Peatland carbon dynamics in distinctively warmer world

Nitin Chaudhary[1], Wenxin Zhang[1], Shubhangi Lamba[2], and Sebastian Westermann[3]

[1]Lund University
[2]University of Gothenburg
[3]University of Oslo

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Abstract

Peatlands store large amounts of carbon in the terrestrial ecosystem and it seems that they would shift from being a carbon sink to a carbon source due to recent warming. In this study, we provide a comprehensive analysis of peatland carbon dynamics in distinct future climate conditions. The study examined whether less pronounced warming could further enhance the peatland carbon sink capacity and buffer the effects of climate change. It also determined which trajectory peatland carbon balance would follow, what the main drivers were, and which one would dominate in the future. We found that peatlands could largely retain their carbon sink capacity with reduced rates under the climate change scenario RCP 2.6 to RCP 6.0. They are projected to shift from a carbon sink to a carbon-neutral or a small carbon source in the strong warming scenario RCP 8.5 by the end of this century.

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Peatland carbon dynamics in distinctively warmer world

Nitin Chaudhary[1,2], Wenxin Zhang[1,3], Shubhangi Lamba[4] and Sebastian Westermann[2]

[1.] Department of Physical Geography and Ecosystem Science, Lund University,

Sölvegatan 12, SE- 22362 Lund, Sweden

[2.] Department of Geosciences, University of Oslo,

Sem Sælands vei 1, Geologibygningen, 0371 Oslo, Norway

[3.] Department of Geosciences and Natural Resource Management,

University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen, Denmark

[4.] Department of Biological and Environmental Sciences,

University of Gothenburg, 40530 Gothenburg, Sweden

Abstract

Peatlands store large amounts of carbon in the terrestrial ecosystem and it seems that they would shift from being a carbon sink to a carbon source due to recent warming. In this study, we provide a comprehensive analysis of peatland carbon dynamics in distinct future climate conditions. The study examined whether less pronounced warming could further enhance the peatland carbon sink capacity and buffer the effects of climate change. It also determined which trajectory peatland carbon balance would follow, what the main drivers were, and which one would dominate in the future. We found that peatlands could largely retain their carbon sink capacity with reduced rates under the climate change scenario RCP 2.6 to RCP 6.0. They are projected to shift from a carbon sink to a carbon-neutral or a small carbon source in the strong warming scenario RCP 8.5 by the end of this century.

Plain language summary

Peatlands are important terrestrial ecosystems that take up carbon from the atmosphere but ongoing warming could shift this balance. In this study, we investigated how peatland would behave in the distinct warmer conditions and whether less to moderate warming could increase their carbon sink capacity and reduce the effects of climate change. We found that peatlands would remain a major sink of carbon by the end of this century, although their carbon accumulation rates would somewhat decrease compared to present conditions. Conversely, their sink capacity would substantially reduce in an extremely warmer world and there is a risk that they would turn into a carbon source or sequestering carbon by 2100.

Key Points:

- The effects of climate change on peatland carbon balance under different warming scenarios were determined

- Peatlands will likely remain carbon sink until 2100 in low to moderate warming scenarios
- They are projected to shift from a carbon sink to carbon neutral or a small carbon source in the strong warming scenario RCP 8.5

1. Introduction

Peatlands are considered one of the biggest carbon reserves in the terrestrial ecosystem, comprising 30% of the present-day soil organic carbon pool (Yu 2012). They are also a major source of methane (CH_4), a potent greenhouse gas (Abdalla et al. 2016). Recent observations have shown that the vegetation structure, hydrology, and carbon balance are rapidly changing in many peatlands (Johansson et al. 2006, Pinceloup et al. 2020). These ongoing changes will disturb the prevailing land-atmosphere carbon balance and trigger some pertinent climate-relevant feedbacks (Belyea 2013, Zhu and Zhuang 2016). Studies have indicated that peatlands will continue to act as a carbon sink in the next decades under different warming scenarios, but they will likely become carbon neutral or even a major carbon source by the end of this century (Chaudhary et al. 2017b, Gallego-Sala et al. 2018, Chaudhary et al. 2020, Qiu et al. 2020). To quantify and understand the overall effects of these rapid changes, various advanced peatland models have been employed, but often these models are forced with a distinct set of RCP scenarios (Chaudhary et al. 2020, Qiu et al. 2020, Müller and Joos 2021). It is a common trend to focus on two-three scenarios in modelling studies in order to obtain end-member estimates. All the climate scenarios are developed as a suite of complementary possibilities and the Intergovernmental Panel of Climate Change (IPCC) recommends that modelling studies should consider all the Representative Concentration Pathways (RCP) scenarios for a complete understanding of system behaviour in future conditions (IPCC 2013a). Furthermore, Ritchie and Dowlatabadi (2017) recommend that the ultra-high warming scenario RCP85 should be used with caution for future scientific research or policy studies because the amount of coal that this scenario requires by major fossil fuel consuming countries assume to use in coming decades will likely exceed the estimates of readily available fossil resources. Experts believe that RCP45 and RCP60 are the more realistic scenarios (IPCC 2013b, Ritchie and Dowlatabadi 2017), yet these two scenarios are often omitted from modelling studies.

The purpose of this study is to provide a comprehensive analysis of peatland carbon dynamics in the future climate conditions branching all plausible future warming scenarios. The study will examine whether less pronounced warming can further enhance the peatland carbon sink capacity and buffer the effects of climate change. It will also determine which trajectory peatland carbon balance will follow, what the main drivers are and which one will dominate in the future. This study is a continuation of our previous study (Chaudhary et al. 2020), where we analyzed long-term carbon accumulation rates in the past and in the future, using only a limited number of model points to simulate the observed peatland area under two warming scenarios. In this study, we progress a step forward and perform simulations at one-degree resolution within the observed peatland domain delineated by PEATMAP (Xu et al. 2018) to obtain a an overview of disguised responses of peatlands to four different warming scenarios by the end of the current century. Furthermore, we identify and highlight hotspot regions which are vulnerable to additional warming and likely switch its ecosystem functions between carbon sources or sinks according to our simulations.

2. Methodology

2.1 LPJ-GUESS peatland

LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator; (Smith et al. 2001, Smith et al. 2014) is a second-generation dynamic global vegetation model (DGVM) that is widely employed in global carbon cycle and vegetation dynamics studies (e.g. Saunois et al., 2020). LPJ-GUESS is included as a land surface scheme in the global Earth System Model (ESM) EC-Earth (Alessandri et al. 2017), and the regional ESM, such as RCA-GUESS (Wramneby et al. 2010, Zhang et al. 2014) and RCAO-GUESS (Zhang et al. 2020). LPJ-GUESS simulates vegetation structure and composition in response to a changing climate from local to global scales. It is a process-based model of vegetation dynamics which incorporates physiological changes and biogeochemistry of terrestrial ecosystems. It dynamically simulates water and carbon fluxes through coupled vegetation, soil, and hydrological interaction. Recently, new peatland and permafrost formulations with a unique representation of spatial heterogeneity were implemented in LPJ-GUESS (Chaudhary et al. 2017a). In particular, dynamic annual multi-layer peat accumulation, freezing-thawing cycles, lateral flow, and spatial heterogeneity in the framework of the dynamic vegetation model have for the first time been considered in the model (see Table S1 in Chaudhary et al. (2017a)), with applications from local to regional scales. Our previous studies have demonstrated that the mechanistic multi-layer peat accumulation scheme can simulate vegetation dynamics, permafrost, and peat distribution across the pan-Arctic region in a reasonably robust way. The current scheme consists of many important key mechanisms and interactions controlling the non-linear peatland dynamics (Chaudhary et al. 2018). Phenomena such as the 'hump-backed' relation between the average rate of peat formation and water table position, the cyclicity among micro-formations, internal eco-hydrological feedbacks and multi-directionality, which have been frequently observed in many peatland sites, can be simulated and explained using this detailed model scheme. In this study, we have employed the customized Arctic version of LPJ-GUESS that includes dynamic peat accumulation and decomposition functionalities with a freeze-thaw cycle. In the model, peat accumulates due to an imbalance between annual litter input and decomposition. The decomposition rate is controlled by the litter quality and thermo-hydrological conditions within the peat soil. The peat layers become more recalcitrant when sufficient labile peat material is decomposed over time. The current set up also features a unique individual- and patch-based representation of small–scale heterogeneity where the different vegetation units compete for resources, such as light and space. Over time, some patches gain height, while the surface elevation of others decreases or remains unaffected. The adjustment in the height of these dynamic patches drives the water flow from elevated to low-lying patches and affects vegetation and biochemical properties of peatlands. For more information about the model and its functionalities, refer to Chaudhary et al. (2017a)

Using this model, we have performed four experiments with all RCP warming scenarios: RCP26, RCP45, RCP60, and RCP85. The future climate forcing for these RCP scenarios were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) runs with the IPSL-CM5 (Dufresne et al. 2013). The model is forced with daily temperature, precipitation, and cloudiness data which were constructed by interpolating monthly values. The peat initiation surface was constructed using peat basal age values (Chaudhary et al. 2020) and this surface determines the length of the simulated peat accumulation period. The climate data are divided in three different periods: Holocene climate, transient, and future runs. In the Holocene experiment, the model was run from prescribed basal age in calendar years before present (cal. BP) until the year 1900. In the transient run, the CRU TS 3.0 global gridded climate data set (Mitchell and Jones 2005) was used until the year 2005 and the future runs were performed from 2006 to 2100 using RCP warming scenarios. The model output variables examined for this study include recent and near-future pan-Arctic carbon accumulation rates, net primary productivity, decomposition rates, dominant plant cover and permafrost distribution. A detailed description of model structure, data requirement, and simulation protocol is available in Chaudhary et al. (2020) and references therein.

3. Results and Discussion

3.1 Peatland carbon accumulation rates in the 21st century

Modelled northern peatlands have accumulated carbon at a rate of 20-35 g C m^{-2} year^{-1} between 1990-2000 (see Figure 1) with an average of 25.3 g C m^{-2} year^{-1}. It was found that carbon sink capacity of the peatlands sharply declines in the first two decades of the 21st century under all warming experiments, reaching a point beyond which each scenario followed their trajectories regulated by their respective thermo-hydrological regimes and internal dynamics. In the RCP85 experiment, the carbon sink capacity of peatlands is projected to continuously steadily reduce throughout the entire period. This decline in peat carbon accumulation rate is quite sharp in the first and last two decades of the 21st century and peatlands overall become near neutral or even a small net carbon source by the end of this century under RCP85. In the RCP26 and RCP45 experiments, similar declining trends in the carbon sink capacity have been noticed, but at comparatively smaller magnitudes, with average carbon accumulation rates remaining between 10-20 g C m^{-2} year^{-1} after 2020. In the RCP60 experiment, after an initial decline in the first two decades, carbon accumulation rates stabilize and fluctuate between 15-20 g C m^{-2} year^{-1}, largely remaining in the range of average long-term Holocene carbon accumulation rates. The peatland carbon sink capacity declines marginally after 2060 and then strengthens again in the last few decades after 2080 in this scenario. It is interesting to note that there is virtually no difference between RCP26, RCP45 and RCP60, which indicates that peatlands are quite robust to future climate changes for a wide range of future warming trends (Fig. 1). However, there is a clear climatic threshold to RCP85, beyond which the system starts behaving very differently, fully loosing its capacity to sequester carbon by the end of this century.

Overall, it is projected that peatlands turn into a small source of carbon by the end of this century in RCP85, while peatland carbon accumulation rates remain within the range of long-term Holocene carbon accumulation rates under the moderate warming experiment RCP60. In the ultra-low and low warming experiments (RCP26 and RCP45), peatlands remain a major sink of carbon by the end of this century, although the carbon accumulation rates are somewhat decreased compared to today.

If we look at the spatial distribution of peatland carbon accumulation rates, the majority of peatlands showed an increase in their carbon accumulation rates from the 19th to 20th century (Fig. 2b). The mean carbon accumulation rates at the beginning of the 20th century were predicted to be around 25 g C m^{-2} year^{-1} which steadily increased to 30-32 g C m^{-2} year^{-1} by the end of the 20th century. Peatlands located in central and Eastern Europe, northeastern US, southeastern Canada and along the Russian-Chinese border were found to be most vulnerable to additional climate warming and predicted to become a strong source of carbon, as the climate becomes progressively warmer. Conversely, peatlands in Siberia, the Hudson Bay lowlands and western Canada strengthen their carbon sink capacity. In short, low latitude peatlands are predicted to become a greater source of carbon, but other regions enhance their carbon sink capacity and counteract those losses in the model (Fig. 2c-j). The moderate warming since the 19th century benefited the overall peatland carbon accumulation rates, but this gain was rapidly compensated by a warming-driven increase in decomposition rates in the first two decades of this century (Figs. 1 and 3).

It is interesting to note that peatlands have already experienced enhanced warming in the first two decades which means that the majority of them may already have a reduced carbon sink capacity and carbon accumulation rates. If future warming follows comparatively moderate warming trend (RCP60), the carbon accumulation rates of peatlands are projected to recover after an initial decrease, but the non-mitigation high-end scenario RCP85 paints a bleak picture. To better understand the differences between the two scenarios, longer runs beyond 2100 are required to get a clearer picture of whether the rates stabilize or continue to decrease, in which case peatlands could eventually become a strong source of carbon.

3.2 Controls of vegetation productivity and decomposition rates on peat accumulation

The main uncertainties in quantifying the peatland carbon balance in the coming century arise from future trajectories of primary productivity and respiration rates. Some studies note that net primary productivity will override decomposition rates and accelerate the carbon accumulation (Wilson et al. 2017, Zhang et al. 2018a), while others argue that the respiration rates remain high and gains in the net primary productivity do not catch up to temperature-driven microbial decomposition (Hugelius et al. 2020). Our results suggest that the soil respiration will override the increases in net primary productivity in the RCP85 experiment (Fig. 3), while soil respiration and net primary productivity change by more similar magnitudes in the other scenarios, so that the overall carbon accumulation does not change strongly.

The main mechanism behind the higher productivity in the model is a temperature-dependent spring onset of photosynthesis which leads to a longer growing season in a warmer climate. This results in plants allocating additional production to the canopy, leading to increased leaf area and canopy growth, which further intercepts light and increases production. The increase in the modelled primary productivity is similar to the one observed in tundra warming experiments and satellite data (Olsrud et al. 2010, Berner et al. 2020). On the other hand, decomposition is exponentially related to soil temperature in the model, so temperature increases can substantially amplify the respiration rates. From Figs. 3 and 4, it can be seen that the net primary productivity increases as the temperature gets warmer particularly in mid and low latitude regions, but the increase in primary productivity is compensated by an increase in soil respiration rates. The respiration rates are higher in low latitude regions and remain moderate (5-10 g C m^{-2}) in mid and high latitudes.

Our results suggest that low latitude areas will be dominated by tall shrubs, while higher latitudes feature mosses, graminoids, and dwarf shrubs, collectively characterized as tundra vegetation. As the climate gets warmer, high latitude plant types will lose their ecological niche in many areas. While areas with high moisture content maintain their plant cover assemblage of mosses and graminoids, some areas show encroachment by tall shrubs. The net primary productivity in these regions is projected to increase, leading to increased carbon accumulation in the soil. The underlying mechanism is an increase in light availability which favours taller shrubs by out-competing smaller ground vegetation through shading. Shrub expansion and densification due to recent warming trends have been documented in many studies (Rundqvist et al. 2011, Liljedahl et al. 2020) which is in line with our findings.

3.3 Permafrost distribution

We found that almost 58% of peatlands were underlined by permafrost in beginning of the 20th century which reduced to 56% by the end of it. Hugelius et al. (2020) also found that that almost half of the peatlands are underlain by permafrost which affects their biogeochemistry and carbon cycle. Permafrost peatlands are characterized by ice-rich conditions and observations show that these ice-rich peatlands have been continuously thawing, which changes net primary productivity and carbon accumulation rates. Our simulation results suggest that today's permafrost peatlands start to thaw under all future warming scenarios, resulting in deeper active layer depths (Fig. 6a and b), while the rate of permafrost loss is dependent on the warming scenario. In line with recent studies (Zhang et al. 2018b, Turetsky et al. 2019, Hugelius et al. 2020), the permafrost extent starts shrinking from the southern limit in our simulations, creating space for new vegetation assemblages, which in turn modifies the carbon accumulation rates in those regions. Permafrost-peatlands are predicted to completely disappear from many regions within a few decades, underlining their vulnerability to ongoing warming. According to our simulations, permafrost peatland fractions are predicted to reduce to 39.91%, 35.36%, 35.39% and 29.1% under RCP26, RCP45, RCP.6.0 and RCP85 respectively.

Conclusion

Peatlands are an important long-term carbon sink in the global climate system and the ongoing warming trend has the potential to modify the peatland carbon balance by the end of this century. In this study, we used a state-of-the-art peatland model to simulate the peatland carbon balance in mid and high latitude regions of the Northern Hemisphere. We found that peatlands can largely retain their carbon sink capacity for the climate change scenario RCP 2.6 to RCP 6.0, but are projected to shift from a carbon sink to carbon neutral or a small carbon source in the strong warming scenario RCP 8.5. While the past warming in the 19^{th} and 20^{th} century has increased the carbon accumulation rates across the pan-Arctic, those gains seem to be reverse by further warming.

Figures:

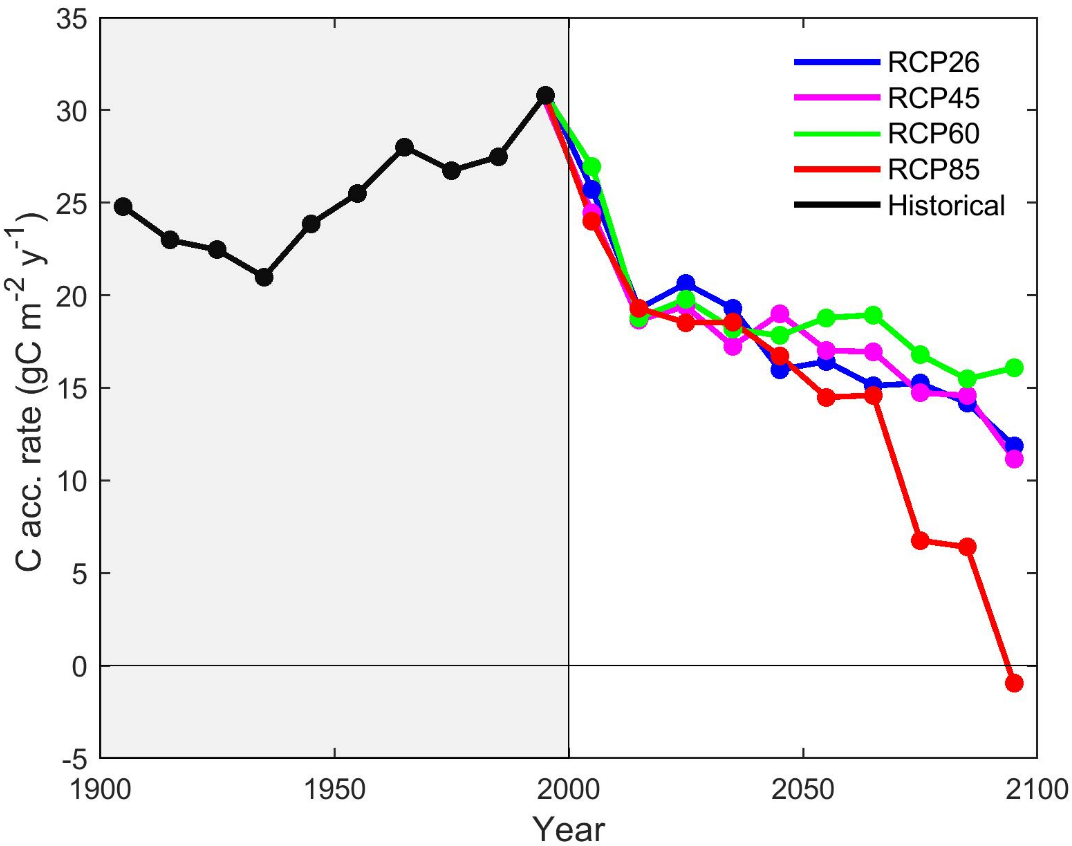

Fig. 1. Modelled carbon accumulation (decadal mean) rates for different RCP scenarios

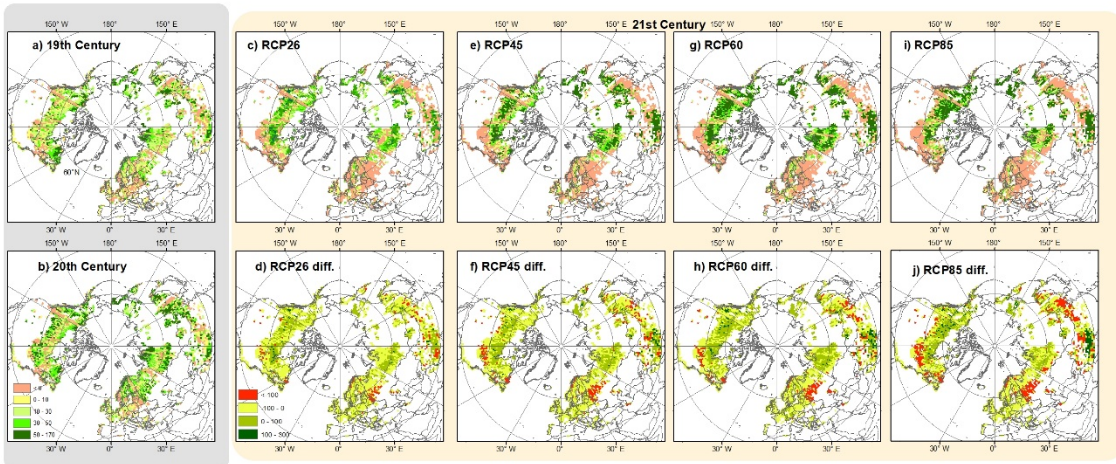

Fig. 2. Modelled carbon accumulation rates (in g C m^{-2}) across pan-Arctic under different RCP warming scenarios

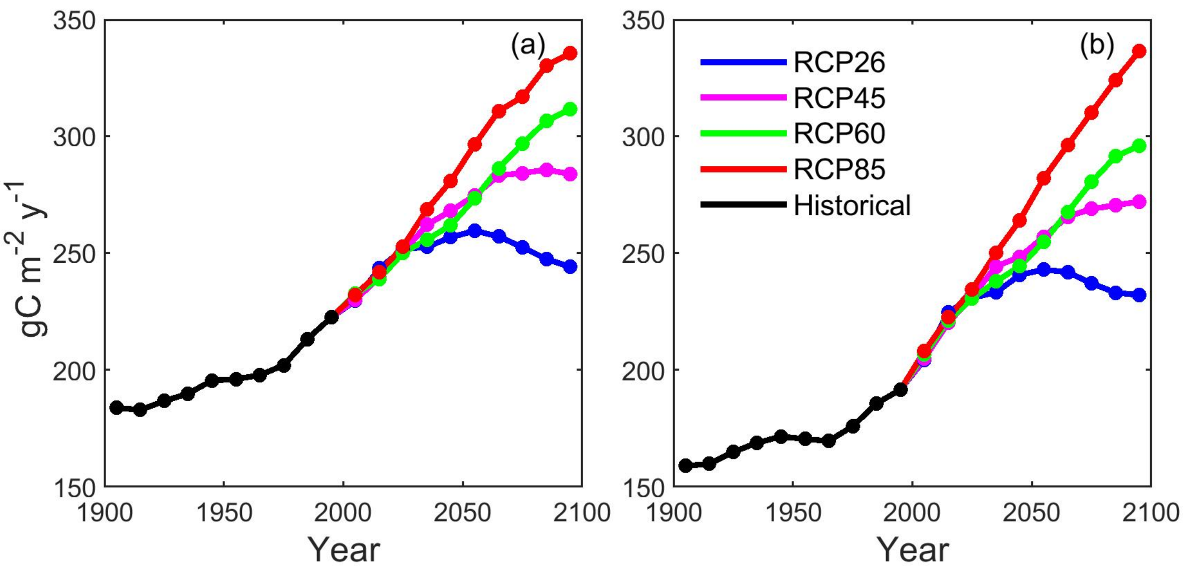

Fig. 3. (a) Modelled net primary productivity and (b) respiration rates across pan-Arctic under different RCP warming scenarios

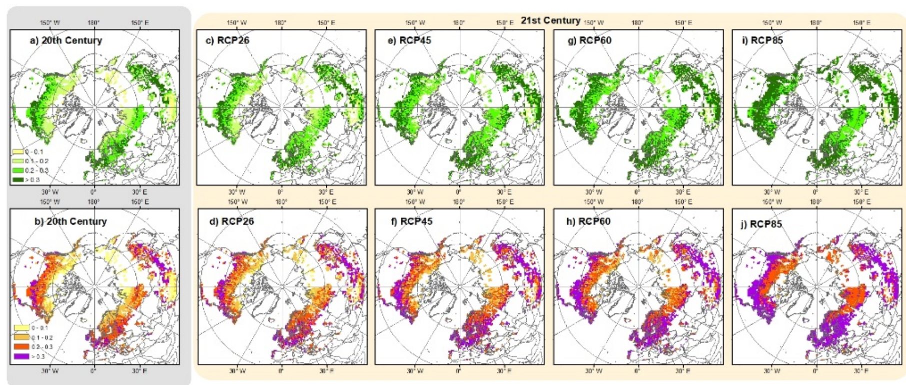

Fig. 4. Modelled net primary productivity and peat decomposition rates (in kg C m^{-2}) in northern peatland sites for different RCP scenarios

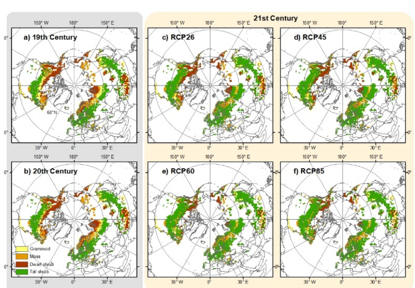

Fig. 5. Modelled dominant plant types in northern peatland sites under different RCP scenarios

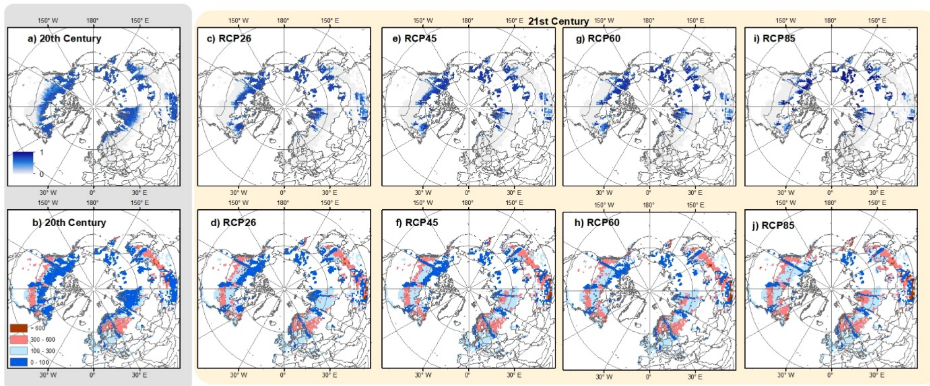

Fig. 6. Modelled permafrost distribution (in fraction 0 to 1) and active layer depth (in cm) in northern peatland sites for different RCP scenarios

DATA AVAILABILITY

Data archiving is underway in PANGEA data repository (https://www.pangaea.de/)

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