Timmermann, 2007) to minimize the difference from CRU data (He et al., 2014). Climate fields include monthly precipitation, monthly air temperature, monthly net incoming solar radiation, and monthly vapor pressure at resolution of $2.5° \times 2.5°$. We used the same time-dependent forcing atmospheric carbon dioxide concentration data for model input as were used in ECBilt-CLIO transient simulations from the Taylor Dome (Timm and Timmermann, 2007). The historical climate data used for the simulation through the 20th century were monthly CRU2.0 data (Mitchell et al., 2004).

2.5 Simulations and Sensitivity Test

Simulations for pixels located on the Kenai Peninsula from 15 to 5 ka were first conducted with the parameterized model. The peat-core data from four peatlands on the Kenai Peninsula, Alaska (Jones and Yu, 2010; Yu et al., 2010) (see Wang et al. (2016) Table 3) were used to compare with the simulations. The observed data include the peat depth, bulk density of both organic and inorganic matters at 1-cm interval, and age determinations. The simulated C accumulation rates represent the actual ("true") rates at different times in the past. However, the calculated accumulation rates from peat cores are considered as "apparent" accumulation rates, as peat would continue to decompose since the time of formation until present when the measurement was made (Yu, 2012). To facilitate comparison between simulated and observed accumulation rates, we converted the simulated "true" accumulation rates to "apparent" rates, following the approach by Spahni et al. (2013). That is, we summed the annual net C accumulation over each 500-year interval and deducted the total amount of C decomposition from that time period, then dividing by 500 years.

Second, we conducted a transient regional simulation driven with monthly climatic data (Figure 3) from 15 ka to 2000 AD. The simulation was conducted assuming all grid cells were taken up by upland ecosystems to get the upland soil C spatial distributions during different time periods. We then conducted the second simulation assuming all grid cells were dominated by peatland ecosystems following Table 3 to obtain the distributions of peat SOC accumulation. Finally, we used the inundation fraction map to extract both uplands and peatlands and estimated the corresponding SOC stocks within each grid, which were then summed up to represent the Alaskan SOC stock. We also used the observed mean C content of 46.8% in peat mass and bulk density of 166 ± 76 kg m^{-3} in Alaska (Loisel et al., 2014) to estimate peat depth distribution from the simulated peat SOC density (kg C m^{-2}).

Third, we conducted a series of extra simulations to further examine how uncertain climates and vegetation distribution affect our results. We used the original forcing data as the standard scenario and the warmer (monthly temperature $+5$℃) and cooler (-5℃) as other two scenarios while keeping the rest forcing data unchanged. Similarly, we used the original forcing data as the standard scenario and the wetter (monthly precipitation +10 mm) and drier (−10 mm) to test the effect from precipitation. To further study if vegetation distribution has stronger effects on SOC accumulation than climate in Alaska, we simply replaced SBP with SP and replaced the upland forests with tundra at the beginning of 15 ka. We then conducted the simulation under "warmer" and "wetter" conditions simultaneously as described before while keeping the vegetation distribution unchanged.

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~~3. Results~~

~~3.1 Simulated Peatland Carbon Accumulation Rates at Site Level~~

~~Our paleo simulation showed a large peak of peat C accumulation rates at 11-9 ka during the HTM (Figure 4). The simulated "true" and "apparent" rates captured this primary feature in peat-core data at almost all sites (Jones and Yu, 2010). The simulated magnitude of this peak was similar to observations at No Name Creek and Horse Trail Fen, but overestimated at Kenai Gasfield and Swanson Fen at 10-9 ka (late-HTM). The secondary peak of C accumulation rates appeared at 6-5 ka in the mid-Holocene. The simulation successfully estimated both peaks at Swanson Fen, No Name Creek, and Kenai Gasfield, but with overestimated magnitude at Swanson Fen. The comparison between simulation and observation using averages in 500-year bins revealed a high correlation (~~$\cancel{R^2 = 0.90, 0.88, \text{and } 0.39}$~~), especially at No Name Creek and Horse Trail Fen. The simulated SOC accumulation rates corresponded well to the synthesis curves at four sites (Figure 4b).~~

~~3.2 Vegetation Carbon Storage~~

~~Model simulations showed an overall low mean annual vegetation C storage before the HTM (15-11 ka) (Figure 5a), paralleled to the relatively low annual NPP (Figure 5b). The *Sphagnum* dominated peatland represented the lowest vegetation C storage (2.5 kg C m^{-2}), much lower than the *Sphagnum*-black spruce peatland (1 kg C m^{-2}). Upland vegetation showed a generally higher C storage, with the highest amount of C stored in boreal evergreen needleleaf forests (2 kg C m^{-2}). The upland forests also showed a higher rate of annual NPP (0.31-0.35 kg C m^{-2}yr^{-1}). C storage of alpine and moist tundra was higher than peatlands, while the annual NPP were lower (0.08-0.1 kg C m^{-2}yr^{-1}). Higher NPP were shown in almost all vegetation types during the early Holocene. There were no significant changes of vegetation C storage in peatlands and tundra compared with boreal forests. All vegetation showed a higher NPP and vegetation C during the late-HTM. Mean annual vegetation C exceeded 0.5 g C m^{-2} and 1.3 g C m^{-2} for *Sphagnum* and black spruce peatlands. Evergreen forest stored over 4.7 kg C m^{-2}. During the mid-Holocene, almost all vegetation types represented a decrease in both NPP and vegetation C. The plant productivity along with the vegetation C began to slightly increase at late-Holocene and became stable, possibly resulted from the rising temperature.~~

~~Approximately 2 Pg C was stored in both upland and peatland vegetation in Alaska before the HTM (Figure 6). Upland moist tundra accounted for the most amount of C due to its large area. At the early HTM, evergreen needleleaf forest area became the largest, and about 1.9 Pg C was stored in boreal forests. More C was stored in black spruce peatland also because of the forest formation. Boreal forest accounted for 3.5 Pg C at the late HTM. Decrease of vegetation C occurred at mid-Holocene. The simulation through the Holocene to present indicated that the lowest amount C was stored in vegetation before the HTM, while vegetation assimilated the largest amount of C during the late-Holocene. We estimated a total 2.9 Pg C~~

~~stored in modern Alaskan vegetation, with 0.4 Pg in peatlands and 2.5 Pg in non-peatlands. The uncertainties of the parameters during the model calibration (Table 4) resulted in a range of 0.3-0.6 Pg C and 2.2-3.1 Pg C in peatlands and non-peatlands, respectively.~~

~~3.3 Soil Carbon Stocks~~

~~Carbon storage in Alaskan non-peatland soils varied spatially (Figure 7). Generally, deciduous broadleaf forests had a higher SOC (8-13 kg C m^{-2}) than evergreen needleleaf forests (3-8 kg C m^{-2}), while moist tundra had the highest SOC (12-25 kg C m^{-2}). The SOC showed an overall increase in both boreal forests and moist tundra during the early-HTM (11-10 ka) (Figures 7a, b). With the continued expansion of the boreal forests during the late-HTM (10-9 ka) (Figure 4c), the spots of low SOC concentration were widely spread (Figure 7c). During the mid- (9-5 ka) and late-Holocene (5 ka-1900 AD), although the wet tundra took back the most area, the SOC decreased (Figure 7d) presumably due to the cooler and drier conditions, which was consistent with the decline in mean annual NPP and vegetation C (Figure 5). An increase occurred again in the last century with mean SOC comparable to the late-HTM (Figure 7f). An average of 3.1 Pg C was simulated before the HTM (Figure 8). The SOC increased sharply during the early-HTM (to 11.5 Pg C) across Alaska and slightly decreased to 9 Pg C at the end of HTM. There was little variation during the mid- and late-Holocene (10.7 Pg C) and the amount increased to 11.2 Pg C at the end of the 20^{th} century. Due to model parameterization (Table 4), the regional soil C estimates ranged from 9 to 15 Pg C at present.~~

~~The peatland SOC showed a different pattern compared to upland soils. Peatlands started to accumulate C at 15 ka mainly in northwestern, southeastern, and south coastal regions of Alaska (Figure 9a). Much less C (<10 kg C m^{-2}) was accumulated in the southeastern coast in comparison to other coastal parts (>15 kg C m^{-2}). Initially, only *Sphagnum* open peatland (SP) existed, with no *Sphagnum* black spruce forested peatland (SBP). At the beginning of the HTM, there was a peatland area of ~4.5× 10^{5} km^{2} (Figure 10). During the early HTM, the SP formed in the north coast and the SBP rapidly expanded in south coast and east central regions, becoming the dominant peatland type in Alaska (Figure 9b). Meanwhile the peatlands area increased to ~13× 10^{5} km^{2} (Figure 10). The SBP continued to expand to the central Alaska during the late HTM (Figure 9c). Although peatlands continued to form towards west in the mid-Holocene (Figures 9d, 10), some areas that were dominated by SBP in interior Alaska stopped accumulating SOC. By the end of the mid-Holocene, almost all the peatlands have formed (Figure 10) and some grids showed negative accumulation in the late Holocene (Figure 9e). However, as the global warming began in the 20th century, SOC accumulation increased rapidly again (Figure 9f).~~

~~The mean annual SOC accumulation rates increased from 0.9 to 28.7 g C m^{-2}yr^{-1}and from 0 to 57.1 g C m^{-2}yr^{-1} in the early HTM (11-10 ka) for SP and SBP, respectively, with an area-weighted rate of 41.6 C m^{-2}yr^{-1} (Figure 11). The accumulation rate of the SP increased to 48.6 g C m^{-2}yr^{-1} while the rate of SBP slightly decreased to 56.7 g C m^{-2}yr^{-1} with an overall rate 54.7 C m^{-2}yr^{-1} in the late HTM (10-9 ka) (Figure 11), followed by a drop to 22.7 and 13.1 g C m^{-2}yr^{-1} in the mid-Holocene (Figure 11). Late-Holocene rates ranged from 9.8 to -8.0 g C m^{-2}yr^{-1} for SP and SBP. The rates of SP and SBP reached 42.5 and 33.2 g C m^{-2}yr^{-1} respectively in the 20th century.~~

~~The change in total SOC stock corresponded well to the mean annual accumulation rates during the last 15,000 years (Figures 8, 11). A total of 37.4 Pg C was estimated to accumulate in Alaskan peatlands, with 23.9 Pg C in SP and 13.5 Pg C in SBP, from 15 ka to 2000 AD. The total peat C stock had an uncertainty range of 27-48 Pg C depending on model parameters (Table 4). The peatlands in the northern and southern coastal regions showed the highest SOC densities (>150 kg C m^{-2}), while some central regions had the lowest (<20 kg C m^{-2}) (Figure 12a). For newly formed peatlands in west central part and west coast, <100 kg C m^{-2} SOC was accumulated. The non-peatland SOC distribution was mainly decided by the vegetation types, with high densities (>15 kg C m^{-2}) in west and north coast where tundra dominated and low densities (<10 kg C m^{-2}) in central and east parts where boreal forests dominated (Figure 12b).~~

~~We used the observed mean C content of 46.8% in peat mass and bulk density of 166±76 kg m^{-3} in Alaska (Loisel et al., 2014) to estimate peat depth at each peat grid cell from the simulated peat SOC density (kg C m^{-2}). The spatial pattern of peat depth is identical to the SOC distribution, with most regions having peat depths of <2.5 m (Figure 12c). Based on the modern land area in each TEM gird cell and the inundation map, we estimated a weighted average depth of 1.9 m (ranging from 1.1 to 2.7 m, considering uncertainty in bulk density values) for Alaska peatlands. We also combined the SOC in both peatlands and non-peatlands results together to generate the total SOC distribution (Figure 12d). Soils at northern coast had the highest densities, many grids had SOC >40 kg C m^{-2}. Southwestern coast and eastern central Alaska also showed a high total SOC accumulation (>40 kg C m^{-2}). Central, eastern parts and west coast had the lowest SOC densities (<20 kg C m^{-2}).~~

~~3.4 Sensitivity Test~~

~~We found that NPP and decomposition rates changed simultaneously, but NPP had the dominant effect as the net SOC accumulation rate of Alaska increased and decreased under warmer and cooler conditions, respectively (Figures 13a, c, e). The net SOC accumulation rate increased as the condition became wetter and vice versa (Figures 13b, d, f). We also found an increase of SOC from 11.2 to 14.6 Pg C for upland mineral soils and 37.5 to 71 Pg C for peatlands after replacing the SP to SBP and upland forest systems with tundra. Meanwhile, under "warmer" and "wetter" conditions, the upland and peatland SOC increased by 13.8 Pg C and 35 Pg C, respectively.~~

~~4. Discussion~~

~~4.1 Effects of Climate on Ecosystem Carbon Accumulation~~

~~The simulated climate by ECBilt-CLIO model showed that among the six time periods, the coolest temperature appeared at 15-11 ka, followed by the late Holocene (5 ka-1900 AD). Those two periods were also generally dry (Figure 3f). The former represented colder and drier climate before the onset of the Holocene and the HTM (Barber and Finney, 2000; Edwards et al., 2001). The latter represented post-HTM neoglacial cooling, which caused permafrost aggradation across northern high latitudes (Oksanen et al., 2001; Zoltai, 1995).~~

~~The simulated NPP, vegetation C density and storage were highest during the HTM (Figures 5, 6). The highest C accumulation rates in both peatlands and non-peatlands occurred at the time (Figures 7-11). ECBilt-CLIO simulated an increase of temperature in the growing season (Figure 3c), also leading to a stronger seasonality of temperature during the HTM (Kaufman et al., 2004, 2016), caused by the maximum summer insolation (Berger and Loutre, 1991; Renssen et al., 2009). The highest mean annual and highest summer precipitations were~~

~~also simulated during the 10-9 ka period. The highest vegetation C uptake and SOC accumulation rates coincided with the warmest summer and the wetter-than-before conditions, suggesting a strong link between those climate variables and C dynamics in Alaska. Enhanced climate seasonality characterized by warmer summer, enhanced summer precipitation and possibly earlier snow melt during the HTM increased NPP, as shown in our sensitivity test. Annual NPP increased by 40 and 20 g C m^{-2} yr^{-1} under the warmer and wetter scenarios, respectively (Figures 13a, b), indicating summer temperature and precipitation were the primary controls over NPP. Warmer condition could positively affect the SOC decomposition (Nobrega et al., 2007). Furthermore, hydrological effect can also be significant as higher precipitation could raise the water-table position, allowing less space for aerobic respiration. As shown in the sensitivity test, warmer and wetter could lead to an increase of decomposition up to 35 and 15 g C m^{-2} yr^{-1}, respectively (Figures 13c, d). Such climatic effects on ecosystem productivity were consistent with modern studies (Tucker et al., 2001; Kimball et al., 2004; Linderholm, 2006). Our results did not show a decrease in total heterotrophic respiration throughout Alaska from the higher precipitation, presumably due to a much larger area of upland soils (1.3×10^6 km^2) than peatland soils (0.26×10^6 km^2), as higher precipitation would cause higher aerobic respiration in the unsaturated zone of upland soils. The relatively low vegetation NPP and C density, along with the low total vegetation and soil C stocks during 15-11 ka period and late-Holocene were consistent with the unfavorable cool and dry climate conditions (Figures 5, 6, 8, 11). Our previous simulations at four peatland sites in Alaska (Wang et al., 2016) suggested that temperature had the most significant effect on peat accumulation rate, followed by the seasonality of net solar radiation and temperature. Precipitation and the interactive effect from temperature and precipitation had some certain effects (p<0.05). The period from 15 to 11 ka~~

~~experienced lower snowfall than the HTM. The combination of decreased snowfall and lower temperature could result in deeper frost depth due to the decreased insulative effects of the snowpack, and therefore shortening the period for active photosynthetic C uptake, leading to an overall low productivity (McGuire et al., 2000; Stieglitz et al., 2003). The positive effect of temperature on SOC accumulation as shown in this study, may help explain the coincidence between low SOC accumulation rates across the northern peatland domain and the cooler condition during the neoglacial period (Marcott et al., 2013; Vitt et al., 2000; Peteet et al., 1998; Yu et al. 2010). The stimulation of SOC accumulation from the warming and the rapid SOC accumulation rates during the 20th century in our study suggested a continue C sink will exist under the warmer and wetter climate conditions in the 21st century, as also concluded in Spahni et al. (2013).~~

~~The 20th century represented a temperature rise induced by global warming. It was still 1.1 °C lower than the late-HTM, suggesting the warmest climate during the HTM, which agreed with the previous study (Stafford et al., 2000). It was also lower than the mid-Holocene, which compared favorably with other estimates (Anderson and Brubaker, 1993; Kaufman et al., 2004). However, the annual precipitation during modern time estimated from other studies was higher than the HTM and mid-Holocene (Barber and Finney, 2000). The model output we used may overestimate the precipitation in the HTM, which could subsequently overestimate the water-table position and thus, the annual C accumulation rates. As studied, regional precipitation varies largely depending on the local topography (Stafford et al., 2000), thus the estimates with large-scale climate models have a large uncertainty. Great heterogeneity is produced from using large climatic controls (e.g., insolation and sea ice extent), which casts limits for accurately simulating~~

~~the location- and topographic-specific climate data, especially precipitation (Whitlock and Bartlein, 1993; Mock and Bartlein, 1995).~~

~~**4.2 Effects of Vegetation Distribution on Ecosystem Carbon Accumulation**~~

~~Different vegetation distributions during various periods led to clear step changes, suggesting vegetation composition is likely to be the primary control on C dynamics. Similarly, SBP areas stored lower C than SP in overall at the spatial scale during each time period (Figure 9). Under cooler and drier climates, forested peatlands generally stopped accumulating SOC during the mid- and late-Holocene with some areas accompanied by a negative accumulation rate (Figures 9d,e), suggesting that such type of peatland could be more vulnerable to climate change due to its low C storage.~~

~~As key parameters controlling C dynamics in the model (e.g., maximum rate of photosynthesis, litter fall C) are ecosystem type specific, vegetation distribution change may have a dominant effect on simulated regional plant productivity and C storage. Our sensitivity test indicated that by replacing all vegetation types with forest systems, there was a total increase of 36.9 Pg in upland and peatland soils. There was also an increase of 48.8 Pg C under warmer and wetter conditions. These tests indicated that both climate and vegetation distribution have significant effects on C storage.~~

~~However, the high correlation between climate and ecosystem C dynamics as discussed above indicated that climate was probably the fundamental driver for vegetation composition changes over time. The vegetation changes as reconstructed from fossil pollen data during different time periods followed the general climate history during the last 15,000 years (He et al., 2014). Upland alpine and moist tundra stored the largest amounts of C due to their large areas~~

~~among all vegetation types, as forests areas were limited before the HTM (Figure 6). On the basis of the observed relationship between the distributions of basal ages of peat samples and vegetation types (Table 2, Figure 2), alpine and moist tundra were favorable for peatlands initiation under a cooler climate. No forested peatlands formed before the HTM. Under the warm condition in the HTM, boreal evergreen needleleaf and deciduous broadleaf forests expanded (Figures 2b, c) as indicated by other studies (Bartlein et al., 2011; Edwards et al., 2005; Williams et al., 2001). Meanwhile, large areas were taken up by forested peatlands, characterized by the sharp increase of SOC storage in such ecosystems. The cooler temperature during the mid-Holocene limited the productivity of tree plants, leading to the retreat of trees. This is broadly consistent with other studies (Prentice et al., 1996; Edwards et al., 2000; Williams et al., 2001; Bigelow et al., 2003). Large proportion of forested peatlands thus changed back into *Sphagnum* spp. peatlands. The retreat of treeline on the Seward Peninsula in the cooler mid-Holocene likely reflects much shorter and cooler growing seasons, influenced by an expansion of sea ice in the Bering Sea (Crockford and Frederick, 2007) and the onset of the cooler Neoglacial climate. Forested peatlands ceased accumulating SOC in central Alaska with an overall low accumulation rates through the whole mid- to late-Holocene (Figures 8, 9, 11).~~

~~4.3 Comparison between Simulated Carbon Dynamics and Other Estimates~~

~~A large variation of "true" peat C accumulation rates was simulated on the Kenai Peninsula (Figure 4a), ranging from -4 (that is, peat C loss) to 50 C m^{-2} yr^{-1}. We simulated an average of peat SOC "apparent" accumulation rate of 11.4 g C m^{-2} yr^{-1} from 15 to 5 ka (Figure 4b), which was slightly higher than the observed average rate from four sites (10.45 g C m^{-2} yr^{-1}). The simulated rate during the HTM was 26.5 g C m^{-2} yr^{-1}, up to five times higher than the rest of the Holocene (5.04 g C m^{-2} yr^{-1}). The simulation results corresponded to~~

~~the observations, in which an average rate of 20 C m^{-2} yr^{-1} from 11.5 to 8.6 ka was observed, four times higher than 5 C m^{-2} yr^{-1} over the rest of the Holocene.~~

~~We estimated an average peat SOC “apparent” accumulation rate of 13 g C $m^{-2}yr^{-1}$ (2.3 Tg C yr^{-1} for the entire Alaska) from 15 ka to 2000 AD, lower than the value of 18.6 g C $m^{-2}yr^{-1}$ as estimated from peat cores for northern peatlands (Yu et al., 2010), and slightly higher than the observed rate of 13.2 g C $m^{-2}yr^{-1}$ from four peatlands in Alaska (Jones and Yu, 2010). A simulated peak occurred during the HTM with the rate 29.1 g C $m^{-2}yr^{-1}$ (5.1 Tg C yr^{-1}), which was slightly higher than the observed 25 g C $m^{-2}yr^{-1}$ for northern peatlands and ~20 g C $m^{-2}yr^{-1}$ for Alaska (Yu et al., 2010). It was almost four times higher than the rate 6.9 g C $m^{-2}yr^{-1}$ (1.4 Tg C yr^{-1}) over the rest of the Holocene, which corresponded to the peat core-based observations of ~5 g C $m^{-2}yr^{-1}$. The mid- and late Holocene showed much slower C accumulation at a rate approximately five folds lower than during the HTM. This corresponded to the observation of a six-fold decrease in the rate of new peatland formation after 8.6 ka (Jones and Yu 2010). The C accumulation rates increased abruptly to 39.2 g C $m^{-2}yr^{-1}$during the last century, within the field-measured average apparent rate range of 20-50 g C $m^{-2}yr^{-1}$ over the last 2000 years (Yu et al., 2010).~~

~~The SOC stock of northern peatlands has been estimated in many studies, ranging from 210 to 621 Pg (Oechel 1989; Gorham 1991; Armentano and Menges, 1986; Turunen et al., 2002; Yu et al., 2010; see Yu 2012 for a review). Assuming Alaskan peatlands were representative of northern peatlands and using the area of Alaskan peatlands (0.45×10^6 km^2; Kivinen and Pakarinen, 1981) divided by the total area of northern peatlnads (~4×10^6 km^2; Maltby and Immirzi 1993), we estimated a SOC stock of 23.6-69.9 Pg C for Alaskan peatlands. Our model~~

~~estimated 27-48 Pg C had been accumulated from 15 ka to 2000 AD. The uncertainty may be resulted from peat basal age distributions and the peatland area, as we used modern inundation data to estimate an area of 0.26×10^6 km^2. By incorporating the observed basal age distribution, we estimated that approximately 68% of Alaskan peatlands had formed by the end of the HTM, similar to the estimation from observed basal peat ages that 75% peatlands have formed by 8.6 ka (Jones and Yu 2010).~~

~~The northern circumpolar soils were estimated to cover approximately 18.78×10^6 km^2 (Tarnocai et al., 2009). The non-peatland soil C stock was estimated to be in the range of 150-191 Pg C for boreal forests (Apps et al., 1993; Jobbagy and Jackson, 2000), and 60-144 Pg C for tundra (Apps et al., 1993; Gilmanov and Oechel, 1995; Oechel et al., 1993) in the 0-100 cm depth. Using the difference between Alaskan total land area (1.69×10^6 km^2) and peatland area (0.45×10^6 km^2), we estimated that the non-peatland area in Alaska was 1.24×10^6 km^2. Therefore, Alaska non-peatland area contained 17-27 Pg C by using the ratio of Alaskan non-peatland over northern non-peatland. In comparison, our estimate of 9-15 Pg C within 1-meter depth suggested that our model might have underestimated the C stock for non-peatland soils. Meanwhile, our estimated 2.5-3.7 Pg C stored in the Alaskan vegetation was lower than the previous estimate of 5 Pg (Balshi et al., 2007; McGuire et al., 2009). The underestimation could be resulted from the uncertainties in both peatland area fraction within each grid and the model parameterization.~~

~~The simulated modern SOC distribution (Figure 12c) was largely consistent with the study of Hugelius et al. (2014) (see Figure 3 in the paper). The model captured the high peat SOC density areas on northern and southwestern coasts of Alaska, where observational data showed some locations with SOC >75 kg C m^{-2}. This corresponded to our model simulation that~~

~~many grids had the SOC >75 kg C m^{-2} in those areas. The observed overall average SOC density of >40 kg C m^{-2} was also consistent with our simulation. Eastern part and west coast had the lowest SOC densities, corresponding to the model result that most grids in those areas had SOC values between 20 and 40 kg C m^{-2}. Our estimated average peat depth of 1.9 m ranging from 1.1 to 2.7 m from simulated peat SOC density was similar to the observed mean depth of 2.29 m for Alaskan peatlands (Gorham et al., 1991, 2012). Our estimates (Figure 12d) showed a high correlation with the 64 observed peat samples (Figure 14) ($R^2 = 0.45$). The large intercept of the regression line (101 cm) suggested that the model may not perform well in estimating the grids with low peat depths (<50 cm).~~

3. Results and Discussion

3.1 Simulated Peatland Carbon Accumulation Rates at Site Level

Our paleo simulations showed a large peak of peat C accumulation rates at 11-9 ka during the HTM (Figure 4). The simulated "true" and "apparent" rates captured this primary feature in peat-core data at almost all sites (Jones and Yu, 2010; See Wang e al. (2016) Table 3 for sites details). We simulated an average of peat SOC "apparent" accumulation rate of 11.4 g C m^{-2} yr^{-1} from 15 to 5 ka, which was slightly higher than the observations at four sites (10.45 g C m^{-2} yr^{-1}). The simulated rate during the HTM was 26.5 g C m^{-2} yr^{-1}, up to five times higher than the rest of the Holocene (5.04 g C m^{-2} yr^{-1}). This corresponded to the observed average rate of 20 C m^{-2} yr^{-1} from 11.5 to 8.6 ka, which is, four times higher than 5 C m^{-2} yr^{-1} over the rest of the Holocene.

3.2 Vegetation Carbon

Model simulations showed an overall low vegetation C before the HTM (15-11 ka) (Figure 5a), paralleled to the relatively low annual NPP (Figure 5b). The lowest amount of C (~0.8 kg C m^{-2}) was stored in *Sphagnum*-dominated peatland. *Sphagnum*-black spruce peatland also had low vegetation C density (~1 kg C m^{-2}). Upland vegetation showed a generally higher C storage, among which boreal evergreen needleleaf forest ranked the first (~2 kg C m^{-2}). Highest NPP accompanied by highest vegetation carbon appeared during the HTM (11-9 ka) (Figures 5a and b). Lower annual C uptake along with lower C was found during mid- and late-Holocene (9 ka-19th), where peatland ecosystems exhibited the most obvious drops (Figures 5a and b).

In general, vegetation held about 2 Pg C before the HTM (Figure 6). Upland tundra ecosystems accounted for the most amount of C. During the HTM, Boreal evergreen needleleaf forest reached its highest and had an overwhelming proportion over total C. Similarly, a peak of total vegetation C appeared at the same time, averaging around 4.3 Pg C. Large decrease occurred at the mid-Holocene and a slight decline continued till the late-Holocene. We estimated a total 2.9 Pg C stored in modern Alaskan vegetation, with 0.4 Pg in peatlands and 2.5 Pg in non-peatlands. The uncertainties during the model calibration (Table 4) resulted in 0.3-0.6 Pg C and 2.2-3.1 Pg C in peatlands (see Wang et al. (2016) for model parameters) and non-peatland vegetation (see Tang and Zhuang (2008) for uncertainty analyses for upland vegetation), respectively. Our estimation of 2.5-3.7 Pg C stored in the Alaskan vegetation was lower than the previous estimate of 5 Pg (Balshi et al., 2007; McGuire et al., 2009), presumably due to the prior ranges of model parameters used from Tang and Zhuang (2008). Our overestimation of peatland area may also lead to a reduction of Alaskan non-peatland area.

3.3 Soil Carbon

Carbon storage in Alaskan non-peatland soils varied spatially (Figure 7). Moist tundra had the highest SOC density (12-25 kg C m^{-2}), followed by deciduous broadleaf forest (8-13 kg C m^{-2}) and evergreen needleleaf forest (3-8 kg C m^{-2}) through all time slices between 15 ka and 2000 AD. Dramatic changes of vegetation types have occurred in Alaska during different periods (Figure 2). Before the HTM (15-11 ka), the terrestrial ecosystem was dominated by tundra. Northwestern coast and eastern interior was covered by moist tundra. Southwestern Alaska and the interior south of the Brooks Range were dominated by alpine tundra (Figure 2a). The basal ages of peat samples from Gorham et al. (2012) suggested that peatlands were likely to form from the (alpine) tundra ecosystems, although patches of boreal deciduous broadleaf forest and boreal evergreen needleleaf and mixed forest appeared at the north of the Alaska Range. Initially, only *Sphagnum* open peatland (SP) existed, with less C (<10 kg C m^{-2}) sequestrated in the southeastern Brooks Range in comparison with southwestern and northwestern coastal parts (>15 kg C m^{-2}) (Figure 8a). Approximately 4.5$\times 10^5$ km^2 area was covered by peatlands at the beginning of the HTM (~11 ka) (Figure 9). During the HTM (11-9 ka), boreal deciduous broadleaf and boreal evergreen needleleaf and mixed forests expanded (Figures 8b and c). Coastal tundra (moist wet tundra) covered north of the Brooks Range between 11 and 10 ka, where SP continued its expansion (Figure 8b). *Sphagnum*-black spruce forested peatland began forming in southwestern coast and eastern interior regions, with a rapid increase of total peatland area to about 13$\times 10^5$ km^2 (Figure 9). At 10-9 ka, boreal deciduous forest expanded to north of the Brooks Range, making forest the dominant biome in Alaska (Figure 2c). Prevailing forest ecosystems indicated a large expansion of peatland, with SBP covering the interior Alaska

(Figure 8c). During the mid-Holocene (9-5 ka), the terrestrial landscape generally resembled present-day ecosystems (Bigelow et al., 2003). Boreal evergreen needleleaf and mixed forest prevailed in southern and interior Alaska with tundra returned to north of the Brooks Range and western Alaska (Figures 2d and e). Although SP kept forming towards west, some areas dominated by SBP in interior Alaska ceased accumulating C (Figure 8d). At 5k-19th, almost all the peatlands have formed, with some interior regions exhibiting a C loss (Figure 8e). C accumulation increased again in the last century, averaging about 20 kg C m^{-2} kyr^{-1} (Figure 8f). We found that the distribution of SOC densities of both upland and peatland varied greatly depending on the vegetation distribution within each time slice, indicating that vegetation composition might be a major factor controlling regional C dynamics.

An average peat SOC “apparent” accumulation rate of 13 g C $m^{-2}yr^{-1}$ (2.3 Tg C yr^{-1} for the entire Alaska) was estimated from 15 ka to 2000 AD (Figure 10), lower than 18.6 g C $m^{-2}yr^{-1}$ as estimated from peat cores for northern peatlands (Yu et al., 2010), and slightly higher than the observed rate of 13.2 g C $m^{-2}yr^{-1}$ from four peatlands in Alaska (Jones and Yu, 2010). A simulated peak occurred during the HTM with the rate 29.1 g C $m^{-2}yr^{-1}$ (5.1 Tg C yr^{-1}), which was slightly higher than the observed 25 g C $m^{-2}yr^{-1}$ for northern peatlands and ~20 g C $m^{-2}yr^{-1}$ for Alaska (Yu et al., 2010). It was almost four times higher than the rate 6.9 g C $m^{-2}yr^{-1}$ (1.4 Tg C yr^{-1}) over the rest of the Holocene, which corresponded to the peat core-based observations of ~5 g C $m^{-2}yr^{-1}$. The mid- and late Holocene showed much slower C accumulation at a rate approximately five folds lower than during the HTM. This corresponded to the observation of a six-fold decrease in the rate of new peatland formation after 8.6 ka (Jones and Yu 2010). The C accumulation rates increased abruptly to 39.2 g C $m^{-2}yr^{-1}$during the last century, within the field-measured average apparent rate range of 20-50 g $\mathrm{C\ m^{-2}yr^{-1}}$ over the last 2000 years (Yu et al., 2010).

The SOC stock of northern peatlands has been estimated in many studies, ranging from 210 to 621 Pg (Oechel 1989; Gorham 1991; Armentano and Menges, 1986; Turunen et al., 2002; Yu et al., 2010; see Yu 2012 for a review). Assuming Alaskan peatlands were representative of northern peatlands and using the area of Alaskan peatlands (0.45×10^6 $\mathrm{km^2}$; Kivinen and Pakarinen, 1981) divided by the total area of northern peatlnads (~4×10^6 $\mathrm{km^2}$; Maltby and Immirzi 1993), we estimated a SOC stock of 23.6-69.9 Pg C for Alaskan peatlands. Our model estimated 27-48 Pg C (23.9 Pg C in SP and 13.5 Pg C in SBP) had been accumulated from 15 ka to 2000 AD (Figure 11), due to uncertain parameters (Table 4, see Wang et al. (2016) for model parameters). The uncertainty can also be resulted from peat basal age distributions and the estimation of total peatland area using modern inundation data as discussed above. By incorporating the observed basal age distribution to determine the expansion of peatland through time, we estimated that approximately 68% of Alaskan peatlands had formed by the end of the HTM, similar to the estimation from observed basal peat ages that 75% peatlands have formed by 8.6 ka (Jones and Yu 2010).

The northern circumpolar soils were estimated to cover approximately 18.78$\times 10^6$ $\mathrm{km^2}$ (Tarnocai et al., 2009). The non-peatland soil C stock was estimated to be in the range of 150-191 Pg C for boreal forests (Apps et al., 1993; Jobbagy and Jackson, 2000), and 60-144 Pg C for tundra in the 0-100 cm depth (Apps et al., 1993; Gilmanov and Oechel, 1995; Oechel et al., 1993). 1.24×10^6 $\mathrm{km^2}$ non-peatland area was estimated from the total land area of Alaska (1.69$\times 10^6$ $\mathrm{km^2}$). Therefore, Alaska non-peatland soil C stock contained 17-27 Pg C by using the ratio of Alaskan over northern non-peatland. In comparison, we modeled 9-15 Pg C (within 1-meter depth), depending on the prior ranges of model parameters from Tang and Zhuang (2008).

The simulated modern SOC distribution (Figure 12c) was largely consistent with the study of Hugelius et al. (2014) (see Figure 3 in the paper). The model captured the SOC density on northern and southwestern coasts of Alaska with most grids >40 kg $\mathrm{C\ m^{-2}}$ on average. Those regions also showed high SOC density (>75 kg $\mathrm{C\ m^{-2}}$), which was also exhibited in our result. East part and west coast had the lowest SOC densities, corresponding to the simulation result that most grids had SOC values between 20 and 40 kg $\mathrm{C\ m^{-2}}$. We estimated an average peat depth of 1.9$\pm$0.8 m considering the uncertainties within dry bulk densities. It was similar to the observed mean depth of 2.29 m for Alaskan peatlands (Gorham et al., 1991, 2012). Our estimates (Figure 12d) showed a relatively high correlation with the 64 observed peat samples, especially with higher depths (Figure 13) ($R^2 = 0.45$). The large intercept of the regression line (101 cm) suggested that the model might have not performed well in estimating the grids with low peat depths (<50 cm). The peat characteristics (e.g., bulk density) from location to location may differ largely, even if within the same small region. Thus, it is difficult to capture the observed variations of peat depths as we used the averaged bulk density of whole Alaska.

3.4 Effects of Climate on Ecosystem Carbon Accumulation

The simulated climate by ECBilt-CLIO model showed that among the six time periods, the coolest temperature appeared at 15-11 ka, followed by the mid- and late- Holocene (5 ka-1900 AD). Those two periods were also generally dry (Figure 3f). The former represented colder and drier climate before the onset of the Holocene and the HTM (Barber and Finney, 2000; Edwards et al., 2001). The latter represented post-HTM neoglacial cooling, which has caused permafrost aggradation across northern high latitudes (Oksanen et al., 2001; Zoltai, 1995).

The simulated NPP, vegetation C density and storage were highest during the HTM. Annual C accumulation rates also reached the highest (Figures 5-11). The variation of NPP has a similar pattern of the climate (see Figure 3 for climate variables), where higher NPP, along with higher vegetation C coincided with warmer temperatures and enhanced precipitation during the HTM, compared to other time periods. ECBilt-CLIO simulated a warmest summer and a prolonged growing season, leading to a stronger seasonality of temperature during the HTM (Kaufman et al., 2004, 2016), in line with the orbitally-induced maximum summer insolation (Berger and Loutre, 1991; Renssen et al., 2009). The coincidence between the highest vegetation C uptake and SOC accumulation rates and the warmest summer and the wetter-than-before conditions indicated a strong link between those climate variables and C dynamics in Alaska. Enhanced climate seasonality characterized by warmer summer, enhanced summer precipitation and possibly earlier snow melt during the HTM accelerated the photosynthesis and subsequently increased NPP (Tucker et al., 2001; Kimball et al., 2004; Linderholm, 2006). As shown in our sensitivity test, annual NPP was increased by 40 and 20 $\mathrm{g\ C\ m^{-2}\ yr^{-1}}$ under the warmer and wetter scenarios, respectively (Figures 14a, b). Meanwhile, warmer condition could positively affect the SOC decomposition (Nobrega et al., 2007). However, it could be offset to a certain extent via the hydrological effect, as higher precipitation could raise the water-table position, allowing less space for aerobic heterotrophic respiration. Our sensitivity test results indicated that warmer and wetter conditions could lead to an increase of decomposition up to 35 and 15 $\mathrm{g\ C\ m^{-2}\ yr^{-1}}$, respectively (Figures 14c, d). We did not find a decrease in total heterotrophic respiration throughout Alaska from the higher precipitation. It was presumably due to a much larger area of upland soils (1.3×10^6 km^2) than peatland soils (0.26×10^6 km^2), as higher precipitation would cause higher aerobic respiration in the unsaturated zone of upland soils, and consequently stimulated the SOC decomposition. The relatively low NPP and vegetation C density, along with the lower total soil C stocks were consistent with the unfavorable cool and dry climate conditions at 15-11 ka and during the mid- and late- Holocene. Statistical analysis indicated that temperature had the most significant effect on peat SOC accumulation rate, followed by the seasonality of NIRR (Wang et al., 2016). The seasonality of temperature, the interaction of temperature and precipitation, and precipitation alone also showed significance. The strong link between climate factors and C dynamics may explain the lower SOC accumulation during the neoglacier cooling period (Marcott et al., 2013; Vitt et al., 2000; Peteet et al., 1998; Yu et al. 2010). The rapid peat SOC accumulation during the 20th century under warming and wetter climate may suggest a continuous C sink in this century, as concluded in Spahni et al. (2013). However, the rising temperature in the future may have positive effects on heterotrophic respiration and simultaneously increase evapotranspiration and lower water table. This could increase aerobic decomposition and thus switch the Alaskan peatland from a C sink into a C source. Moreover, the increasing anthropogenic activities including land use will probably increase drought and subsequently enhance the risk of fire, releasing carbon to the atmosphere. The fate of Alaskan SOC stock and the biogeochemical cycling of the terrestrial ecosystems under future scenarios need further investigation.

3.5 Effects of Vegetation Distribution on Ecosystem Carbon Accumulation

Climate variables significantly affect C dynamics within each time slice. However, different vegetation distributions during various periods led to clear step changes, suggesting vegetation composition was likely to be another primary factor (Figures 6, 7, 8, and 11). As key parameters controlling C dynamics in the model (e.g., maximum rate of photosynthesis, litter fall C, maximum rate of monthly NPP) are ecosystem type specific, vegetation distribution changes may drastically affect regional plant productivity and C storage. Our sensitivity test indicated that by replacing all vegetation types with forests, there was a total increase of 36.9 Pg in upland plus peatland soils. There was also an increase of 48.8 Pg C under warmer and wetter conditions, suggesting that both climate and vegetation distribution may have played important roles in carbon accumulation.

The vegetation changes reconstructed from fossil pollen data during different time periods followed the general climate history during the last 15,000 years. For instance, the migration of dark boreal forests over snow-covered tundra during the HTM was probably induced by the warmer and wetter climate resulted from the insolation changes (He et al., 2014). The cooler and drier climate after the mid-Holocene limited the growth of boreal broadleaf conifers (Prentice et al., 1992), and therefore resulted in the replacement of broadleaf forest with needleleaf forest and tundra ecosystems. Since the parameters of our model for individual vegetation type were static, parameterizing the model using modern site-level observations might have introduced uncertainty to parameters, which may result in regional simulation uncertainties. Assuming each parameter as constant (e.g. the lowest water-table boundary, see Wang et al. (2016) for details) over time may also weaken the model's response to different climate scenarios. Furthermore, applying static vegetation maps at millennial scales and using modern elevation and pH data may simplify the complicated changes of landscape and terrestrial ecosystems, as vegetation can shift within hundreds of years (Ager and Brubake, 1985; see He et al. (2014) discussion section). Relatively coarse spatial resolution (0.5° ×0.5°) in P-TEM simulations may also introduce uncertainties. In addition, because we used the modern inundation map to delineate the peatland and upland within each grid cell, we might have overestimated the total peatland area since not all inundated areas are peatlands. Linking field-estimated basal ages of peat cores to the vegetation types during each period involves large uncertainties due to the limitation of the peat classification and insufficient peat samples. Thus, the estimated spatially explicit basal age data shall also introduce a large uncertainty to our regional quantification of carbon accumulation.

5. Conclusions

We used a biogeochemistry model for both peatland and non-peatland ecosystems to quantify the C stock and its changes over time in terrestrial ecosystems of Alaska during the last 15,000 years. The simulated peat SOC accumulation rates were compared with peat-core data from four peatlands on the Kenai Peninsula in southern Alaska. The model well estimated the peat SOC accumulation rates trajectory throughout the Holocene, indicating the model's suitability for simulating peat C dynamics. Our regional simulation showed that 36-63 Pg C had been accumulated in Alaskan land ecosystems since 15,000 years ago, including 27-48 Pg C in peatlands and 9-15 Pg C in non-peatlands (within 1 m depth). We also estimated that 2.5-3.7 Pg C was stored in contemporary Alaskan vegetation, with 0.3-0.6 Pg C in peatlands and 2.2-3.1 Pg C in non-peatlands. The estimated average rate of peat C accumulation was 2.3 Tg C yr^{-1} with a peak (5.1 Pg C yr^{-1}) in the Holocene Thermal Maximum (HTM), four folds higher than the rate of 1.4 Pg C yr^{-1} over the rest of the Holocene. The 20th century represented another high SOC accumulation period after the much lowered accumulation rate in the late Holocene. We estimated an average depth of 1.9 m of peat in Alaskan peatlands, similar to the observed mean depth. We found that the changes of vegetation distribution due to the climatic change were the key factors to the spatial variations of SOC accumulation in different time periods. The warming in the HTM characterized by the increased summer temperature and increased seasonality of solar radiation, along with the higher precipitation might have played an important role in causing the high C accumulation rates. Under warming climate conditions, Alaskan peatlands may continue acting as C sink in the future.

6. Acknowledgment. We acknowledge the funding support from a NSF project IIS-1027955 and a DOE project DE-SC0008092. We also acknowledge the SPRUCE project to allow us use its data. Data presented in this paper are publicly accessible: ECBilt-CLIO Paleosimulation (http://apdrc.soest.hawaii.edu/datadoc/sim2bl.php), CRU2.0 (http://www.cru.uea.ac.uk/data). Model parameter data and model evaluation process are in Wang et al. (2016). Other simulation data including model codes are available upon request from the corresponding author (qzhuang@purdue.edu).

7. References

~~Anderson, P. M., & Brubaker, L. B. (1993). Holocene vegetation and climate histories of Alaska. *Global climates since the last glacial maximum*, 385-400.~~

~~Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., ... & Vinson, T. S. (1993). Boreal forests and tundra. *Water, Air, and Soil Pollution*, *70*(1-4), 39-53.~~

~~Armentano, T. V., & Menges, E. S. (1986). Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *The Journal of Ecology*, 755-774.~~

~~Assessment, A. C. I. (2005). Forests, land management and agriculture.*Arctic Climate Impact Assessment*, 781-862.~~

~~Balshi, M. S., McGuire, A. D., Zhuang, Q., Melillo, J., Kicklighter, D. W., Kasischke, E., ... & Burnside, T. J. (2007). The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: A process-based analysis. *Journal of Geophysical Research: Biogeosciences*, *112*(G2).~~

~~Barber, V. A., & Finney, B. P. (2000). Late Quaternary paleoclimatic reconstructions for interior Alaska based on paleolake-level data and hydrologic models. *Journal of Paleolimnology*, *24*(1), 29-41.~~

~~Bartlein, P. J., Harrison, S. P., Brewer, S., Connor, S., Davis, B. A. S., Gajewski, K., ... & Prentice, I. C. (2011). Pollen-based continental climate reconstructions at 6 and 21 ka: a global synthesis. *Climate Dynamics*, *37*(3-4), 775-802.~~

~~Belyea, L. R. (2009). Nonlinear dynamics of peatlands and potential feedbacks on the climate system. *Carbon cycling in northern peatlands*, 5-18.~~

~~Berger, A., & Loutre, M. F. (1991). Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews*, *10*(4), 297-317.~~

~~Bigelow, N. H., Brubaker, L. B., Edwards, M. E., Harrison, S. P., Prentice, I. C., Anderson, P. M., ... & Kaplan, J. O. (2003). Climate change and Arctic ecosystems: 1. Vegetation changes north of 55 N between the last glacial maximum, mid-Holocene, and present. *Journal of Geophysical Research: Atmospheres*, *108*(D19).~~

~~Bridgham, S. D., Megonigal, J. P., Keller, J. K., Bliss, N. B., & Trettin, C. (2006). The carbon balance of North American wetlands. *Wetlands*, *26*(4), 889-916.~~

~~Carter, A. J., & Scholes, R. J. (2000). SoilData v2. 0: generating a global database of soil properties. *Environmentek CSIR, Pretoria, South Africa*.~~

~~Change, I. C. (2013). The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *New York: Cambridge University Press*, *1*, 535-1.~~

~~Change, I. C. (2014). Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press, Cambridge, UK and New York, NY*.~~

~~Chivers, M. R., Turetsky, M. R., Waddington, J. M., Harden, J. W., & McGuire, A. D. (2009). Effects of experimental water table and temperature manipulations on ecosystem CO2 fluxes in an Alaskan rich fen.*Ecosystems*, *12*(8), 1329-1342.~~

~~Churchill, A. (2011). The response of plant community structure and productivity to changes in hydrology in Alaskan boreal peatlands. *Master Thesis*, University of Alaska, Fairbanks, AK, USA. 119 pp.~~

~~Conrad, R. (1999). Contribution of hydrogen to methane production and control of hydrogen concentrations in methanogenic soils and sediments.*FEMS Microbiology Ecology*, *28*(3), 193-202.~~

~~Crockford, S. J., & Frederick, S. G. (2007). Sea ice expansion in the Bering Sea during the Neoglacial: Evidence from archaeozoology. *The Holocene*,*17*(6), 699-706.~~

~~Davidson, E. A., Trumbore, S. E., & Amundson, R. (2000). Biogeochemistry: soil warming and organic carbon content. *Nature*, *408*(6814), 789-790.~~

~~Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(7081), 165-173.~~

~~Edwards, M. E., Anderson, P. M., Brubaker, L. B., Ager, T. A., Andreev, A. A., Bigelow, N. H., ... & Jolly, D. (2000). Pollen-based biomes for Beringia 18,000, 6000 and 0 14C yr bp. *Journal of Biogeography*, *27*(3), 521-554.~~

~~Edwards, M. E., Mock, C. J., Finney, B. P., Barber, V. A., & Bartlein, P. J. (2001). Potential analogues for paleoclimatic variations in eastern interior Alaska during the past 14,000 yr: atmospheric-circulation controls of regional temperature and moisture responses. *Quaternary Science Reviews*, *20*(1), 189-202.~~

~~Edwards, M. E., Brubaker, L. B., Lozhkin, A. V., & Anderson, P. M. (2005). Structurally novel biomes: a response to past warming in Beringia. *Ecology*,*86*(7), 1696-1703.~~

~~Euskirchen, E. S., McGuire, A. D., & Chapin, F. S. (2007). Energy feedbacks of northern high-latitude ecosystems to the climate system due to reduced snow cover during 20th century warming. *Global Change Biology*,*13*(11), 2425-2438.~~

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

~~Frolking, S., Talbot, J., Jones, M. C., Treat, C. C., Kauffman, J. B., Tuittila, E. S., & Roulet, N. (2011). Peatlands in the Earth's 21st century climate system. *Environmental Reviews*, *19*(NA), 371-396.~~

~~Gilmanov, T. G., & Oechel, W. C. (1995). New estimates of organic matter reserves and net primary productivity of the North American tundra ecosystems. *Journal of Biogeography*, 723-741.~~

~~Gorham, E. V. I. L. L. E. (1990). Biotic impoverishment in northern peatlands. *The earth in transition: patterns and processes of biotic impoverishment. Cambridge University Press, Cambridge, UK*, 65-98.~~

~~Gorham, E. (1991). Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological applications*, *1*(2), 182-195.~~

~~Gorham, E., Lehman, C., Dyke, A., Clymo, D., & Janssens, J. (2012). Long-term carbon sequestration in North American peatlands. *Quaternary Science Reviews*, *58*, 77-82.~~

~~He, Y., Jones, M. C., Zhuang, Q., Bochicchio, C., Felzer, B. S., Mason, E., & Yu, Z. (2014). Evaluating CO 2 and CH 4 dynamics of Alaskan ecosystems during the Holocene Thermal Maximum. *Quaternary Science Reviews*, *86*, 63-77.~~

~~Hinzman, L. D., Viereck, L. A., Adams, P. C., Romanovsky, V. E., & Yoshikawa, K. (2006). Climate and permafrost dynamics of the Alaskan boreal forest. *Alaska's Changing Boreal Forest*, 39-61.~~

~~Hobbie, S. E. (2000). Interactions between litter lignin and nitrogenitter lignin and soil nitrogen availability during leaf litter decomposition in a Hawaiian montane forest. *Ecosystems*, *3*(5), 484-494.~~

~~Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E., Ping, C. L., ... & O'Donnell, J. A. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps.*Biogeosciences*, *11*(23), 6573-6593.~~

~~Huybers, P. (2006). Early Pleistocene glacial cycles and the integrated summer insolation forcing. *Science*, *313*(5786), 508-511.~~

~~Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological applications*, *10*(2), 423-436.~~

~~Jones, M. C., & Yu, Z. (2010). Rapid deglacial and early Holocene expansion of peatlands in Alaska. *Proceedings of the National Academy of Sciences*,*107*(16), 7347-7352.~~

~~Jones, P. D., & Moberg, A. (2003). Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. *Journal of Climate*, *16*(2), 206-223.~~

~~Kane, E. S., Turetsky, M. R., Harden, J. W., McGuire, A. D., & Waddington, J. M. (2010). Seasonal ice and hydrologic controls on dissolved organic carbon and nitrogen concentrations in a boreal-rich fen. *Journal of Geophysical Research: Biogeosciences*, *115*(G4).~~

~~Kaufman, D. S., Ager, T. A., Anderson, N. J., Anderson, P. M., Andrews, J. T., Bartlein, P. J., ... & Dyke, A. S. (2004). Holocene thermal maximum in the western Arctic (0–180 W). *Quaternary Science Reviews*, *23*(5), 529-560.~~

~~Kaufman, D.S., Axford, Y.L., Henerson, A., McKay, N.P., Oswald, W.W., Saenger, C., Anderson, R.S., Bailey, H.L., Clegg, B., Gajewski, K., Hu, F.S., Jones, M.C., Massa, C., Routson, C.C., Werner, A., Wooller, M.J., Yu, Z., 2016. Holocene climate changes in eastern Beringia (NW North America) e a systemic review of multi-proxy evidence. *Quaternary Science Reviews*, this volume. http://dx.doi.org/10.1016/ j.quascirev.2015.10.021.~~

~~Keller, J. K., & Bridgham, S. D. (2007). Pathways of anaerobic carbon cycling across an ombrotrophic–minerotrophic peatland gradient.~~

~~Keller, J. K., & Takagi, K. K. (2013). Solid-phase organic matter reduction regulates anaerobic decomposition in bog soil. *Ecosphere*, *4*(5), 1-12.~~

~~Kimball, J. S., McDonald, K. C., Running, S. W., & Frolking, S. E. (2004). Satellite radar remote sensing of seasonal growing seasons for boreal and subalpine evergreen forests. *Remote Sensing of Environment*, *90*(2), 243-258.~~

~~Kivinen, E., and P. Pakarinen. (1981). Geographical distribution of peat resources and major peatland complex types in the world. Annales Academiae Scientarum Fennicae, Series A, Number 132.~~

~~Kleinen, T., Brovkin, V., von Bloh, W., Archer, D., & Munhoven, G. (2010). Holocene carbon cycle dynamics. *Geophysical Research Letters*, *37*(2).~~

~~Kuhry, P., & Vitt, D. H. (1996). Fossil carbon/nitrogen ratios as a measure of peat decomposition. *Ecology*, *77*(1), 271-275.~~

~~Linderholm, H. W. (2006). Growing season changes in the last century.*Agricultural and Forest Meteorology*, *137*(1), 1-14.~~

~~Loisel, J., Gallego-Sala, A. V., & Yu, Z. (2012). Global-scale pattern of peatland Sphagnum growth driven by photosynthetically active radiation and growing season length. *Biogeosciences*, *9*(7), 2737-2746.~~

~~Loisel, J., Yu, Z., Beilman, D. W., Camill, P., Alm, J., Amesbury, M. J., ... & Belyea, L. R. (2014). A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *the Holocene*, 0959683614538073.~~

~~Maltby, E., & Immirzi, P. (1993). Carbon dynamics in peatlands and other wetland soils regional and global perspectives. *Chemosphere*, *27*(6), 999-1023.~~

~~Manabe, S., & Wetherald, R. T. (1980). On the distribution of climate change resulting from an increase in CO2 content of the atmosphere. *Journal of the Atmospheric Sciences*, *37*(1), 99-118.~~

~~Manabe, S., & Wetherald, R. T. (1986). Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. *Science*, *232*(4750), 626-628.~~

~~Marcott, S. A., Shakun, J. D., Clark, P. U., & Mix, A. C. (2013). A reconstruction of regional and global temperature for the past 11,300 years.*science*, *339*(6124), 1198-1201.~~

~~Matthews, E., & Fung, I. (1987). Methane emission from natural wetlands: Global distribution, area, and environmental characteristics of sources.*Global biogeochemical cycles*, *1*(1), 61-86.~~

~~McGuire, A. D., Melillo, J. M., Kicklighter, D. W., & Joyce, L. A. (1995). Equilibrium responses of soil carbon to climate change: empirical and process-based estimates. *Journal of Biogeography*, 785-796.~~

~~McGuire, A. D., & Hobbie, J. E. (1997). Global climate change and the equilibrium responses of carbon storage in arctic and subarctic regions. In*Modeling the Arctic system: A workshop report on the state of modeling in the Arctic System Science program* (pp. 53-54).~~

~~McGuire, A. D., Melillo, J. M., Randerson, J. T., Parton, W. J., Heimann, M., Meier, R. A., ... & Sauf, W. (2000). Modeling the effects of snowpack on heterotrophic respiration across northern temperate and high latitude regions: Comparison with measurements of atmospheric carbon dioxide in high latitudes. *Biogeochemistry*, *48*(1), 91-114.~~

~~McGuire, A. D., Anderson, L. G., Christensen, T. R., Dallimore, S., Guo, L., Hayes, D. J., ... & Roulet, N. (2009). Sensitivity of the carbon cycle in the Arctic to climate change. *Ecological Monographs*, *79*(4), 523-555.~~

~~Melillo, J. M., Kicklighter, D. W., McGuire, A. D., Peterjohn, W. T., & Newkirk, K. (1995, July). Global change and its effects on soil organic carbon stocks. In *Dahlem Conference Proceedings, John Wiley and Sons, New York, John Wiley & Sons, Ltd., Chichster* (pp. 175-189).~~

~~Mock, C. J., & Bartlein, P. J. (1995). Spatial variability of late-Quaternary paleoclimates in the western United States. *Quaternary Research*, *44*(3), 425-433.~~

~~Moore, T. R., Bubier, J. L., Frolking, S. E., Lafleur, P. M., & Roulet, N. T. (2002). Plant biomass and production and CO2 exchange in an ombrotrophic bog. *Journal of Ecology*, *90*(1), 25-36.~~

~~Nobrega, S., & Grogan, P. (2007). Deeper snow enhances winter respiration from both plant-associated and bulk soil carbon pools in birch hummock tundra. *Ecosystems*, *10*(3), 419-431.~~

~~Oechel, W. C. (1989). Nutrient and water flux in a small arctic watershed: an overview. *Holarctic Ecology*, 229-237.~~

~~Oechel, W. C., Hastings, S. J., Vourlrtis, G., Jenkins, M., Riechers, G., & Grulke, N. (1993). Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source. *Nature*, *361*(6412), 520-523.~~

~~Oksanen, P. O., Kuhry, P., & Alekseeva, R. N. (2001). Holocene development of the Rogovaya river peat plateau, European Russian Arctic.*The Holocene*, *11*(1), 25-40.~~

~~Peteet, D., Andreev, A., Bardeen, W., & Mistretta, F. (1998). Long-term Arctic peatland dynamics, vegetation and climate history of the Pur-Taz region, western Siberia. *Boreas*, *27*(2), 115-126.~~

~~Prentice, C., Guiot, J., Huntley, B., Jolly, D., & Cheddadi, R. (1996). Reconstructing biomes from palaeoecological data: a general method and its application to European pollen data at 0 and 6 ka. *Climate Dynamics*, *12*(3), 185-194.~~

~~Prentice, I. C. (2008). Terrestrial nitrogen cycle simulation with a dynamic global vegetation model. *Global Change Biology*, *14*(8), 1745-1764.~~

~~Raich, J. W., Rastetter, E. B., Melillo, J. M., Kicklighter, D. W., Steudler, P. A., Peterson, B. J., ... & Vorosmarty, C. J. (1991). Potential net primary productivity in South America: application of a global model. *Ecological Applications*, *1*(4), 399-429.~~

~~Renssen, H., Seppä, H., Heiri, O., Roche, D. M., Goosse, H., & Fichefet, T. (2009). The spatial and temporal complexity of the Holocene thermal maximum. *Nature Geoscience*, *2*(6), 411-414.~~

~~Roulet, N. T., Lafleur, P. M., Richard, P. J., Moore, T. R., Humphreys, E. R., & Bubier, J. I. L. L. (2007). Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, *13*(2), 397-411.~~

~~Schuur, E. A., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin, S. V., ... & Mazhitova, G. (2008). Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle.*BioScience*, *58*(8), 701-714.~~

~~Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., ... & Thonicke, K. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model.*Global Change Biology*, *9*(2), 161-185.~~

~~Spahni, R., Joos, F., Stocker, B. D., Steinacher, M., & Yu, Z. C. (2013). Transient simulations of the carbon and nitrogen dynamics in northern peatlands: from the Last Glacial Maximum to the 21st century. *Climate of the Past*, *9*(3), 1287-1308.~~

~~Stafford, J. M., Wendler, G., & Curtis, J. (2000). Temperature and precipitation of Alaska: 50 year trend analysis. *Theoretical and Applied Climatology*, *67*(1-2), 33-44.~~

~~Stieglitz, M., Déry, S. J., Romanovsky, V. E., & Osterkamp, T. E. (2003). The role of snow cover in the warming of arctic permafrost. *Geophysical Research Letters*, *30*(13).~~

~~Stocker, B. D., Strassmann, K., & Joos, F. (2011). Sensitivity of Holocene atmospheric CO 2 and the modern carbon budget to early human land use: analyses with a process-based model. *Biogeosciences*, *8*(1), 69-88.~~

~~Stocker, B. D., Spahni, R., & Joos, F. (2014). DYPTOP: a cost-efficient TOPMODEL implementation to simulate sub-grid spatio-temporal dynamics of global wetlands and peatlands. *Geoscientific Model Development*, *7*(6), 3089-3110.~~

~~Tang, J., & Zhuang, Q. (2008). Equifinality in parameterization of process-based biogeochemistry models: A significant uncertainty source to the estimation of regional carbon dynamics. *Journal of Geophysical Research: Biogeosciences*, *113*(G4).~~

~~Tang, J., & Zhuang, Q. (2009). A global sensitivity analysis and Bayesian inference framework for improving the parameter estimation and prediction of a process-based Terrestrial Ecosystem Model. *Journal of Geophysical Research: Atmospheres*, *114*(D15).~~

~~Tang, J., Zhuang, Q., Shannon, R. D., & White, J. R. (2010). Quantifying wetland methane emissions with process-based models of different complexities. *Biogeosciences*, *7*(11), 3817-3837.~~

~~Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., & Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region. *Global biogeochemical cycles*, *23*(2).~~

~~Timmermann, A., Timm, O., Stott, L., & Menviel, L. (2009). The roles of CO2 and orbital forcing in driving southern hemispheric temperature variations during the last 21 000 Yr*. *Journal of Climate*, *22*(7), 1626-1640.~~

~~Tucker, C. J., Slayback, D. A., Pinzon, J. E., Los, S. O., Myneni, R. B., & Taylor, M. G. (2001). Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. *International journal of biometeorology*, *45*(4), 184-190.~~

~~Turetsky, M. R., Treat, C. C., Waldrop, M. P., Waddington, J. M., Harden, J. W., & McGuire, A. D. (2008). Short-term response of methane fluxes and methanogen activity to water table and soil warming manipulations in an Alaskan peatland. *Journal of Geophysical Research: Biogeosciences*,*113*(G3).~~

~~Turunen, J., Tomppo, E., Tolonen, K., & Reinikainen, A. (2002). Estimating carbon accumulation rates of undrained mires in Finland–application to boreal and subarctic regions. *The Holocene*, *12*(1), 69-80.~~

~~Vitt, D. H., Halsey, L. A., Bauer, I. E., & Campbell, C. (2000). Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. *Canadian Journal of Earth Sciences*, *37*(5), 683-693.~~

~~Wang, S., Zhuang, Q., Yu, Z., Bridgham, S., & Keller, J. (2016). Quantifying peat carbon accumulation in Alaska using a process-based biogeochemistry model. *Journal of Geophysical Research: Biogeosciences* (Under revision).~~

~~Whitlock, C., & Bartlein, P. J. (1993). Spatial variations of Holocene climatic change in the Yellowstone region. *Quaternary Research*, *39*(2), 231-238.~~

~~Williams, J. W., Webb, T., Richard, P. H., & Newby, P. (2000). Late Quaternary biomes of Canada and the eastern United States. *Journal of Biogeography*, *27*(3), 585-607.~~

~~Yu, Z., Beilman, D. W., & Jones, M. C. (2009). Sensitivity of northern peatland carbon dynamics to Holocene climate change. *Carbon cycling in northern peatlands*, 55-69.~~

~~Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., & Hunt, S. J. (2010). Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, *37*(13).~~

~~Yu, Z. C. (2012). Northern peatland carbon stocks and dynamics: a review.*Biogeosciences*, *9*(10), 4071-4085.~~

~~Zhuang, Q., Romanovsky, V. E., & McGuire, A. D. (2001). Incorporation of a permafrost model into a large-scale ecosystem model: Evaluation of temporal and spatial scaling issues in~~

~~simulating soil thermal dynamics.*Journal of Geophysical Research: Atmospheres, 106*(D24), 33649-33670.~~

~~Zhuang, Q., McGuire, A. D., O'neill, K. P., Harden, J. W., Romanovsky, V. E., & Yarie, J. (2002). Modeling soil thermal and carbon dynamics of a fire chronosequence in interior Alaska. *Journal of Geophysical Research: Atmospheres, 107*(D1).~~

~~Zhuang, Q., McGuire, A. D., Melillo, J. M., Clein, J. S., Dargaville, R. J., Kicklighter, D. W., ... & Hobbie, J. E. (2003). Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th century: a modeling analysis of the influences of soil thermal dynamics. *Tellus B, 55*(3), 751-776.~~

~~Zhuang, Q., Melillo, J. M., Kicklighter, D. W., Prinn, R. G., McGuire, A. D., Steudler, P. A., ... & Hu, S. (2004). Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model. *Global Biogeochemical Cycles, 18*(3).~~

~~Zhuang, Q., Zhu, X., He, Y., Prigent, C., Melillo, J. M., McGuire, A. D., ... & Kicklighter, D. W. (2015). Influence of changes in wetland inundation extent on net fluxes of carbon dioxide and methane in northern high latitudes from 1993 to 2004. *Environmental Research Letters, 10*(9), 095009.~~

~~Zimov, S. A., Schuur, E. A., & Chapin III, F. S. (2006). Permafrost and the global carbon budget. *Science(Washington), 312*(5780), 1612-1613.~~

~~Zoltai, S. C. (1995). Permafrost distribution in peatlands of west-central Canada during the Holocene warm period 6000 years BP. *Géographie physique et Quaternaire, 49*(1), 45-54.~~

Ager, T. A., & Brubaker, L.: Quaternary palynology and vegetational history of Alaska. Pollen Records of Late Quaternary North American Sediments, 353-384, 1985.

Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., ... & Vinson, T. S.: Boreal forests and tundra. Water, Air, and Soil Pollution, 70(1-4), 39-53, 1993.

Armentano, T. V., & Menges, E. S.: Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. The Journal of Ecology, 755-774, 1986.

Assessment, A. C. I.: Forests, land management and agriculture.Arctic Climate Impact Assessment, 781-862, 2005.

Balshi, M. S., McGuire, A. D., Zhuang, Q., Melillo, J., Kicklighter, D. W., Kasischke, E., ... & Burnside, T. J.: The role of historical fire disturbance in the carbon dynamics of the pan-boreal region: A process-based analysis. Journal of Geophysical Research: Biogeosciences, 112(G2), 2007.

Barber, V. A., & Finney, B. P.: Late Quaternary paleoclimatic reconstructions for interior Alaska based on paleolake-level data and hydrologic models. Journal of Paleolimnology, 24(1), 29-41, 2000.

Belyea, L. R.: Nonlinear dynamics of peatlands and potential feedbacks on the climate system. Carbon cycling in northern peatlands, 5-18, 2009.

Berger, A., & Loutre, M. F.: Insolation values for the climate of the last 10 million years. Quaternary Science Reviews, 10(4), 297-317, 1991.

Bigelow, N. H., Brubaker, L. B., Edwards, M. E., Harrison, S. P., Prentice, I. C., Anderson, P. M., ... & Kaplan, J. O.: Climate change and Arctic ecosystems: 1. Vegetation changes north of 55 N between the last glacial maximum, mid-Holocene, and present. Journal of Geophysical Research: Atmospheres, 108(D19), 2003.

Bridgham, S. D., Megonigal, J. P., Keller, J. K., Bliss, N. B., & Trettin, C.: The carbon balance of North American wetlands. Wetlands, 26(4), 889-916, 2006.

Carter, A. J., & Scholes, R. J.: SoilData v2. 0: generating a global database of soil properties. Environmentek CSIR, Pretoria, South Africa, 2000.

Change, I. C.: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, 2014.

Change, I. C.: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press, 1, 535-1, 2013.

Chivers, M. R., Turetsky, M. R., Waddington, J. M., Harden, J. W., & McGuire, A. D.: Effects of experimental water table and temperature manipulations on ecosystem CO2 fluxes in an Alaskan rich fen.Ecosystems, 12(8), 1329-1342, 2009.

Churchill, A.: The response of plant community structure and productivity to changes in hydrology in Alaskan boreal peatlands. Master Thesis, University of Alaska, Fairbanks, AK, USA. 119 pp, 2011.

Conrad, R.: Contribution of hydrogen to methane production and control of hydrogen concentrations in methanogenic soils and sediments.FEMS Microbiology Ecology, 28(3), 193-202, 1999.

Davidson, E. A., & Janssens, I. A.: Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440(7081), 165-173, 2006.

Davidson, E. A., Trumbore, S. E., & Amundson, R.: Biogeochemistry: soil warming and organic carbon content. Nature, 408(6814), 789-790, 2000.

Edwards, M. E., Mock, C. J., Finney, B. P., Barber, V. A., & Bartlein, P. J.: Potential analogues for paleoclimatic variations in eastern interior Alaska during the past 14,000 yr: atmospheric-circulation controls of regional temperature and moisture responses. Quaternary Science Reviews, 20(1), 189-202, 2001.

Euskirchen, E. S., McGuire, A. D., & Chapin, F. S.: Energy feedbacks of northern high-latitude ecosystems to the climate system due to reduced snow cover during 20th century warming. Global Change Biology,13(11), 2425-2438, 2007.

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

Frolking, S., Talbot, J., Jones, M. C., Treat, C. C., Kauffman, J. B., Tuittila, E. S., & Roulet, N.: Peatlands in the Earth's 21st century climate system. Environmental Reviews, 19(NA), 371-396, 2011.

Gilmanov, T. G., & Oechel, W. C.: New estimates of organic matter reserves and net primary productivity of the North American tundra ecosystems. Journal of Biogeography, 723-741, 1995.

Gorham, E. V. I. L. L. E.: Biotic impoverishment in northern peatlands. The earth in transition: patterns and processes of biotic impoverishment. Cambridge University Press, Cambridge, UK, 65-98, 1990.

Gorham, E., Lehman, C., Dyke, A., Clymo, D., & Janssens, J.: Long-term carbon sequestration in North American peatlands. Quaternary Science Reviews, 58, 77-82, 2012.

Gorham, E.: Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecological applications, 1(2), 182-195, 1991.

He, Y., Jones, M. C., Zhuang, Q., Bochicchio, C., Felzer, B. S., Mason, E., & Yu, Z.: Evaluating CO 2 and CH 4 dynamics of Alaskan ecosystems during the Holocene Thermal Maximum. Quaternary Science Reviews, 86, 63-77, 2014.

Hinzman, L. D., Viereck, L. A., Adams, P. C., Romanovsky, V. E., & Yoshikawa, K.: Climate and permafrost dynamics of the Alaskan boreal forest. Alaska's Changing Boreal Forest, 39-61, 2006.

Hobbie, S. E.: Interactions between litter lignin and nitrogenitter lignin and soil nitrogen availability during leaf litter decomposition in a Hawaiian montane forest. Ecosystems, 3(5), 484-494, 2000.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E., Ping, C. L., ... & O'Donnell, J. A.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps.Biogeosciences, 11(23), 6573-6593, 2014.

Jobbágy, E. G., & Jackson, R. B.: The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological applications, 10(2), 423-436, 2000.

Jones, M. C., & Yu, Z.: Rapid deglacial and early Holocene expansion of peatlands in Alaska. Proceedings of the National Academy of Sciences,107(16), 7347-7352, 2010.

Jones, P. D., & Moberg, A.: Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. Journal of Climate, 16(2), 206-223, 2003.

Kane, E. S., Turetsky, M. R., Harden, J. W., McGuire, A. D., & Waddington, J. M.: Seasonal ice and hydrologic controls on dissolved organic carbon and nitrogen concentrations in a boreal-rich fen. Journal of Geophysical Research: Biogeosciences, 115(G4), 2010.

Kaufman, D. S., Ager, T. A., Anderson, N. J., Anderson, P. M., Andrews, J. T., Bartlein, P. J., ... & Dyke, A. S.: Holocene thermal maximum in the western Arctic (0–180 W). Quaternary Science Reviews, 23(5), 529-560, 2004.

Kaufman, D.S., Axford, Y.L., Henerson, A., McKay, N.P., Oswald, W.W., Saenger, C., Anderson, R.S., Bailey, H.L., Clegg, B., Gajewski, K., Hu, F.S., Jones, M.C., Massa, C., Routson, C.C., Werner, A., Wooller, M.J., Yu, Z.: Holocene climate changes in eastern Beringia (NW North America) e a systemic review of multi-proxy evidence. Quaternary Science Reviews, this volume. http://dx.doi.org/10.1016/ j.quascirev.2015.10.021, 2016.

Keller, J. K., & Bridgham, S. D.: Pathways of anaerobic carbon cycling across an ombrotrophic–minerotrophic peatland gradient, 2007.

Keller, J. K., & Takagi, K. K.: Solid-phase organic matter reduction regulates anaerobic decomposition in bog soil. Ecosphere, 4(5), 1-12, 2013.

Kimball, J. S., McDonald, K. C., Running, S. W., & Frolking, S. E.: Satellite radar remote sensing of seasonal growing seasons for boreal and subalpine evergreen forests. Remote Sensing of Environment, 90(2), 243-258, 2004.

Kivinen, E., and P. Pakarinen.: Geographical distribution of peat resources and major peatland complex types in the world. Annales Academiae Scientarum Fennicae, Series A, Number 132, 1981.

Kleinen, T., Brovkin, V., & Schuldt, R. J.: A dynamic model of wetland extent and peat accumulation: results for the Holocene.Biogeosciences, 9(1), 235-248, 2012.

Kuhry, P., & Vitt, D. H.: Fossil carbon/nitrogen ratios as a measure of peat decomposition. Ecology, 77(1), 271-275, 1996.

Linderholm, H. W.: Growing season changes in the last century.Agricultural and Forest Meteorology, 137(1), 1-14, 2006.

Loisel, J., Gallego-Sala, A. V., & Yu, Z.: Global-scale pattern of peatland Sphagnum growth driven by photosynthetically active radiation and growing season length. Biogeosciences, 9(7), 2737-2746, 2012.

Loisel, J., Yu, Z., Beilman, D. W., Camill, P., Alm, J., Amesbury, M. J., ... & Belyea, L. R.: A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. the Holocene, 0959683614538073, 2014.

Maltby, E., & Immirzi, P.: Carbon dynamics in peatlands and other wetland soils regional and global perspectives. Chemosphere, 27(6), 999-1023, 1993.

Manabe, S., & Wetherald, R. T.: On the distribution of climate change resulting from an increase in CO2 content of the atmosphere. Journal of the Atmospheric Sciences, 37(1), 99-118, 1980.

Manabe, S., & Wetherald, R. T.: Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. Science, 232(4750), 626-628, 1986.

Marcott, S. A., Shakun, J. D., Clark, P. U., & Mix, A. C.: A reconstruction of regional and global temperature for the past 11,300 years.science, 339(6124), 1198-1201, 2013.

Matthews, E., & Fung, I.: Methane emission from natural wetlands: Global distribution, area, and environmental characteristics of sources.Global biogeochemical cycles, 1(1), 61-86, 1987.

McGuire, A. D., & Hobbie, J. E.: Global climate change and the equilibrium responses of carbon storage in arctic and subarctic regions. InModeling the Arctic system: A workshop report on the state of modeling in the Arctic System Science program, pp. 53-54, 1997.

McGuire, A. D., Anderson, L. G., Christensen, T. R., Dallimore, S., Guo, L., Hayes, D. J., ... & Roulet, N.: Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs, 79(4), 523-555, 2009.

McGuire, A. D., Melillo, J. M., Kicklighter, D. W., & Joyce, L. A.: Equilibrium responses of soil carbon to climate change: empirical and process-based estimates. Journal of Biogeography, 785-796, 1995.

Melillo, J. M., Kicklighter, D. W., McGuire, A. D., Peterjohn, W. T., & Newkirk, K.: Global change and its effects on soil organic carbon stocks. In Dahlem Conference Proceedings, John Wiley and Sons, New York, John Wiley & Sons, Ltd., Chichster, pp. 175-189, 1995.

Mitchell, T. D., Carter, T. R., Jones, P. D., Hulme, M., & New, M.: A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100).Tyndall centre for climate change research working paper, 55(0), 25, 2004.

Moore, T. R., Bubier, J. L., Frolking, S. E., Lafleur, P. M., & Roulet, N. T.: Plant biomass and production and CO2 exchange in an ombrotrophic bog. Journal of Ecology, 90(1), 25-36, 2002.

Nobrega, S., & Grogan, P.: Deeper snow enhances winter respiration from both plant-associated and bulk soil carbon pools in birch hummock tundra. Ecosystems, 10(3), 419-431, 2007.

Oechel, W. C., Hastings, S. J., Vourlrtis, G., Jenkins, M., Riechers, G., & Grulke, N.: Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source. Nature, 361(6412), 520-523, 1993.

Oechel, W. C.: Nutrient and water flux in a small arctic watershed: an overview. Holarctic Ecology, 229-237, 1989.

Oksanen, P. O., Kuhry, P., & Alekseeva, R. N.: Holocene development of the Rogovaya river peat plateau, European Russian Arctic.The Holocene, 11(1), 25-40, 2001.

Peteet, D., Andreev, A., Bardeen, W., & Mistretta, F.: Long-term Arctic peatland dynamics, vegetation and climate history of the Pur-Taz region, western Siberia. Boreas, 27(2), 115-126, 1998.

Prentice, I. C., Cramer, W., Harrison, S. P., Leemans, R., Monserud, R. A., & Solomon, A. M.: Special paper: a global biome model based on plant physiology and dominance, soil properties and climate. Journal of biogeography, 117-134, 1992.

Raich, J. W., Rastetter, E. B., Melillo, J. M., Kicklighter, D. W., Steudler, P. A., Peterson, B. J., ... & Vorosmarty, C. J.: Potential net primary productivity in South America: application of a global model. Ecological Applications, 1(4), 399-429, 1991.

Renssen, H., Seppä, H., Heiri, O., Roche, D. M., Goosse, H., & Fichefet, T.: The spatial and temporal complexity of the Holocene thermal maximum. Nature Geoscience, 2(6), 411-414, 2009.

Roulet, N. T., Lafleur, P. M., Richard, P. J., Moore, T. R., Humphreys, E. R., & Bubier, J. I. L. L.: Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. Global Change Biology, 13(2), 397-411, 2007.

Saarinen, T.: Biomass and production of two vascular plants in a boreal mesotrophic fen. Canadian Journal of Botany, 74(6), 934-938, 1996.

Schuur, E. A., Bockheim, J., Canadell, J. G., Euskirchen, E., Field, C. B., Goryachkin, S. V., ... & Mazhitova, G.: Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle.BioScience, 58(8), 701-714, 2008.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., ... & Thonicke, K.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model.Global Change Biology, 9(2), 161-185, 2003.

Spahni, R., Joos, F., Stocker, B. D., Steinacher, M., & Yu, Z. C.: Transient simulations of the carbon and nitrogen dynamics in northern peatlands: from the Last Glacial Maximum to the 21st century. Climate of the Past, 9(3), 1287-1308, 2013.

Stocker, B. D., Spahni, R., & Joos, F.: DYPTOP: a cost-efficient TOPMODEL implementation to simulate sub-grid spatio-temporal dynamics of global wetlands and peatlands. Geoscientific Model Development, 7(6), 3089-3110, 2014.

Stocker, B. D., Strassmann, K., & Joos, F.: Sensitivity of Holocene atmospheric CO 2 and the modern carbon budget to early human land use: analyses with a process-based model. Biogeosciences, 8(1), 69-88, 2011.

Tang, J., & Zhuang, Q.: A global sensitivity analysis and Bayesian inference framework for improving the parameter estimation and prediction of a process-based Terrestrial Ecosystem Model. Journal of Geophysical Research: Atmospheres, 114(D15), 2009.

Tang, J., & Zhuang, Q.: Equifinality in parameterization of process-based biogeochemistry models: A significant uncertainty source to the estimation of regional carbon dynamics. Journal of Geophysical Research: Biogeosciences, 113(G4), 2008.

Tang, J., Zhuang, Q., Shannon, R. D., & White, J. R.: Quantifying wetland methane emissions with process-based models of different complexities. Biogeosciences, 7(11), 3817-3837, 2010.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., & Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region. Global biogeochemical cycles, 23(2), 2009.

Timm, O., & Timmermann, A.: Simulation of the Last 21 000 Years Using Accelerated Transient Boundary Conditions*. Journal of Climate,20(17), 4377-4401, 2007.

Tucker, C. J., Slayback, D. A., Pinzon, J. E., Los, S. O., Myneni, R. B., & Taylor, M. G.: Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. International journal of biometeorology, 45(4), 184-190, 2001.

Turetsky, M. R., Treat, C. C., Waldrop, M. P., Waddington, J. M., Harden, J. W., & McGuire, A. D.: Short-term response of methane fluxes and methanogen activity to water table and soil warming manipulations in an Alaskan peatland. Journal of Geophysical Research: Biogeosciences,113(G3), 2008.

Turunen, J., Tomppo, E., Tolonen, K., & Reinikainen, A.: Estimating carbon accumulation rates of undrained mires in Finland–application to boreal and subarctic regions. The Holocene, 12(1), 69-80, 2002.

Vitt, D. H., Halsey, L. A., Bauer, I. E., & Campbell, C.: Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of Earth Sciences, 37(5), 683-693, 2000.

Wang, S., Zhuang, Q., Yu, Z., Bridgham, S., & Keller, J. K.: Quantifying peat carbon accumulation in Alaska using a process-based biogeochemistry model, Journal of Geophysical Research: Biogeosciences., 121, doi: 10.1002/2016JG003452, 2016.

XU-RI and PRENTICE, I. C.: Terrestrial nitrogen cycle simulation with a dynamic global vegetation model. Global Change Biology, 14: 1745–1764. doi:10.1111/j.1365-2486.2008.01625.x, 2008.

Yu, Z. C.: Northern peatland carbon stocks and dynamics: a review. Biogeosciences, 9(10), 4071-4085, 2012.

Yu, Z., Beilman, D. W., & Jones, M. C.: Sensitivity of northern peatland carbon dynamics to Holocene climate change. Carbon cycling in northern peatlands, 55-69, 2009.

Yu, Z., Loisel, J., Brosseau, D. P., Beilman, D. W., & Hunt, S. J.: Global peatland dynamics since the Last Glacial Maximum. Geophysical Research Letters, 37(13), 2010.

Zhuang, Q., McGuire, A. D., Melillo, J. M., Clein, J. S., Dargaville, R. J., Kicklighter, D. W., ... & Hobbie, J. E.: Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th century: a modeling analysis of the influences of soil thermal dynamics. Tellus B, 55(3), 751-776, 2003.

Zhuang, Q., McGuire, A. D., O'neill, K. P., Harden, J. W., Romanovsky, V. E., & Yarie, J.: Modeling soil thermal and carbon dynamics of a fire chronosequence in interior Alaska. Journal of Geophysical Research: Atmospheres, 107(D1), 2002.

Zhuang, Q., Melillo, J. M., Kicklighter, D. W., Prinn, R. G., McGuire, A. D., Steudler, P. A., ... & Hu, S.: Methane fluxes between terrestrial ecosystems and the atmosphere at northern high latitudes during the past century: A retrospective analysis with a process-based biogeochemistry model. Global Biogeochemical Cycles, 18(3), 2004.

Zhuang, Q., Melillo, J. M., McGuire, A. D., Kicklighter, D. W., Prinn, R. G., Steudler, P. A., ... & Hu, S.: Net emissions of CH4 and CO2 in Alaska: Implications for the region's greenhouse gas budget. Ecological Applications, 17(1), 203-212, 2007.

Zhuang, Q., Romanovsky, V. E., & McGuire, A. D.: Incorporation of a permafrost model into a large-scale ecosystem model: Evaluation of temporal and spatial scaling issues in simulating soil thermal dynamics.Journal of Geophysical Research: Atmospheres, 106(D24), 33649-33670, 2001.

Zhuang, Q., Zhu, X., He, Y., Prigent, C., Melillo, J. M., McGuire, A. D., ... & Kicklighter, D. W.: Influence of changes in wetland inundation extent on net fluxes of carbon dioxide and methane in northern high latitudes from 1993 to 2004. Environmental Research Letters, 10(9), 095009, 2015.

Zimov, S. A., Schuur, E. A., & Chapin III, F. S.: Permafrost and the global carbon budget. Science(Washington), 312(5780), 1612-1613, 2006.

Zoltai, S. C.: Permafrost distribution in peatlands of west-central Canada during the Holocene warm period 6000 years BP. Géographie physique et Quaternaire, 49(1), 45-54, 1995.

~~Table 1. Assignment of biomized fossil pollen data to the vegetation types in TEM (He et al., 2014).~~

~~TEM upland vegetation~~	~~TEM peatland vegetation~~	~~BIOMISE code~~
~~Alpine tundra~~		~~CUSH DRYT PROS~~
~~Moist tundra~~	~~*Sphagnum* spp. open fen~~	~~DWAR SHRU~~
~~Boreal evergreen needleleaf and mixed forest~~	~~*Sphagnum* black spruce bog~~	~~TAIG COCO CLMX COMX~~
~~Boreal deciduous broadleaf forest~~		~~CLDE~~

~~Table 2. Relations between peatland basal age and vegetation distribution~~

~~Peatland basal age~~	~~Vegetation types~~	~~Location~~
~~15-11 ka~~	~~alpine tundra~~	~~south, northwestern, and southeastern coast~~
~~11-10 ka~~	~~moist tundra~~ ~~boreal evergreen needleleaf forest~~ ~~boreal deciduous broadleaf forest~~	~~south, north, and southeastern coast~~ ~~east-central part~~
~~10-9 ka~~	~~moist tundra~~ ~~boreal evergreen needleleaf forest~~ ~~boreal deciduous broadleaf forest~~	~~south and north coast~~ ~~central part~~
~~9-5 ka~~	~~moist tundra~~ ~~boreal evergreen needleleaf forest~~	~~central part~~
~~5 ka-1900 AD~~	~~moist tundra~~ ~~boreal evergreen needleleaf forest~~	~~west coast~~

~~Table 3. Description of sites and variables used for parameterizing the core carbon and nitrogen module (CNDM).~~

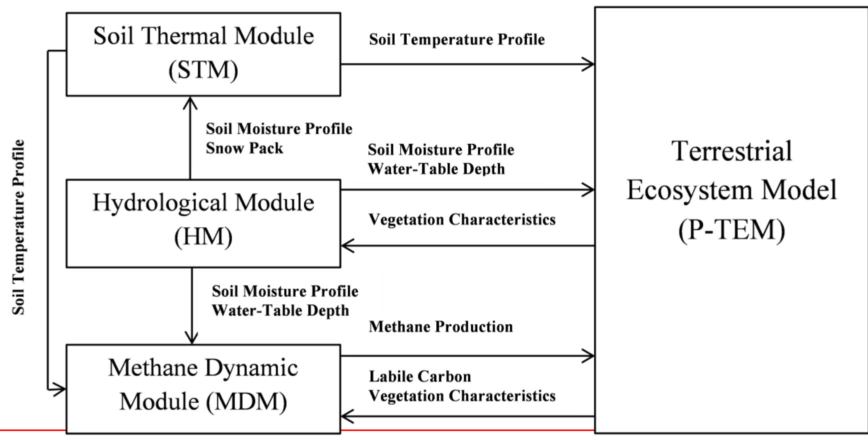
~~Site[a]~~	~~Vegetation~~	~~Observed variables for CNDM parameterization~~	~~References~~
~~APEXCON~~	~~Moderate rich open fen with sedges (*Carex* sp.), spiked rushes (*Eleocharis* sp.), *Sphagnum* spp., and brown mosses (e.g., *Drepanocladus aduncus*)~~	~~Mean annual aboveground NPP in 2009; Mean annual belowground NPP in 2009; Aboveground biomass in 2009~~	~~Chivers et al. (2009) Turetsky et al. (2008) Kane et al. (2010) Churchill et al. (2011)~~
~~APEXPER~~	~~Peat plateau bog with black spruce (*Picea mariana*), *Sphagnum* spp., and feather mosses~~		

~~[a]The Alaskan Peatland Experiment (APEX) site is adjacent to the Bonanza Creek Experimental Forest (BCEF) site, approximately 35 km southwest of Fairbanks, AK. The area is classified as continental boreal climate with a mean annual temperature of -2.9°C and annual precipitation of 269 mm, of which 30% is snow (Hinzman et al., 2006).~~

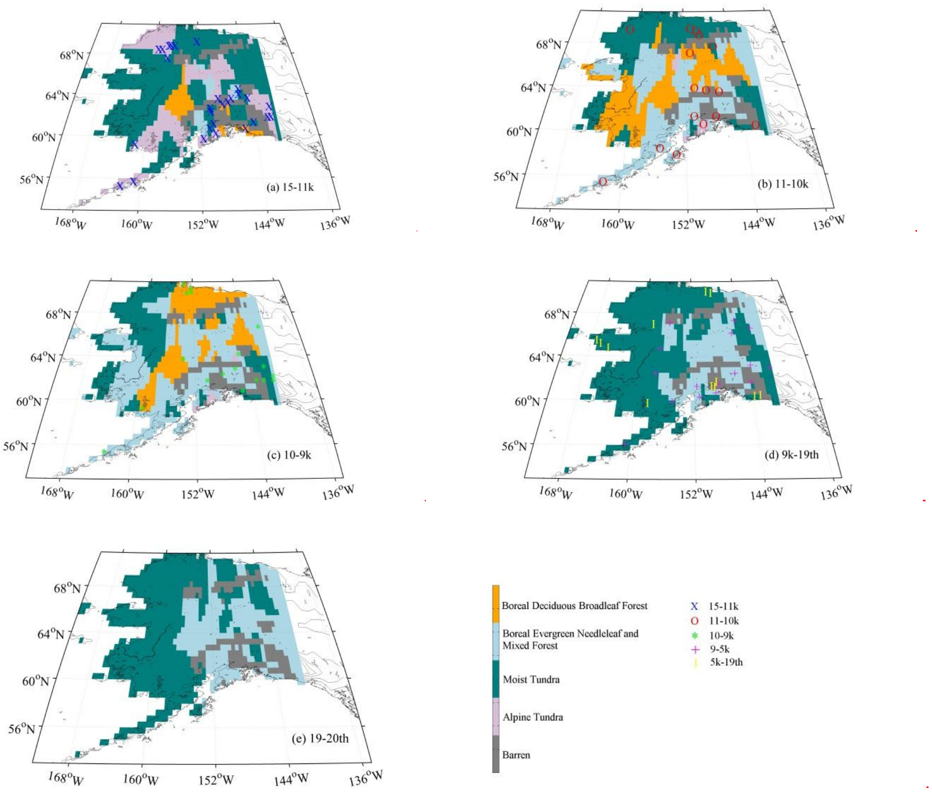
~~Table 4. Carbon pools and fluxes used for calibration of CMDM~~

~~Annual Carbon Fluxes or Pools[a]~~	~~*Sphagnum* Open Fen~~		~~*Sphagnum* Black Spruce Bog~~		~~References~~
	~~Observation~~	~~Simulation~~	~~Observation~~	~~Simulation~~	
~~NPP~~	~~445±260~~	~~410~~	~~433±107~~	~~390~~	~~Turetsky et al. (2008), Churchill (2011) Moore et al. (2002) Zhuang et al. (2002) Tarnocai et al. (2009) Kuhry and Vitt (1996)~~
~~Aboveground Vegetation Carbon~~	~~149-287~~		~~423~~		
~~Belowground Vegetation Carbon~~	~~564~~		~~658-1128~~		
~~Total Vegetation Carbon Density~~	~~713-851~~	~~800~~	~~732-1551~~	~~1300~~	
~~Litter Fall Carbon Flux~~	~~300~~	~~333~~	~~300~~	~~290~~	
~~Methane Emission Flux~~	~~19.5~~	~~19.2~~	~~9.7~~	~~12.8~~	

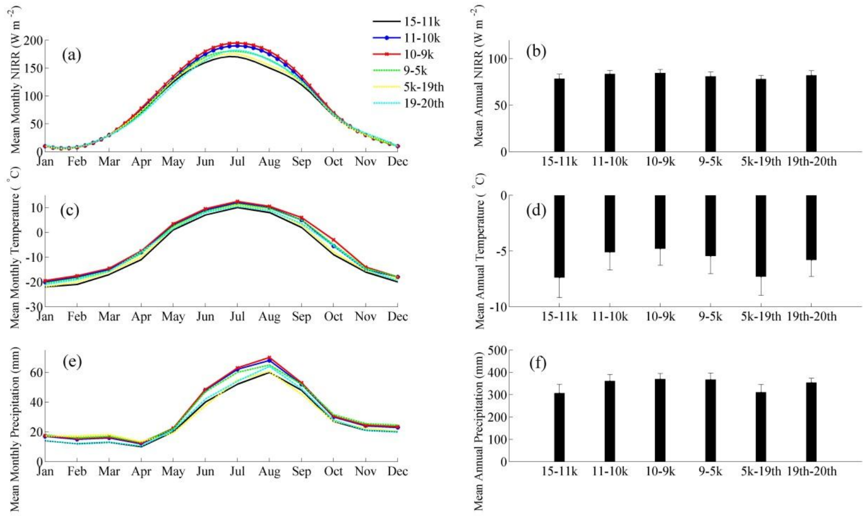
~~[a]Units for annual net primary production (NPP) and litter fall carbon are~~ $\cancel{g\ C\ m^{-2}\ yr^{-1}}$~~. Units for vegetation carbon density are~~ $\cancel{g\ C\ m^{-2}}$~~. Units for Methane emissions are~~ $\cancel{g\ C - CH_4\ m^{-2}\ yr^{-1}}$~~. The simulated total annual methane fluxes were compared with the observations at APEXCON in 2005 and SPRUCE in 2012. A ratio of 0.47 was used to convert vegetation biomass to carbon (Raich 1991).~~



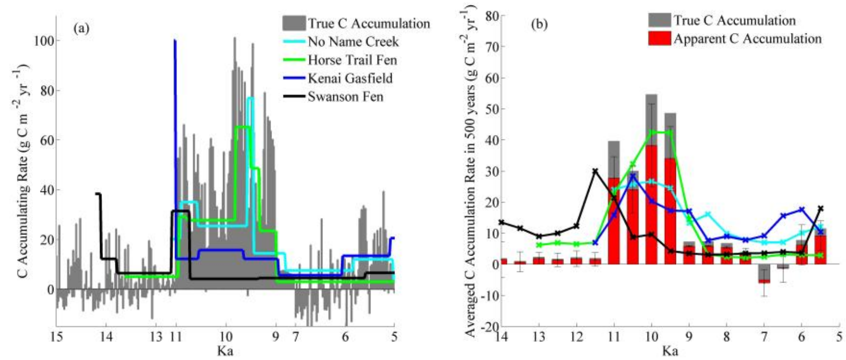
~~Figure 1. P-TEM (Peatland-Terrestrial Ecosystem Model) modeling framework, including a soil thermal module (STM), a hydrologic module (HM), a carbon/ nitrogen dynamic model (CNDM), and a methane dynamics module (MDM) (Wang et al., 2016).~~



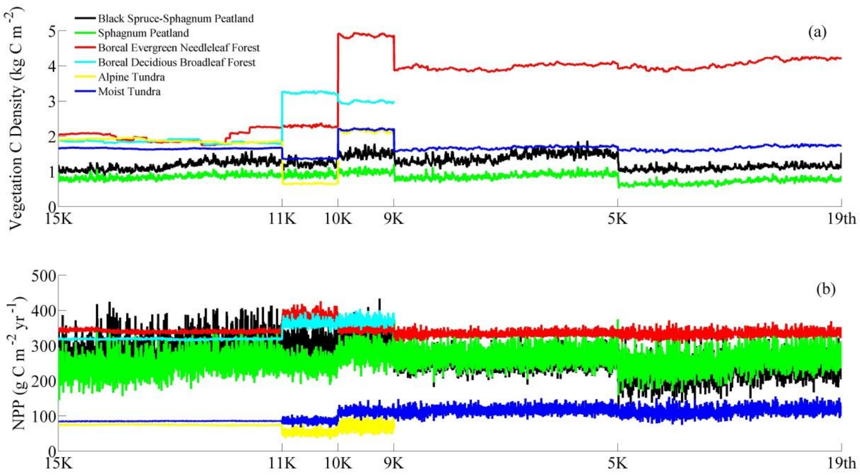
~~Figure 2. Alaskan vegetation distribution maps reconstructed from fossil pollen data during (a) 15-11 ka, (b) 11-10 ka, (c) 10-9 ka, (d) 9 ka -1900 AD, and (e) 1900-2000 AD (He et al., 2014). Symbols represent the basal age of peat samples (n = 102) in Gorham et al. (2012). Barren refers to mountain range and large body areas which could not be interpolated.~~



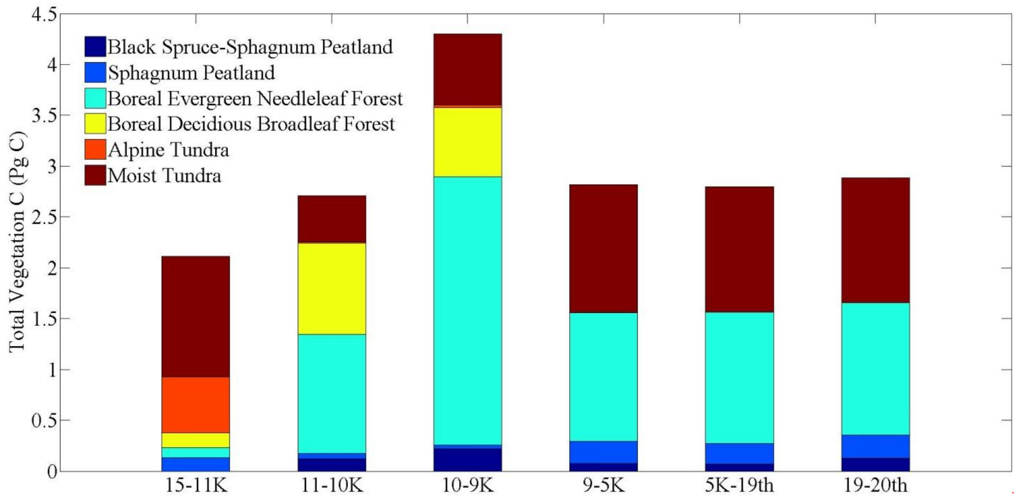
~~Figure 3. Simulated Paleo-climate and other input data from 15 ka to 2000 AD, including (a) mean monthly and (b) mean annual net incoming solar radiation (NIRR, W m^{-2}), (c) mean monthly and (d) mean annual air temperature (°C), (e) mean monthly and (f) mean annual precipitation (mm) (Timm and Timmermann, 2007; He et al., 2014).~~



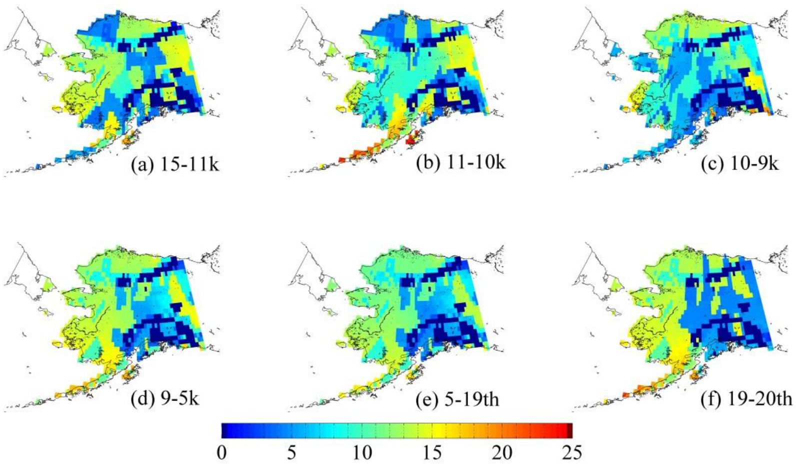
~~Figure 4. Simulated and observed carbon accumulation rates from 15 ka to 5 ka in 20-yr bins (a) and 500-yr bins with standard deviation (b) for No Name Creek, Horse Trail Fen, Kenai Gasfield, and Swanson Fen. Peat-core data were from Jones and Yu (2010).~~



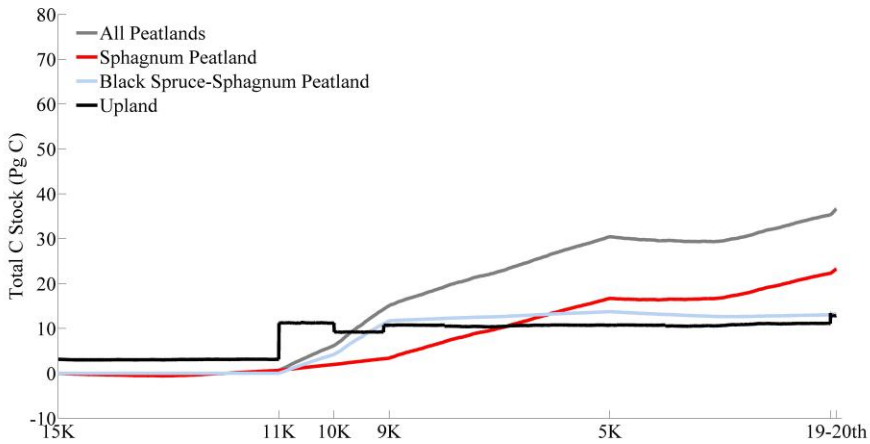
~~Figure 5. Simulated (a) mean vegetation carbon density (kg C m^{-2}) of different vegetation types and (b) NPP (g C $m^{-2}yr^{-1}$).~~



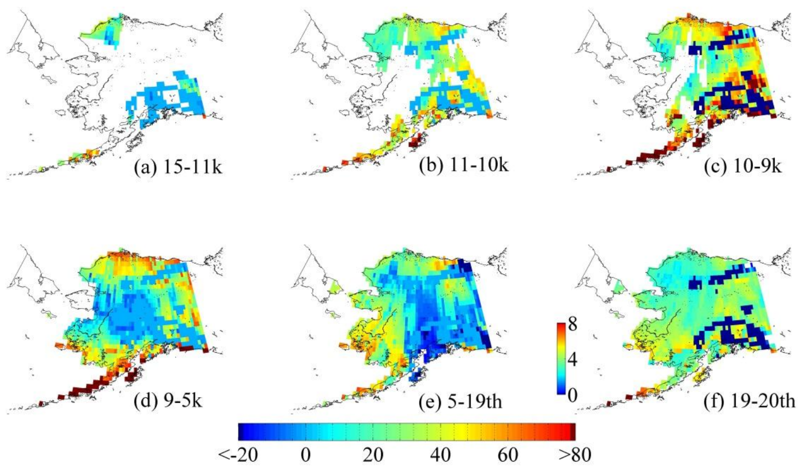
~~Figure 6. Total C (Pg C) stored in vegetation of Alaska for different time periods.~~



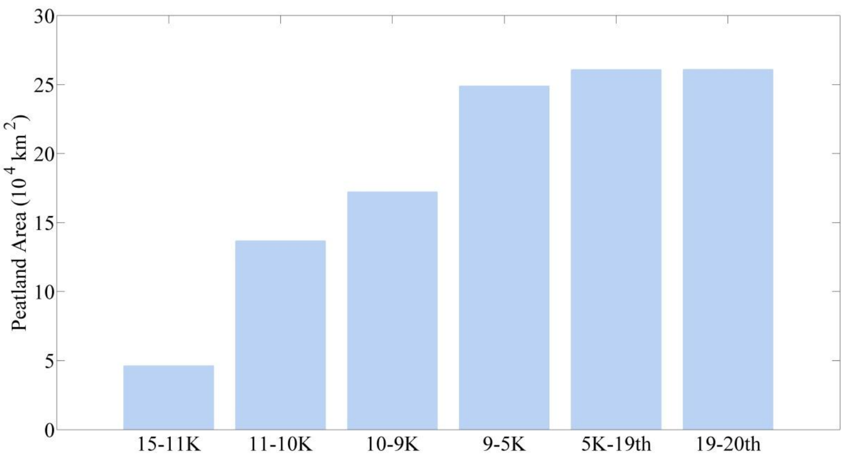
~~Figure 7. Non-peatland (mineral) SOC density (kg C m^{-2}) (cumulative) during (a) 15-11 ka, (b) 11-10 ka, (c) 10-9 ka, (d) 9-5 ka, (e) 5 ka -1900 AD, and (f) 1900-2000 AD.~~



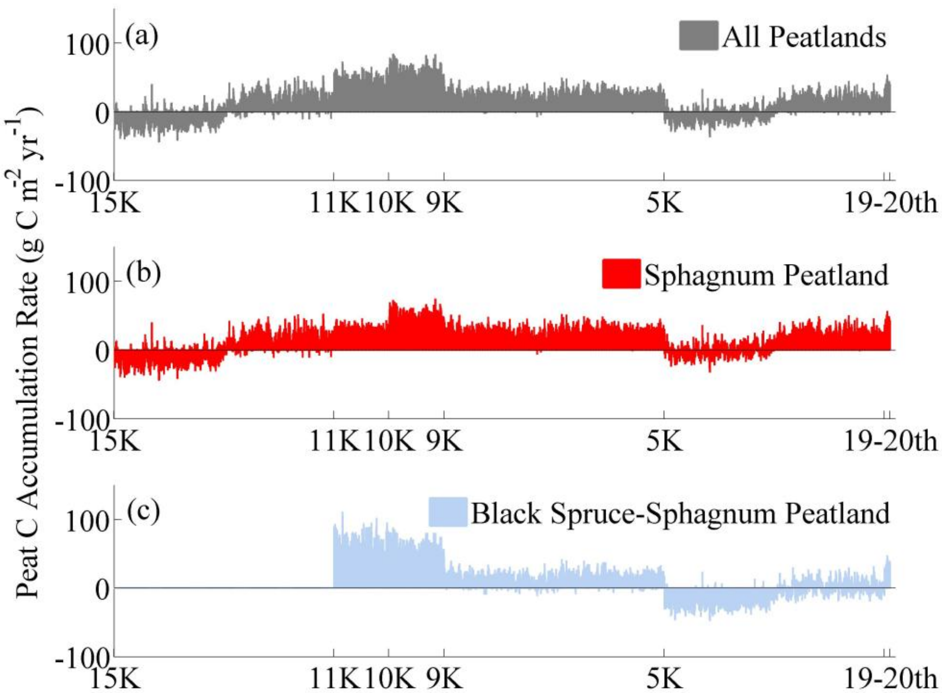
~~Figure 8. Total C stock accumulated from 15 ka to 2000 AD for all peatlands, *Sphagnum* open peatland, *Sphagnum* black spruce peatland, and upland soils.~~



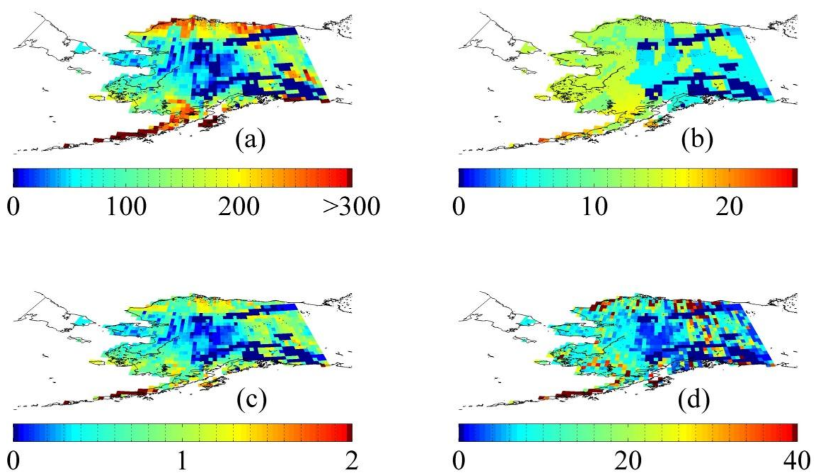
~~Figure 9. Peatland area expansion and peat soil C accumulation per 1000 years (kg C m^{-2} kyr^{-1}) during (a) 15-11 ka, (b) 11-10 ka, (c) 10-9 ka, (d) 9-5 ka, (e) 5 ka -1900 AD, and (f) 1900-2000 AD. The amount of C represents the C accumulation as the difference between the peat C amount in the final year and the first year in each time slice.~~



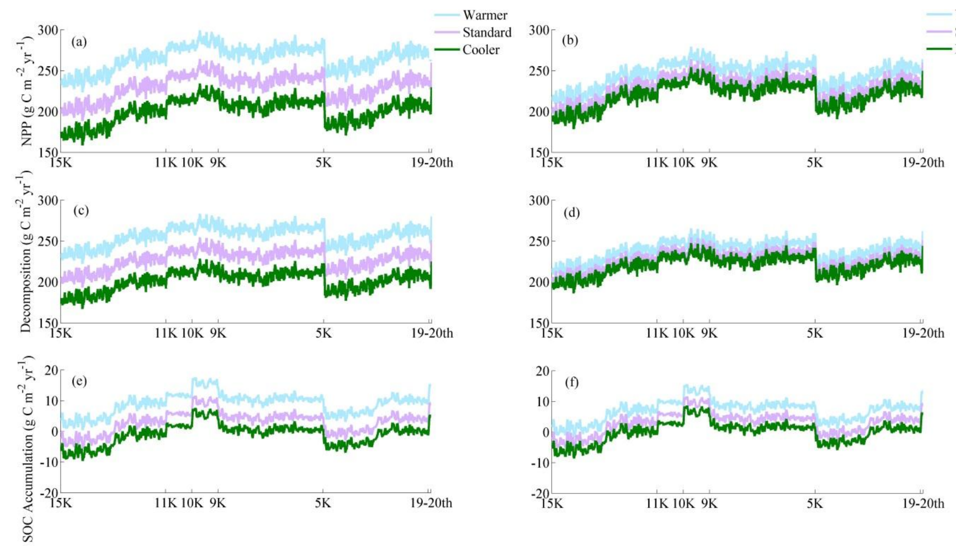
~~Figure 10. Peatland expansion area (10^4 km^2) in different time slices, the area of barren in the map is set to 0 km^2.~~



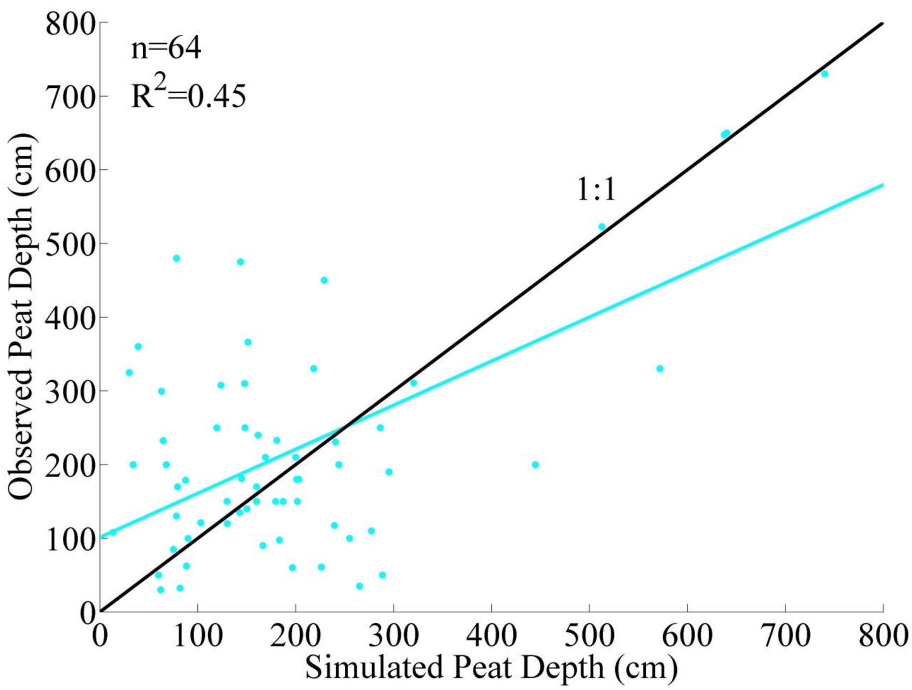
~~Figure 11. Peatland mean C accumulation rates from 15 ka to 2000 AD for (a) weighted average of all peatlands, (b) *Sphagnum* open peatland, and (c) *Sphagnum* black spruce peatland.~~



~~Figure 12. The spatial distribution of (a) total peat SOC density (kg C m^{-2}), (b) total mineral SOC density (kg C m^{-2}), (c) total peat depth (m), and (d) weighted average of total (peatlands plus non-peatlands) SOC density (kg C m^{-2}) in Alaska from 15 ka to 2000 AD.~~



~~Figure 13. Temperature and precipitation effects on (a)(b) annual NPP, (c)(d) annual SOC decomposition rate (aerobic plus anaerobic), and (e)(f) annual SOC accumulation rate of Alaska. A 10-year moving average was applied.~~



~~Figure 14. Field-based estimates and model simulations for peat depths in Alaska: The observed and simulated data are extracted from the same grids on the map. Linear regression line (cyan) is compared with the 1:1 line. The linear regression is significant (P<0.001, n = 64) with R^2 = 0.45, slope = 0.65, and intercept = 101.05 cm. The observations of >1000 cm are treated as outliers.~~

Table 1. Description of sites and variables used for parameterizing the core carbon and nitrogen module (CNDM).

Site[a]	Vegetation	Observed variables for CNDM parameterization	References
APEXCON	Moderate rich open fen with sedges (*Carex* sp.), spiked rushes (*Eleocharis* sp.), *Sphagnum* spp., and brown mosses (e.g., *Drepanocladus aduncus*)	Mean annual aboveground NPP in 2009; Mean annual belowground NPP in 2009; Aboveground biomass in 2009	Chivers et al. (2009) Turetsky et al. (2008) Kane et al. (2010) Churchill et al. (2011)
APEXPER	Peat plateau bog with black spruce (*Picea mariana*), *Sphagnum* spp., and feather mosses		

[a]The Alaskan Peatland Experiment (APEX) site is adjacent to the Bonanza Creek Experimental Forest (BCEF) site, approximately 35 km southwest of Fairbanks, AK. The area is classified as continental boreal climate with a mean annual temperature of -2.9℃ and annual precipitation of 269 mm, of which 30% is snow (Hinzman et al., 2006).

Table 2. Carbon pools and fluxes used for calibration of CMDM

Annual Carbon Fluxes or Pools[a]	*Sphagnum* Open Fen		*Sphagnum*-Black Spruce Bog		References
	Observation	Simulation	Observation	Simulation	
NPP	445±260	410	433±107	390	Turetsky et al. (2008), Churchill (2011) Saarinen et al. (1996) Moore et al. (2002) Zhuang et al. (2002) Tarnocai et al. (2009) Kuhry and Vitt (1996)
Aboveground Vegetation Carbon	149-287		423		
Belowground Vegetation Carbon	347-669		987		
Total Vegetation Carbon Density	496-856	800	1410	1300	
Litter Fall Carbon Flux	300	333	300	290	
Methane Emission Flux	19.5	19.2	9.7	12.8	

[a] Units for annual net primary production (NPP) and litter fall carbon are $g\ C\ m^{-2}\ yr^{-1}$. Units for vegetation carbon density are $g\ C\ m^{-2}$. Units for Methane emissions are $g\ C - CH_4\ m^{-2}\ yr^{-1}$. The simulated total annual methane fluxes were compared with the observations at APEXCON in 2005 and SPRUCE in 2012. A ratio of 0.47 was used to convert vegetation biomass to carbon (Raich 1991).

Table 3. Assignment of biomized fossil pollen data to the vegetation types in TEM (He et al., 2014).

TEM upland vegetation	TEM peatland vegetation	BIOMISE code
Alpine tundra		CUSH DRYT PROS
Moist tundra	*Sphagnum* spp. open fen	DWAR SHRU
Boreal evergreen needleleaf and mixed forest	*Sphagnum*-black spruce bog	TAIG COCO CLMX COMX
Boreal deciduous broadleaf forest		CLDE

Table 4. Relations between peatland basal age and vegetation distribution

Peatland basal age	Vegetation types	Location in Alaska
15-11 ka	alpine tundra	south, northwestern, and southeastern coast
11-10 ka	moist tundra boreal evergreen needleleaf forest boreal deciduous broadleaf forest	south, north, and southeastern coast east central part
10-9 ka	moist tundra boreal evergreen needleleaf forest boreal deciduous broadleaf forest	south and north coast central part
9-5 ka	moist tundra boreal evergreen needleleaf forest	central part
5 ka-1900 AD	moist tundra boreal evergreen needleleaf forest	west coast

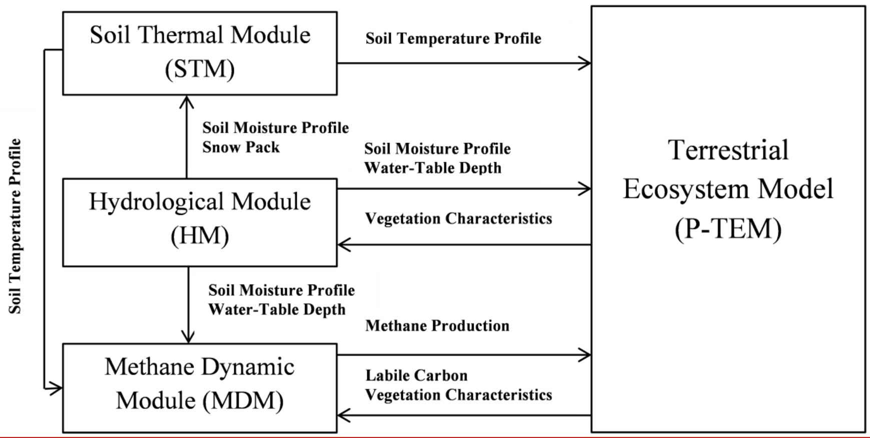


Figure 1. P-TEM (Peatland-Terrestrial Ecosystem Model) framework includes a soil thermal module (STM), a hydrologic module (HM), a carbon/ nitrogen dynamic model (CNDM), and a methane dynamics module (MDM) (Wang et al., 2016).

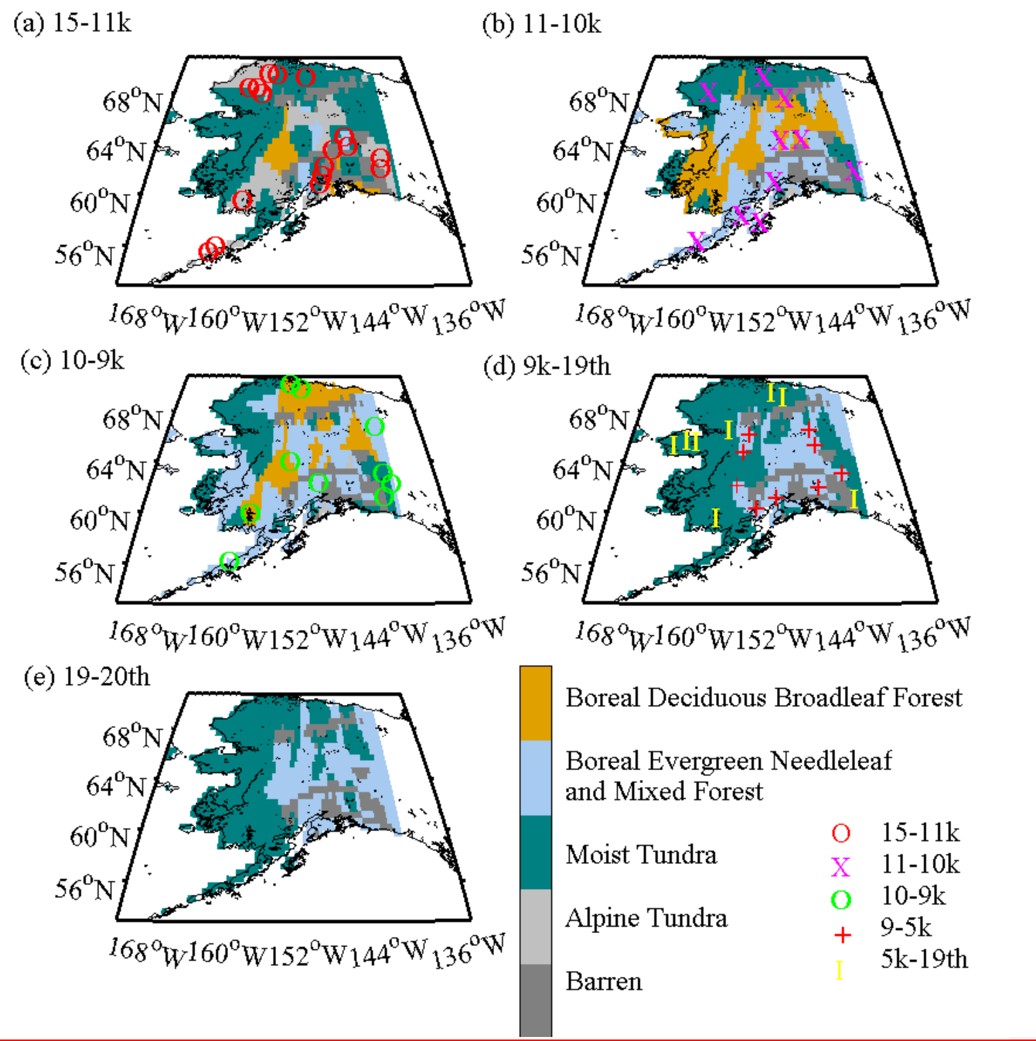


Figure 2. Alaskan vegetation distribution maps reconstructed from fossil pollen data during (a) 15-11 ka, (b) 11-10 ka, (c) 10-9 ka, (d) 9 ka -1900 AD, and (e) 1900-2000 AD (He et al., 2014). Symbols represent the basal age of peat samples (n = 102) in Gorham et al. (2012). Each symbol indicates 1-3 peat samples in the map. Peat samples with basal age 9-5k and 5k-19th are shown in map (d) as there is no change of vegetation distribution during 9k-19th. Barren refers to mountain range and large water body areas that can not be interpolated.

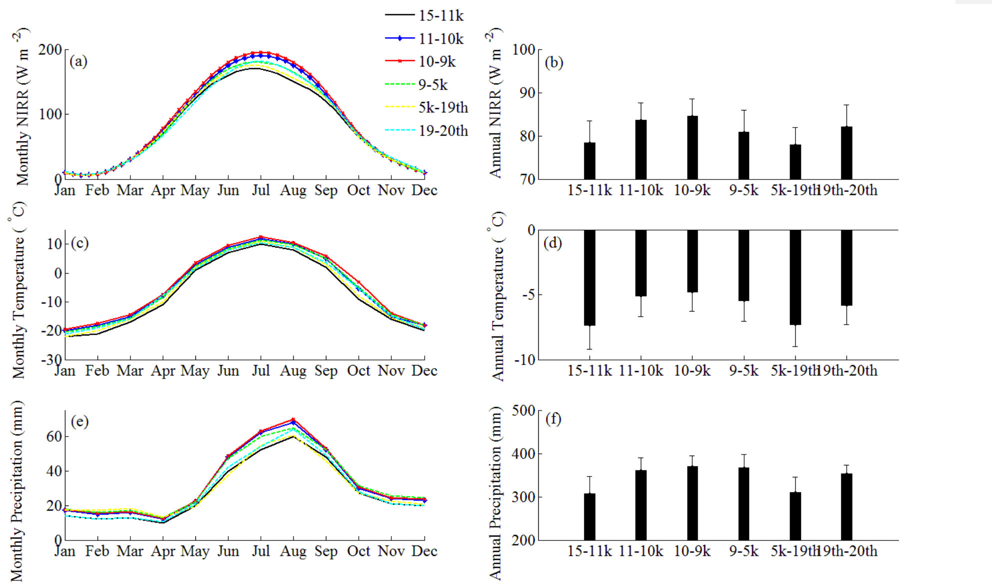


Figure 3. Simulated Paleo-climate and other input data from 15 ka to 2000 AD: (a) mean monthly and (b) mean annual net incoming solar radiation (NIRR, W m^{-2}), (c) mean monthly and (d) mean annual air temperature (°C), (e) mean monthly, and (f) mean annual precipitation (mm) (Timm and Timmermann, 2007; He et al., 2014).

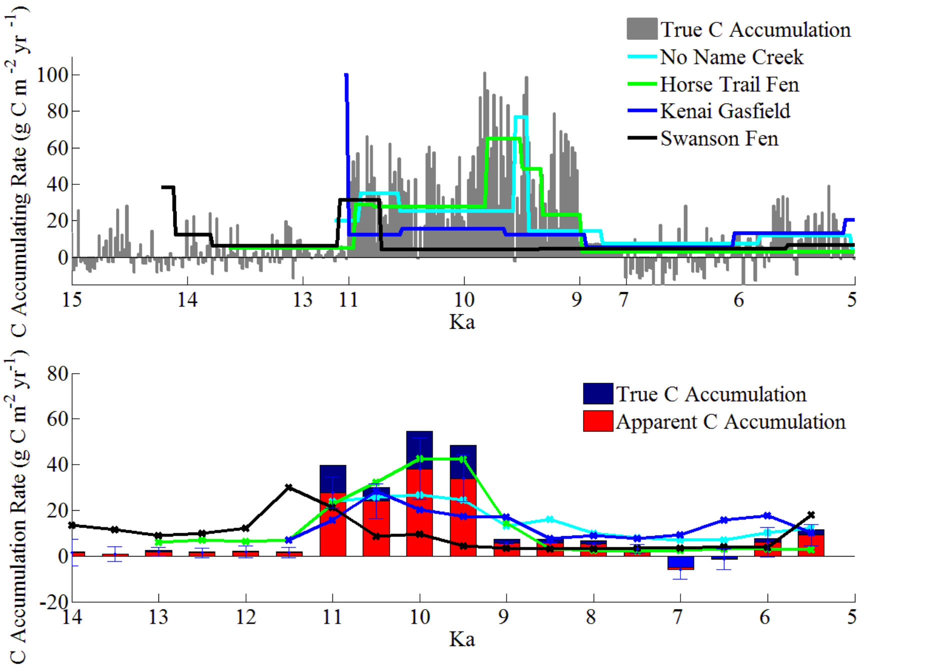


Figure 4. Simulated and observed carbon accumulation rates from 15 ka to 5 ka in 20-yr bins (a) and 500-yr bins with standard deviation (b) for No Name Creek, Horse Trail Fen, Kenai Gasfield, and Swanson Fen. Peat-core data were from Jones and Yu (2010).

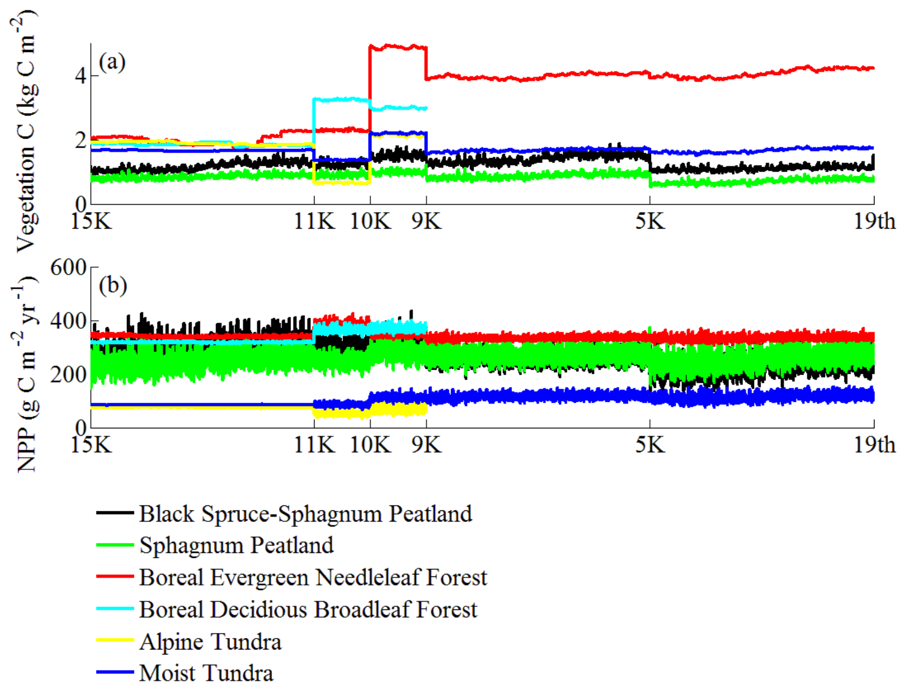


Figure 5. Simulated (a) mean vegetation carbon density (kg C m^{-2}) of different vegetation types and (b) NPP (g C $m^{-2}yr^{-1}$).

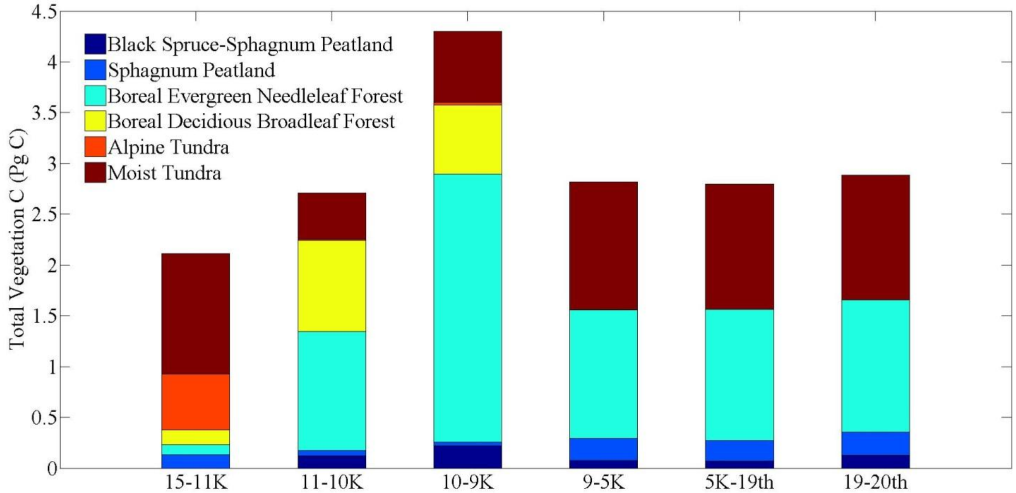


Figure 6. Total C (Pg C) stored in Alaskan vegetation for different time periods.

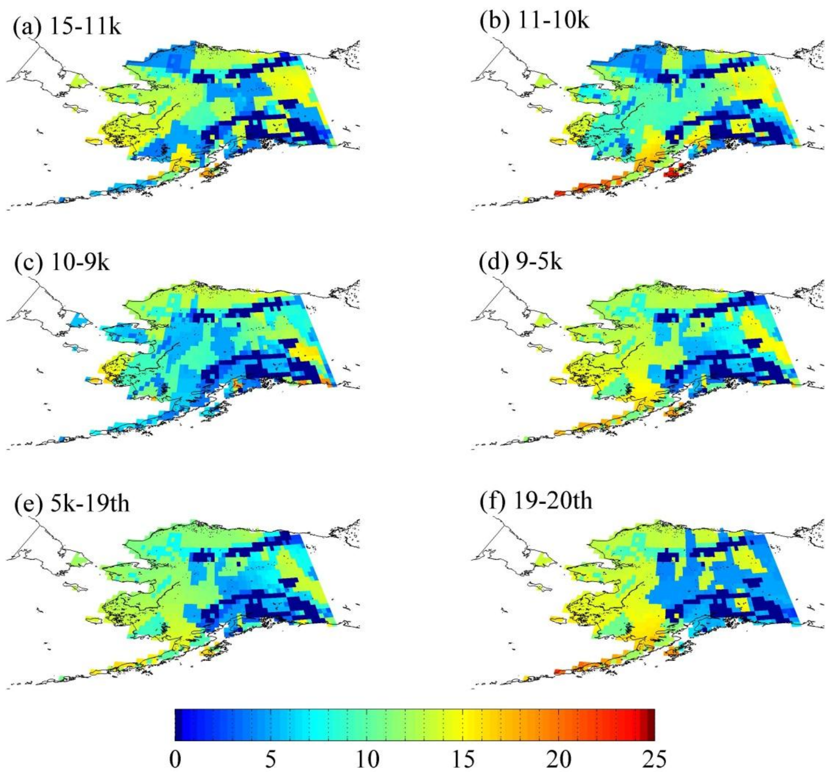


Figure 7. Average non-peatland (mineral) SOC density (kg C m^{-2}) during (a) 15-11 ka, (b) 11-10 ka, (c) 10-9 ka, (d) 9-5 ka, (e) 5 ka -1900 AD, and (f) 1900-2000 AD. The period of 9k-19th in Figure 2d is separated into 9-5k and 5k-19th.

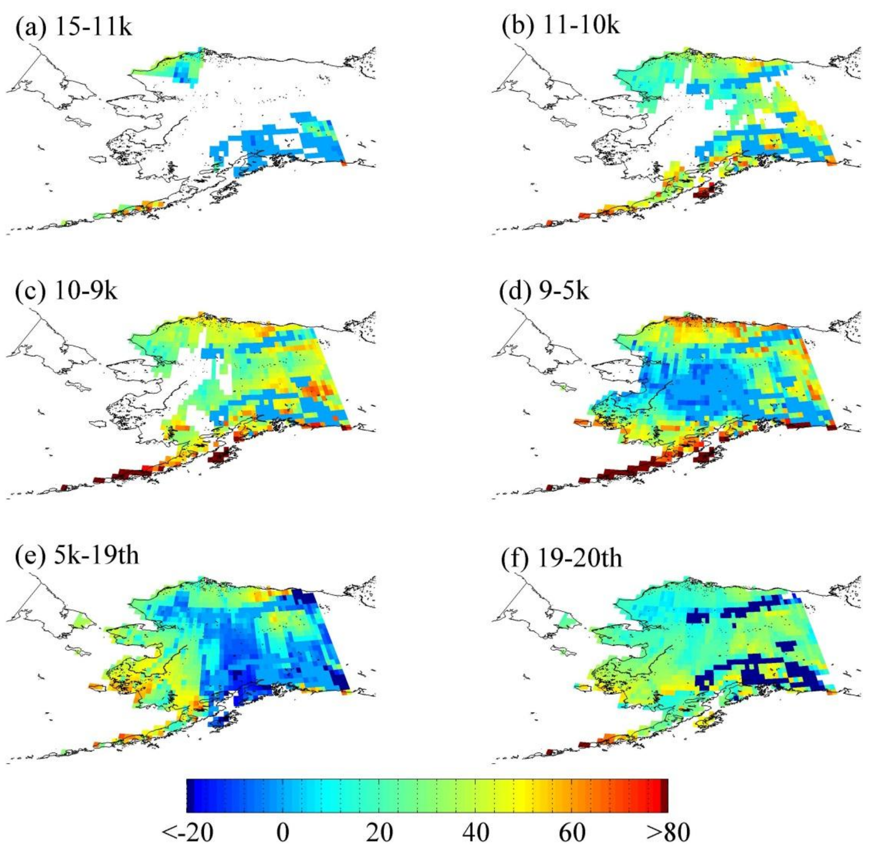
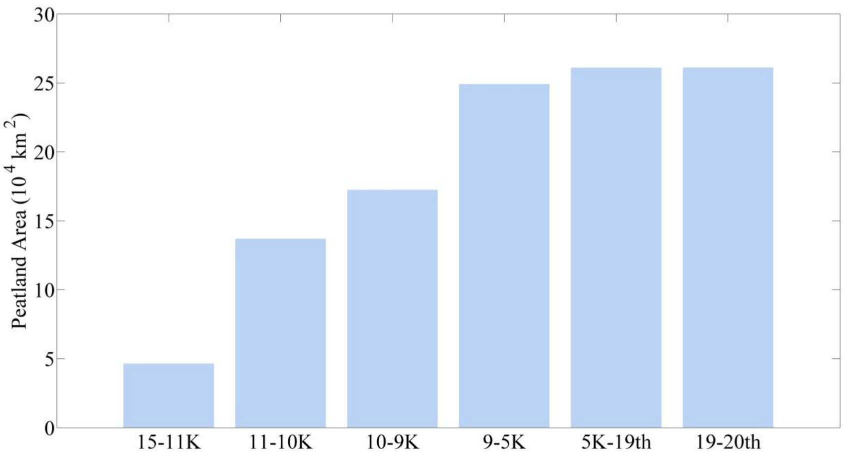


Figure 8. Peatland area expansion and peat soil C accumulation per 1000 years (kg C m^{-2} kyr^{-1}) during (a) 15-11 ka, (b) 11-10 ka, (c) 10-9 ka, (d) 9-5 ka, (e) 5 ka -1900 AD, and (f) 1900-2000 AD. The amount of C represents the C accumulation as the difference between the peat C amount in the final year and the first year in each time slice. The period of 9k-19th in Figure 2d is separated into 9-5k and 5k-19th.



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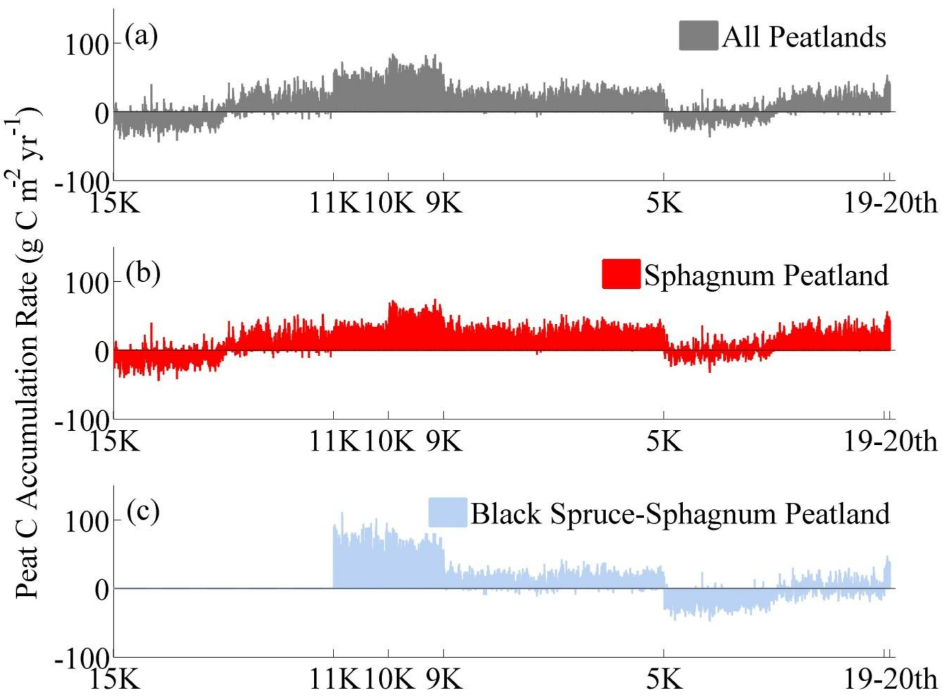


Figure 10. Peatland mean C accumulation rates from 15 ka to 2000 AD for (a) weighted average of all peatlands, (b) *Sphagnum* open peatlands, and (c) *Sphagnum*-black spruce peatlands.

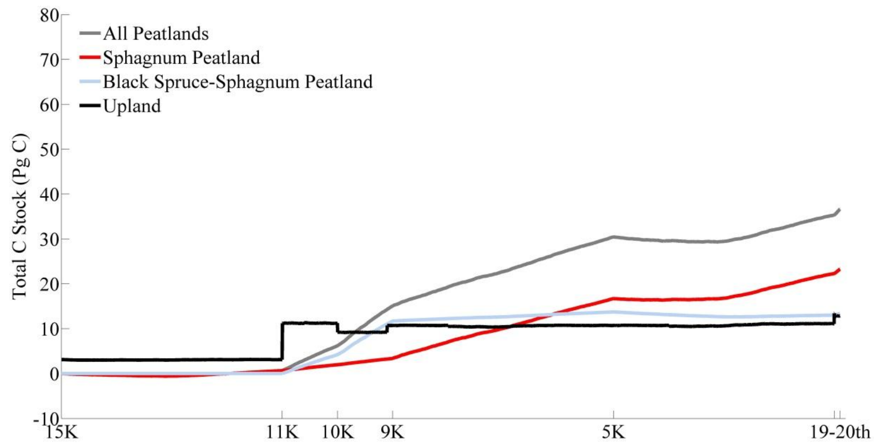
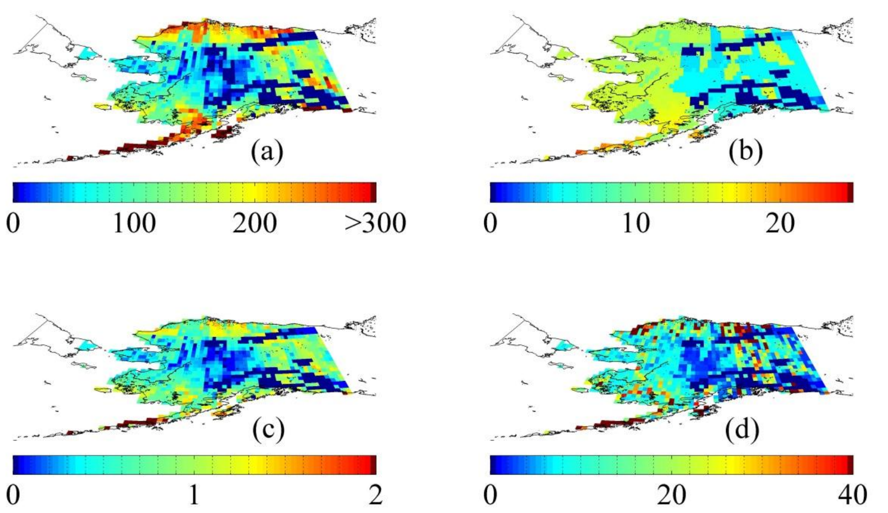


Figure 11. Total C stock accumulated from 15 ka to 2000 AD for all peatlands, *Sphagnum* open peatlands, *Sphagnum*-black spruce peatlands, and upland soils.



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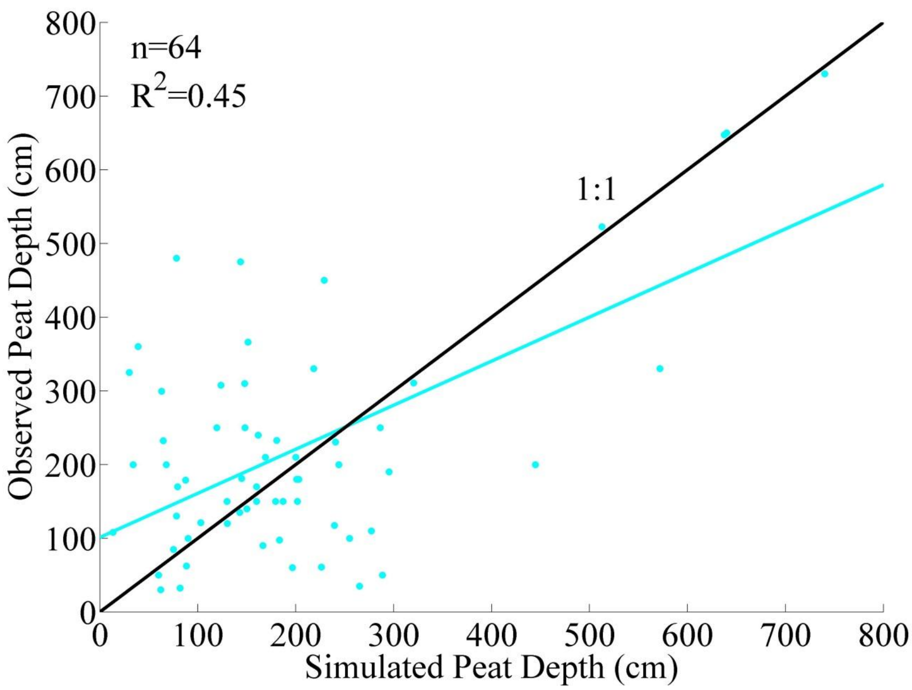

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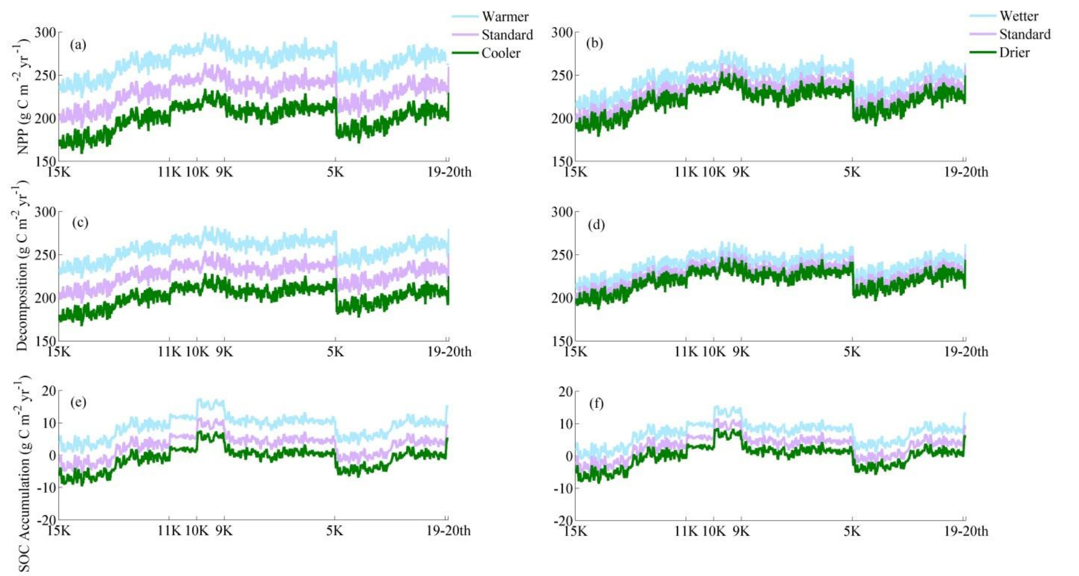

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