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Pronounced and unavoidable impacts of low-end global warming on northern high-latitude land ecosystems

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Author contributions

AI designed the study, conducted analyses, and drafted the manuscript. CPOR and PC led the ISIMIP2b biome sector coordination. JC, MF, and SO conducted simulations. CPOR, PC, MC, MF, TH, and WT commented on the manuscript. AG also commented on the manuscript from the perspective of the permafrost sector.

Data availability statement

The data that support the findings of this study are openly available at http://doi.org/10.5880/PIK.2019.012.

Abstract

Arctic ecosystems are particularly vulnerable to climate change because of Arctic amplification. Here, we assessed the climatic impacts of low-end, 1.5 °C, and 2.0 °C global temperature increases above pre-industrial levels, on the warming of terrestrial ecosystems in northern high latitudes (NHL, above 60 °N including pan-Arctic tundra and boreal forests) under the framework of the Inter-Sectoral Impact Model Intercomparison Project phase 2b protocol. We analyzed the simulated changes of net primary productivity, vegetation biomass, and soil carbon stocks of eight ecosystem models that were forced by the projections of four global climate models and two atmospheric greenhouse gas pathways (RCP2.6 and RCP6.0). Our results showed that considerable impacts on ecosystem carbon budgets, particularly primary productivity and vegetation biomass, are very likely to occur in the NHL areas. The models agreed on increases in primary productivity and biomass accumulation, despite considerable inter-model and inter-scenario differences in the magnitudes of the responses. The inter-model variability highlighted the inadequacies of the present models, which fail to consider important components such as permafrost and wildfire. The simulated impacts were attributable primarily to the rapid temperature increases in the NHL and the greater sensitivity of northern vegetation to warming, which contrasted with the less pronounced responses of soil carbon stocks. The simulated increases of vegetation biomass by 30–60 Pg C in this century have implications for climate policy such as the Paris Agreement. Comparison between the results at two warming levels showed the effectiveness of emission reductions in ameliorating the impacts and revealed unavoidable impacts for which adaptation options are urgently needed in the NHL ecosystems.

Key words: Northern high latitudes, biome sector, climatic impacts, ISIMIP2b, Paris Agreement

1. Introduction

Terrestrial ecosystems, especially in the northern high latitude (NHL) area, are predicted to undergo substantial impacts associated with changes of land use and climate in the next several decades (Warszawski *et al* 2013, IPCC 2014, 2019). Such changes in terrestrial ecosystems are likely to influence human societies through deterioration of ecosystem services such as climate regulation, recreational services, and provision of foods and goods (Malinauskaite *et al* 2019). Moreover, the fact that changes in ecosystem structures and functions are highly likely to exert climatic feedbacks on the human-induced warming (e.g. Arora *et al* 2013) demands that we understand and predict the ecosystem responses to global change.

Ecosystems in the NHL region will be exposed to climatic warming greater than the global average (IPCC 2013, Post *et al* 2019) and may thus be strongly impacted. Biological processes such as plant leaf phenology, primary production, and soil decomposition in the temperature-limited environments of the NHL are particularly sensitive to climatic warming (McGuire *et al* 2009, Richardson *et al* 2018). One of the characteristics of changes in terrestrial ecosystems is that they occur over temporal scales that range from instantaneous (e.g. photosynthetic gas exchange) to centuries or millennia. Examples of the latter include vegetation succession (Hickler *et al* 2012), tree migration (Neilson *et al* 2005), and soil development. Transformation of carbon cycling in the NHL region has attracted particular attention as an early warning of climatic impacts on ecosystems and in relation to climate–carbon cycle feedbacks. Changes in northern plant productivity have been deduced from the amplification of the seasonal cycle of atmospheric CO_2 concentrations (e.g. Graven *et al* 2013). Also, greening trends of northern vegetation have been detected by satellite observations for decades (Myneni *et al* 1997, Goetz *et al* 2005, Piao *et al* 2019). In contrast, soils in the NHL, especially perennially frozen soils, are likely to be degraded by physical and biological decomposition related to rapid temperature rise (Schuur *et al* 2015, Crowther *et al* 2016). It is uncertain whether the NHL is functioning as a net carbon sink or a source and how the system is changing. Nevertheless, the presence of large carbon stocks in the NHL region (e.g. 1100–1500 Pg C in the permafrost region; Hugelius *et al* 2014) suggests that there is potential for a strong climate–carbon cycle feedback that will likely act as a positive climate feedback (Schuur *et al* 2015). The likely interactions of ecological processes such as vegetation demography and disturbances with climatic warming will increase the risk of transgressing tipping points for boreal forest dieback and permafrost thawing in this region (Lenton *et al* 2008, Schaphoff *et al* 2016, Natali *et al* 2019). In the end, the balance between the positive effect of increasing productivity versus the negative effect of soil warming will determine future changes of the NHL carbon balance.

At the 21st Conference of the Parties of the United Nations Framework Convention of Climatic Change, a milestone agreement about global warming mitigation, the Paris Agreement, was negotiated and agreed upon by 196 state parties. The goal of the agreement was to keeo the global temperature rise well below 2 °C (hopefully 1.5 °C) above pre-industrial levels. To reinforce the scientific background to these temperature targets, intensive assessments have been conducted of various sectors such as water resource, agricultural production, and human health (e.g. Jahn 2018, Schleussner *et al* 2018). Special reports on the 1.5/2.0°C climate targets and associated reports with foci on terrestrial, ocean, and cryospheric systems have been published by the Intergovernmental Panel on Climate Change (IPCC 2018, 2019). These reports address various aspects of natural and human systems and demonstrate a higher risk of negative impacts by a 2 °C warming versus 1.5 °C or less. Several studies have assessed the NHL region, but they have usually focused on high-end global warming projections (Ito *et al* 2016, McGuire *et al* 2018). More specific and in-depth analyses using the latest available low-end climate projections are required to better understand climatic impacts in NHL areas so that the effectiveness and limitations of the Paris Agreement can be adequately discussed in terms of climate policy. Several analyses have been conducted in the NHL region, but their reliability and uncertainty differ among sectors because of uneven scientific understanding and data availability. Impacts on biological systems and related risks are, compared to physical systems, even more difficult to evaluate, because biological systems are very heterogeneous and complex (e.g. non-linear responses, acclimation, and interactions among organisms).

This study focused on the impacts of low-end global warming scenarios (1.5 °C and 2.0 °C versus pre-industrial temperatures) on NHL ecosystems in a mitigation-oriented world, in accordance with the Paris Agreement. For this purpose, we used output data from eight global vegetation models that contributed to the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) phase 2b and focused on properties related to the carbon cycle. The ISIMIP phase 2b experiments were designed specifically to quantify impacts of low-end global warming on a mitigation-oriented world using multiple impact models (Frieler *et al* 2017). Use of these ensembles allowed us to assess the ranges of inter-scenario and inter-model variability. Assessment of drastic and extreme events and phenomena that unfold on a centennial or longer timeframe was beyond the primary scope of this work. Such an assessment would be better conducted by other experiments specifically designed with many ensemble simulations and improved benchmarking models. Our study complements previous work and enabled us to analyze at regional to global scales multi-year and multi-decadal phenomena such as time-lagged responses and system transformations that can emerge gradually, especially in ecosystems. Consideration of such issues is highly relevant to policy makers.

2. Methods

2.1. ISIMIP2b experiments

The ISIMIP2b experiments were designed primarily to assess the impacts of 1.5 °C and 2.0 °C global warming above pre-industrial levels (Frieler *et al* 2017). To allow analyses of multiple sectors, the protocol describes several simulations that combine greenhouse gas emission pathways, associated land-use patterns, and climate projections consistent with the Representative Concentration Pathway (RCP) 2.6 and 6.0 (van Vuuren *et al* 2011). In addition to a pre-industrial control experiment (in this study, used only for checking stability after initialization), the models performed historical (1860–2005), future (2006–2099), and extended future (2100–2299) simulations. Both RCPs assumed the middle-of-the-road socioeconomic pathway, SSP2 (Fricko *et al* 2017), but differed with respect to climate stabilization targets and mitigation policy. The RCP 2.6 scenario represents a mitigation-oriented scenario, in which the degree of global warming may not exceed 2.0 °C above pre-industrial levels for an extended period of time, though it may overshoot that target temporarily. To assess long-term, more gradual impacts, climate projections for RCP2.6 were extended to 2299. The RCP6.0 represents a scenario with limited mitigation, in which the degree of global warming may well exceed 2.0 °C. This scenario allowed us to assess rapid global warming impacts and put the low-end warming impacts into the context of a wider risk analysis.

This study used the simulation outputs from the ISIMIP global vegetation models ("biome models", which are described in the next section) in the historical and future projection periods. Most biome models were integrated at a spatial resolution of 0.5° × 0.5° in latitude and longitude and driven by bias-corrected data from as many as four global climate models (GCMs) to cover the range of inter-model variability: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 (Frieler *et al* 2017; see figure S1 for their global mean temperatures). The extended climate projections for the period 2100–2099 were supplied by only the HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 GCMs. The EarthH2Observe, WFDEI, and ERA-interim climate data were merged for the period from 1979 to 2013 and were used to correct the bias of the climate models (Lange 2018). In the historical period, atmospheric CO_2 and land-use conditions changed annually in most models, except for one model (CLM4.5) that used the land-use conditions in 2005 throughout its simulation of historical periods, because the model could not account for transient changes in the extent of irrigation. In the future period, atmospheric CO_2 concentrations varied on the basis of the RCP2.6 and RCP6.0 scenarios. In the NHL regions, future land-use change was predicted to be trivial; hence, for simplicity, we assumed fixed land-use conditions after 2005 (ISIMIP2b Experiments II and III described in Frieler *et al* 2017). The extended climate projections for the period 2100–2299 were considered by using the HadGEM2-ES, IPSL-CM5A-LR, and MIROC5 GCMs.

2.2. Biome models

Eight biome models participated in ISIMIP2b (table S1; Reyer *et al* 2019): The "Carbon Assimilation in the Biosphere" model (CARAIB: Dury *et al* 2010), the "Community Land Model version 4.5" (CLM4.5; Lawrence *et al* 2011), the "Dynamic Land Ecosystem Model" (DLEM; Tian *et al* 2011), the "Lund-Potsdam-Jena model with managed Land" (LPJmL; Bondeau *et al* 2007), the "Lund-Potsdam-Jena General Ecosystem Simulator" (LPJ-GUESS; Smith *et al* 2014), the "Organizing Carbon and Hydrology in Dynamic Ecosystems" (ORCHIDEE-MICT; Guimberteau *et al* 2018), the "Vegetation Global Atmosphere Soil" (VEGAS; Zeng *et al* 2005), and the "Vegetation Integrative SImulator for Trace gases" (VISIT; Ito and Inatomi 2012). Seven of the eight models (except for CLM4.5) participated in phase 2a of ISIMIP, in which the models were benchmarked against a wide range of historical, observational data (e.g. Chang *et al* 2017, Chen *et al* 2017, Ito *et al* 2017, García Cantú *et al* 2018, Wartenburger *et al* 2018). The eight models differ in their conceptualization of ecosystem structure, parameterization of functional processes, and environmental responsiveness, but as the phase 2a benchmarking revealed, they on average captured the present terrestrial carbon budget (figure S2; table S2).

Primarily because of run-time constraints, not all models were driven by all four GCMs. Nevertheless, a total 52 cases of biome model-climate model combinations (available as of September 2019) were used in this study. The use of IPSL-CM5A-LR climate projections to force all biome impact models for both the RCP2.6 and RCP6.0 scenarios allowed us to conduct an inter-model comparison across the eight models for this GCM. The submission of output data from five biome models for four GCM projections allowed us to conduct an inter-climate comparison across the full range of GCMs. Sixteen cases of simulation results were available for the extended period.

2.3. Analyses

We selected three variables that represented ecosystem properties and were relevant to fundamental supporting and regulating ecosystem services for the analyses (Millennium Ecosystem Assessment 2005): annual net primary production (NPP, kg C m^{-2} yr^{-1}), vegetation biomass (CVeg, kg C m^{-2}), and soil carbon stock (CSoil, kg C m^{-2}). We used area-weighted grid-cell average values of these variables. NPP represents ecosystem functional activity and responds directly to environmental change. CVeg, a metric of vegetation height and density, represents vegetation development; its response to cumulative environmental change is based on the turnover of carbon in vegetation pools. CSoil is expected to represent the role of the soil and its effective depth, which are closely related to ecosystem properties (e.g. nutrient- and water-holding capacities). Changes in CVeg and CSoil are key indicators for assessing the carbon balance of the ecosystem. We used the benchmarking results of the ISIMIP2a biome models (e.g., Chang *et al* 2017) to focus on changes during the 21st century that could be simulated by the present models. The NHL grid points north of 60 °N were extracted from the global simulation results for the following analyses.

To clarify the regional characteristics and to separate the effects of multiple factors in a simplified manner, we adopted a conventional factorial approach. First, we considered the change index Φ (dimensionless) for NPP (Φ_{NPP}), CVeg (Φ_{CVeg}), and CSoil (Φ_{CSoil}). The Φ index is defined as follows:

$$\Phi = \Delta_{\mathrm{NHL}} / \Delta_{\mathrm{global}}. \quad (1)$$

Here Δ_{NHL} is the regional mean change and Δ_{global} is the global mean change. In both cases the changes are based on comparisons with the baseline present state (centered around the year ~2000). The Φ index can be defined at an arbitrary period such as the year when global warming by 1.5°C occurs and indicates how severely the NHL region was influenced by climate change relative to the global average.

The characteristics of the changes in the NHL region may result from climatic and biological factors, which may interact in a complicated way. For simplicity, we assumed that Φ could be expressed as the product of climatic and biological terms as follows:

$$\Phi = \Phi_T \times \Phi_B. \quad (2)$$

Here Φ_T is a temperature amplification factor, and Φ_B is the ecosystem response factor. The term Φ_T is defined as the ratio of temperature warming in the NHL (ΔT_{NHL}) to the global (land and ocean) temperature warming (ΔT_{global}) above pre-industrial temperatures. When $\Phi_T > 1$, the implication is that amplified warming occurred in the NHL. The term Φ_B is defined as the ratio of the change of ecosystem variables NPP ($\Phi_{B\text{-}NPP}$), CVeg ($\Phi_{B\text{-}CVeg}$) or CSoil ($\Phi_{B\text{-}CSoil}$) in the NHL to the corresponding global change. When $\Phi_B > 1$, the implication is that the temperature sensitivity is higher for the carbon variables in the NHL than for the corresponding global variable. By definition and from equation (2), the biological term can be obtained as follows for the case of NPP:

$$\Phi_{B-NPP} = \Delta\ NPP_{NHL}/\Delta\ NPP_{global} \quad (3a)$$
$$= \Phi_{NPP}/\Phi_T. \quad (3b)$$

Note that ΔNPP_{NHL} (% per °C), ΔNPP_{global} (% per °C), and the corresponding terms for CVeg and CSoil were compared during the same period of time to avoid artifacts associated with different levels of atmospheric CO_2 concentrations.

For further assessments, two ancillary analyses were conducted. First, we investigated long-term changes in the NHL ecosystem carbon budget during the extended projection period from 2100 to 2299. This analysis was expected to reveal the minimal response of northern ecosystems because climate warming was suppressed to the target level of the Paris Agreement. Second, to demonstrate an impacts on multiple sectors, we conducted an analysis that took into account permafrost change related with biome change. Thawing of permafrost is a focal problem associated with the NHL warming, because it affects the habitat of natural organisms and human society. Also, permafrost thawing is likely to enhance the decomposition of carbon released from frozen soils and thereby lead to emissions of greenhouse gases to the atmosphere (Schuur *et al* 2015; Burke *et al* 2018). Considering the simulation results of the biome models and future permafrost projection maps (Karjalainen *et al* 2019), we preliminarily assessed the changes in CVeg and CSoil in the areas where existing permafrost might be destabilized in the future.

3. Results

The rate of temperature increase in the NHL by the end of the 21st century is projected to be much higher than the global mean, irrespective of climate model or scenario. The 31-yr running mean of ΔT_{global} exceeded 1.5 °C by ca. 2010 to ca. 2051, depending on the climate model , whereas ΔT_{NHL} exceeded 2.0 °C by the same time (figures 1(a) and 1(b)). As shown in figures 1(c) and 1(d), future temperature rise will occur unevenly over Earth's surface. Most land areas will undergo greater warming than the ocean at similar latitudes, and greater warming will occur at higher latitudes. Remarkably, ΔT_{global} determined by the GFDL-ESM2M under RCP2.6 did not exceed 1.5 °C by the end of the 21st century. Given the close linear relationships between ΔT_{global} and ΔT_{NHL} (figure 1(b)), we estimated Φ_T during the period 1950–2099 to range between 1.81 and 2.31 (on average, 2.07) for all climate projections. Close inspection revealed that the relationship between ΔT_{global} and ΔT_{NHL} was approximately linear, but the slopes of the relationship depended on the scenario; table 1 shows Φ_T values at 1.5 and 2.0°C warming levels .

The eight biome models simulated an increase if NPP under both the 1.5 and the 2.0 °C warming scenarios (figures 2(a) and 2(d)). The magnitude of the change differed between the global and NHL; see figures S3 and S4 for results of individual cases. If ΔT_{global} was projected equal 1.5 °C, global NPP increased by 5.3 – 17.3% (on average, 10.7%) from mid-20th century levels, whereas the NPP of the NHL increased by 12.5 – 38.2% (on average, 22.0%). The biome models consistently (i.e., with high probability) simulated the greatest increase of NPP for a large part of NHL terrestrial ecosystems (figures S5(a), (b) and S6(a), (b)). As a result, $\Phi_{B\text{-}NPP}$ for all models equaled 1.32 ± 0.56 for RCP2.6 and 1.38 ± 0.43 for RCP6.0. The corresponding Φ_{NPP} given by equation (2) equaled 2.18 ± 0.93 and 2.22 ± 0.69, respectively (mean ± standard deviation among the models; see Tables 1 and S3 for median). The differences in simulated results between the two RCP scenarios were small. The relative changes of NPP in the NHL were, on average, more than double the global mean and were attributable to the interplay of climatic and biological factors. The biological factor $\Phi_{B\text{-}NPP}$ became larger under the ΔT_{global} = 2.0 °C scenario; in that case $\Phi_{B\text{-}NPP}$ values were 1.92 ± 0.89 for RCP2.6 and 1.66 ± 0.91 for RCP6.0 (mean ± standard deviation of all models). These increases of $\Phi_{B\text{-}NPP}$ indicated an accelerating sensitivity of NPP in the NHL to global warming.

Similarly pronounced response patterns were also found in the simulated CVeg of the NHL (figures 2(b), 2(e)) when one outlier result by VEGAS was excluded. If ΔT_{global} equaled 1.5 °C, global CVeg increased by 3.9 – 15.2% (on average, 7.3%) from mid-20th century levels, whereas the CVeg of the NHL increased by 8.5 – 30.4% (on average, 21.1%). The fact that the biological factor $\Phi_{B\text{-}CVeg}$ did not change under the ΔT_{global} = 2.0 °C scenario (table 1) indicated an approximately linear relationship between the vegetation carbon stock in the NHL and global warming. The response patterns were clearly different for CSoil. In that case the model simulations differed widely; they ranged from a large increase to a small decrease (figures 2(c), (f)). Regionally, there was little consistency among the simulation cases in West Siberia to Europe and interior North America (figures S5(e), (f) and S6(e), (f)). As a result, the model-ensemble response was close to neutral at both the global and NHL scales (figure S3). This was also reflected by $\Phi_{B\text{-}CSoil}$ which did not differ substantially from 1.0 (i.e. global mean response). The wide range of model-specific $\Phi_{B\text{-}CSoil}$ values (–0.25 to 2.89 among models and scenarios) made it difficult to derive a robust outcome from the present simulations.

The difference in global NPP between the two degrees of warming ($\Delta NPP_{2.0\text{–}1.5}$) was 5.3 ± 3.0% of the pre-industrial NPP, whereas in the NHL, the corresponding model average difference was as large as 18.4 ± 8.9% (average of four climate models under RCP2.6 and RCP6.0; figure 2(d)). The corresponding differences in NHL biomass ($\Delta CVeg_{2.0\text{–}1.5}$) and soil carbon ($\Delta CSoil_{2.0\text{–}1.5}$) were 18.0 ± 9.7% and 1.3 ± 1.8%, respectively (figures 2(e) and 2(f)). These differences were distributed widely and heterogeneously over the land areas (figures 3(a–c)). For example, West Siberia, Northern Europe, and northern North America gained more productivity and plant biomass than other NHL regions under the 2.0 °C warming scenario. The increases of NPP and CVeg were widely distributed, whereas negative effects such as degradation by warming occurred in only a few percent of NHL areas (figures 3(d–f)).

The differences of the biological responses between seasons provided insights concerning the underlying mechanisms and implications for observational detection of the responses. Figure 4 compares the simulated monthly NPPs during the pre-industrial era, and the 1980s, for the 1.5 °C and 2.0 °C warming scenarios. The enhancement of NPP throughout the growing season caused the summer NPP in June–August to increase by about 30% because of enhanced photosynthetic capacity. When ΔNPP_{NHL} was calculated based on comparisons with the 1980s (i.e. the beginning of Earth observations by satellite remote sensing), spring and autumn NPPs were also sensitive to climate variability because of the phenological response of vegetation. However, the absolute magnitude of NPP was low in these early and late growing seasons; therefore the annual change was determined mainly by the summer response.

Extended simulations to the end of the 22nd century (figure S7) highlighted long-term ecosystem responses. Along with stabilization of atmospheric CO_2 concentration and global warming, the biome models simulated gradual changes of biomass and less conclusive changes in soil carbon stocks. The range of variability among the biome models and climate projections was comparable for CVeg but became larger for CSoil in both the global simulations (standard deviation among simulations, from 14.7% in 2100 to 19.9% in 2299) and NHL simulations (from 13.4% in 2100 to 29.2% in 2299). Several models (LPJ-GUESS, LPJmL, and ORCHIDEE) showed a ‘peak-out’ of biomass caused by the overshoot of atmospheric CO_2 concentrations. Also, several models showed continuous (or time-lagged) increases of soil carbon stock, by as much as 10% (i.e. hundreds of Pg C) by the end of the 22nd century. Such gradual responses of terrestrial ecosystems to climate change are important for detecting potential long-term impacts and considering ecosystem adaptation.

Further implications of the impacts simulated by the biome models were revealed by the changes in permafrost areas. Whereas only a tiny area was subject to permafrost destabilization under the RCP2.6 scenario, considerable destabilization was projected to occur over a vast area (2.7 × 10^6 km^2), mainly in southernmost areas where permafrost is sporadic, during the late 21st century under the RCP4.5 and 8.5 scenarios (figure S8(a), red area). Interestingly, in these areas, the LPJmL model, which included a permafrost scheme has simulated declines of CSoil by 2299, whereas other models, which did not represent dedicated permafrost processes, simulated gradual increase of soil carbon.

4. Discussion

The results of this study imply that pronounced changes in NHL ecosystems are likely to occur, because of a combination of the amplification of the temperature rise in the NHL and the higher than global-mean responsiveness of especially NPP and CVeg to increases of temperature and CO_2. The simulated increases of NPP and CVeg as well as the small changes of CSoil, in the NHL at around the near-contemporary warming level of 1.0 °C (figure 2) are consistent with observed changes caused by the ongoing temperature rise. For example, such trends have been apparent as greening of the land detected by satellite remote sensing during the last decades (Zhu *et al* 2016, but see Yuan *et al* 2019 for declining trends of productivity induced by dryness) and other scenario studies with global vegetation models (Scholze *et al* 2006, Sitch *et al* 2008, Gonzalez *et al* 2010, Warszawski *et al* 2013, IPCC 2014). The trend of increasing amplitude of the seasonal cycle of atmospheric CO_2 concentrations in the northern latitudes, which can be attributed largely to enhanced photosynthetic activity of NHL vegetation, is also consistent with the simulated enhancements of NPP and CVeg (Forkel *et al* 2016, Piao *et al* 2018). Moreover, the increase of carbon stocks in northern ecosystems is consistent with the observed long-term trend of the atmospheric CO_2 inter-hemispheric gradient (Ciais *et al* 2019). The simulation results of this study imply that these observed terrestrial trends will continue to some extent at warming levels of 1.5 °C and 2.0 °C.

There are ongoing arguments about whether the NHL and surrounding regions will act as a net carbon sink or a source (e.g. Webb *et al* 2016, Euskirchen *et al* 2017), because processes with conflicting effects are exerting influences on ecosystems simultaneously. For example, winter CO_2 emissions may be underestimated in current estimates and future projections of the NHL carbon budget (Natali *et al* 2019). Several long-term monitoring and experimental warming studies have been conducted to estimate future changes in the localized areas of NHL (Bjorkman *et al* in press). However, the heterogeneous, somewhat inconsistent results of ecosystem responses to a certain magnitude of warming revealed by local field experiments have made it difficult to extrapolate from past observations to the future. The simulated impacts of this study were sometimes inconsistent with typical experimental findings. For example, on the basis of estimates by 98 experts, Abbott *et al* (2016) have stated that total biomass in the Arctic could decrease due to water stress and disturbances such as thermokarst, which are not usually included in the present ecosystem models. Crowther *et al* (2016) up-scaled the results of soil warming experiments and concluded that warming by 1–2°C will lead to serious carbon loss from NHL soils. In contrast, the fact that no clear decline of soil carbon has been consistently found in the future CSoil simulated by ISIMIP2b models suggests that a substantial range of uncertainties remains in the carbon stocks simulation by present biome models (Friend *et al* 2014, Tian *et al* 2015). Vegetation biomass is projected to increase by 32.8 ± 19.2 Pg C and by 63.4 ± 38.9 Pg C under +1.5 °C and +2.0 °C warming scenarios, respectively. These net carbon uptakes are equal to the amount of contemporary anthropogenic CO_2 presently emitted in 3 – 6 years (Friedlingstein *et al* 2019). Such a large carbon sequestration by vegetation may imply a significant mitigation potential that would help achieve the goals of the Paris Agreement.

Whether the ongoing climatic change will cause the NHL to reach a tipping point (e.g. boreal forest dieback and permafrost thawing) is a critical question in NHL areas, even under the low-end warming scenario. The increase of NPP and CVeg simulated in most cases implies: 1) that there is a high probability of enhancement of vegetation activity and a low possibility of extensive boreal forest dieback under both the 1.5 and 2.0 °C warming scenarios (even under the 2.5 °C warming scenario, figure 2(e)), or 2) that none the models used in this study have parameterizations that take into consideration non-linear effects such as shifts in fire regimes, insect outbreaks, and dieback from drought. Indeed, there is recent evidence for an increasing influence and interaction of disturbances such as drought, fire and insect outbreaks due to climate change (Seidl *et al* 2017; Hartmann *et al* 2018). These disturbances could significantly influence the NHL, even if they do not formally cross a tipping point, but thay were not covered in detail by the biome models used here. The passive responses of the regional CSoil to the postulated temperature rises might imply a low possibility of extensive soil destabilization. However, we should note that the models used in the present study did not have an accurate scheme of permafrost dynamics to capture enhanced thawing under global warming. These tipping elements might be triggered on a wide scale when high-end global warming levels are reached, and we should take account of their spatial heterogeneity to detect symptoms of regime shifts. Emergence of tipping elements therefore depends on the responsiveness of impact models, and further model constraints are greatly needed to improve research confidence.

Limitations of the present study should be noted. First, the existing biome models are clearly too immature to predict ecological consequences in detail, although the rather robust outcomes across multiple process-based model simulations presented here still have important general implications. Uncertainties in the simulated carbon stocks have been systematically analyzed previously (Nishina *et al* 2015, Tian *et al* 2015) and a large part of the CSoil uncertainty has been attributed to the variability in biome model properties. Second, this study focused on long-term and broad-scale changes; therefore, it did not explicitly consider the impacts of extreme events and a changing disturbance regime. Extreme weather conditions and associated disturbances (e.g. droughts accompanied with severe wildfires) would have profound impacts on the ecosystem carbon cycle (Reichstein *et al* 2013).

Nevertheless, the in-depth analyses of climatic impacts across different sectors that are achievable by ISIMIP2b gives us many advantages that were demonstrated in this study. Notably, the Φ_T values obtained in this study imply that limiting the global temperature rise to 1.5 °C rather than 2.0 °C should be more effective in the NHL regions than the global mean: i.e. the 0.5 °C reduction of global mean temperature would limit regional warming by 0.7 to 0.9 °C. On the one hand, the difference of the climatic impacts on NPP and CVeg between under the 1.5 °C and 2.0 °C scenarios indicated that mitigation efforts could suppress the impacts of an additional 0.5 °C warming. This possibility is most apparent in the NHL regions. On the other hand, the impacts on CSoil simulated by certain models were insensitive to the degree of warming. In terms of climate policy, the ISIMIP will help us to identify effective mitigation and adaptation options in a more informed manner.

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Tables

Table 1. Amplification factors (definitions in equation 1 and 2) of northern high-latitude lands above 60°N for indicated temperature changes and simulated ecosystem carbon budgets at 1, 1.5, 2, and 2.5°C global mean temperature warming levels predicted by the IPSL-CM5A-LR global climate model. Medians and standard deviations (SD) among the seven* model results are shown.

		1 °C		1.5 °C		2 °C		2.5 °C	
Factors **		Median	SD	Median	SD	Median	SD	Median	SD
Φ_T	RCP2.6	1.42		1.66		1.83			
	RCP6.0	1.47		1.62		1.67		1.85	
$\Phi_{B\text{-}NPP}$	RCP2.6	1.29	0.32	1.19	0.28	1.50	0.60		
	RCP6.0	1.28	0.27	1.24	0.26	1.30	0.41	1.39	0.42
$\Phi_{B\text{-}CVeg}$	RCP2.6	1.54	0.45	1.36	0.18	1.40	0.27		
	RCP6.0	1.47	0.41	1.47	0.17	1.26	0.25	1.26	0.33
$\Phi_{B\text{-}CSoil}$	RCP2.6	0.60	0.48	0.47	0.46	0.51	0.68		
	RCP6.0	0.59	0.46	0.50	0.46	0.56	0.55	0.78	0.93

* VEGAS results were not included because of anomalous behaviors (Table S3 for the result including VEGAS).

** Φ_T: temperature change amplification factor, and $\Phi_{B\text{-}NPP}$, $\Phi_{B\text{-}CVeg}$, and $\Phi_{B\text{-}CSoil}$: biological factor for changes in NPP, vegetation biomass (CVeg), and soil carbon (CSoil), respectively.

Figures

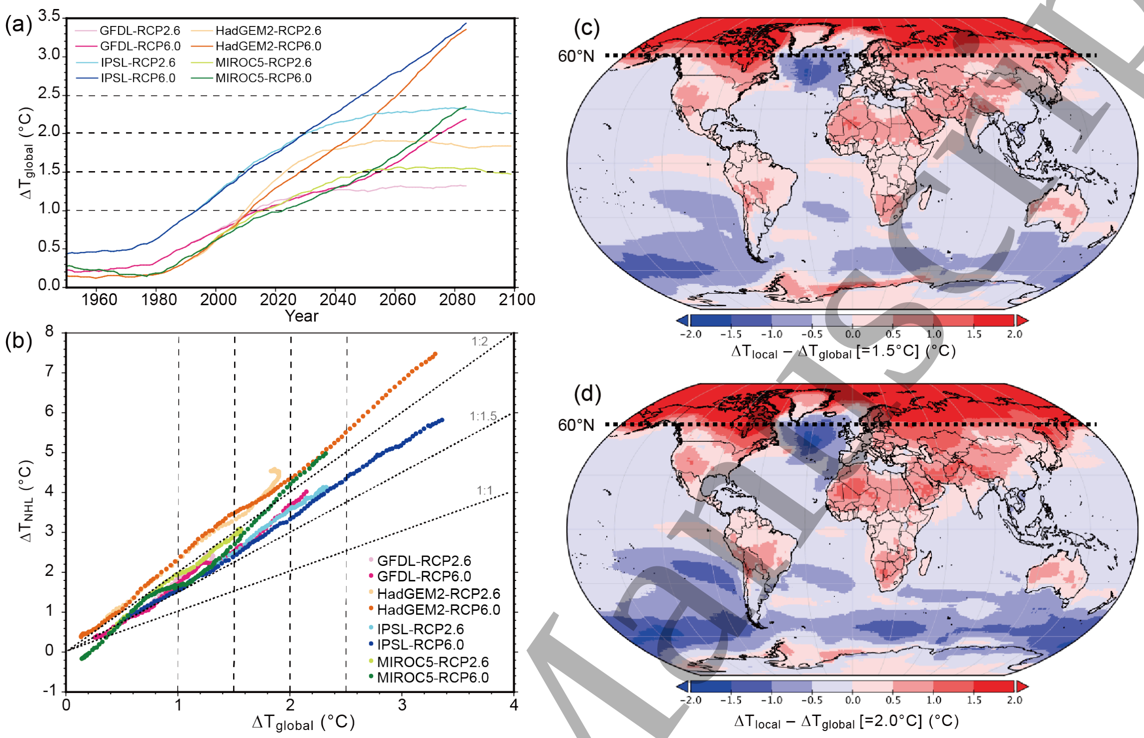

Figure 1. Temperature changes in the climate projections used in ISIMIP2b. (a) Time series of global mean temperature change (ΔT_{global}) relative to pre-industrial levels (mean of 1661–1690 temperatures). (b) Relationships between ΔT_{global} and temperature change in the NHL (ΔT_{NHL}) relative to pre-industrial levels. Distribution of local temperature change in comparison with the global mean temperature change for (c) 1.5 °C and (d) 2.0 °C, respectively, warming scenarios (mean of the four climate model projections with RCP6.0). Red areas have higher warming than the global mean, and blue areas have lower warming. Dashed lines in (c) and (d) indicate 60 °N latitude.

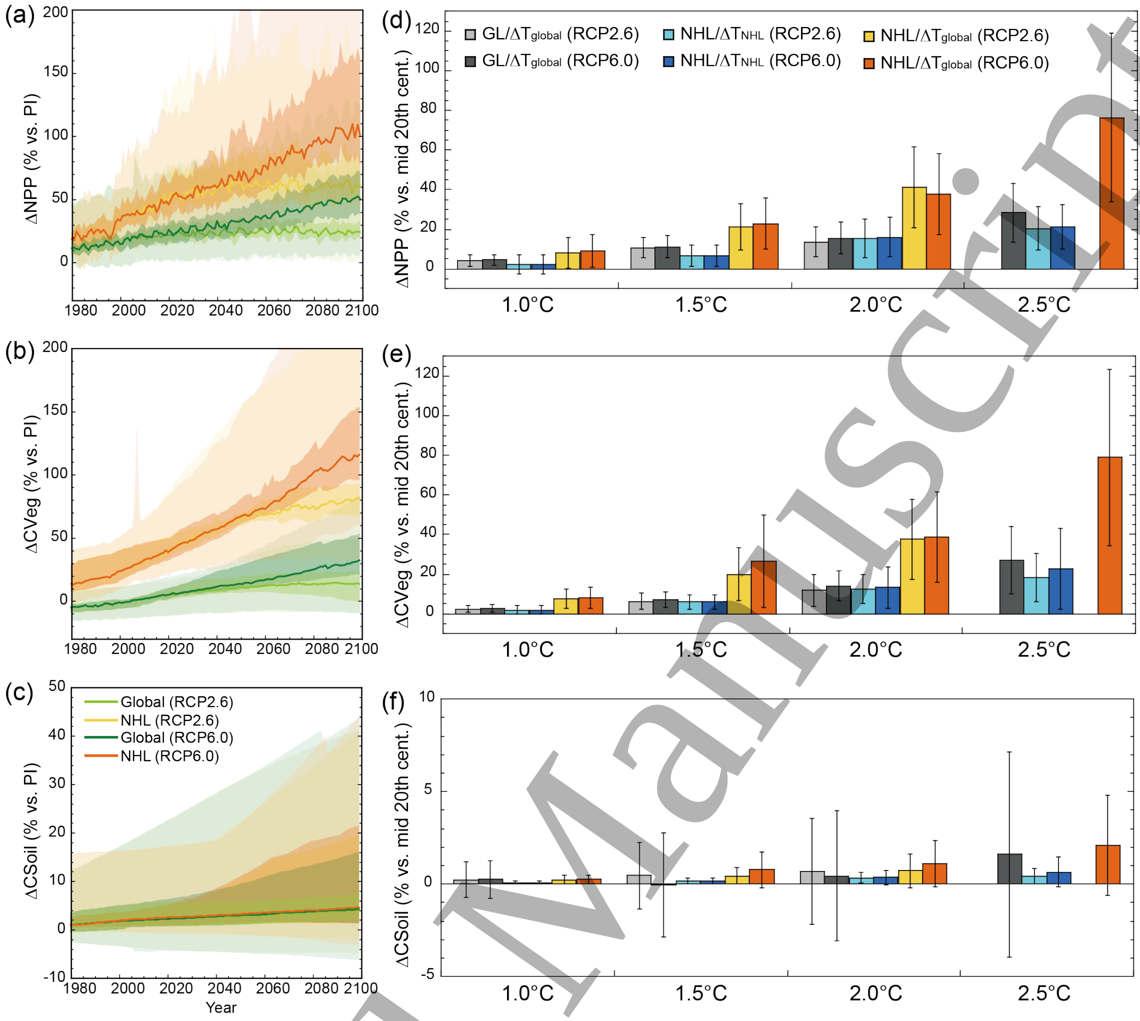

Figure 2. Simulated changes in terrestrial ecosystem carbon budget at global and NHL scales. Time-series of (a) ΔNPP, (b) ΔCVeg, and (c) ΔCSoil by eight biome models driven by four climate-model projections under RCP2.6 and RCP6.0. Aggregated results of (d) ΔNPP, (e) ΔCVeg, and (f) ΔCSoil at warming levels of 1.0, 1.5, 2.0, and 2.5°C for the global (ΔT_{global}) and NHL (ΔT_{NHL}). Error bars show standard deviations among models for the 11-yr period around the year a given warming level is crossed.

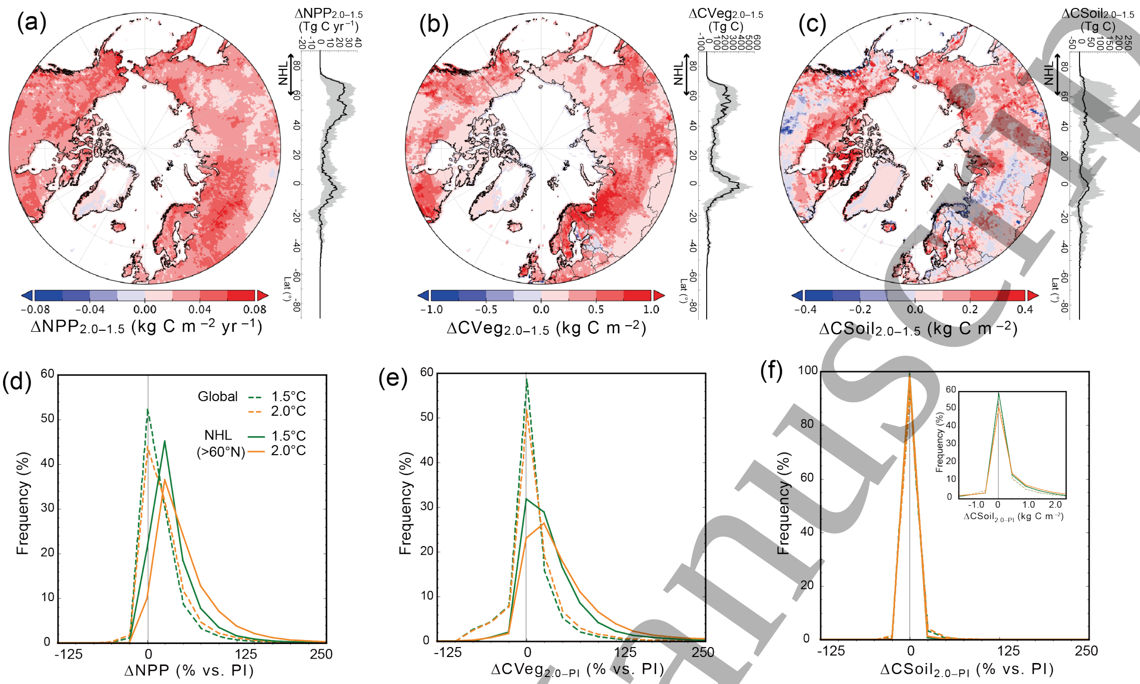

Figure 3. Distributions of the simulated terrestrial carbon budget variables, (a) NPP, (b) CVeg, and (c) CSoil. The differences between results at 1.5 °C and 2.0 °C global warming levels are shown. The line graphs at the right of each map show global latitudinal distributions of the simulated variables. (d, e, f) Frequency distributions of the relative changes (in %) of (d) NPP, (e) CVeg, and (f) CSoil in the global and NHL results at the two global warming levels compared with pre-industrial (PI) conditions. Inset: changes in CSoil, but in units of kg C m^{-2}.

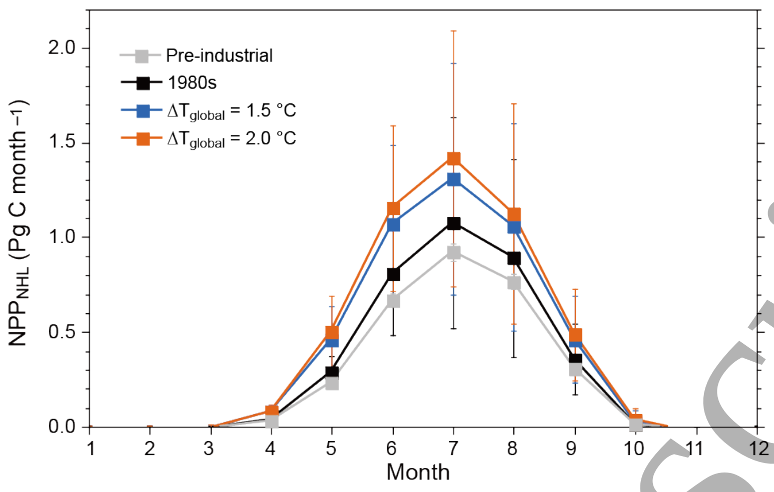

Figure 4. Monthly net primary production (NPP) in the NHL areas simulated by ISIMIP2b models driven by four climate model projections under RCP2.6 and RCP6.0. Mean monthly NPP in the 1980s, when ΔT_{global} reached 1.5 °C (11-yr mean), and when ΔT_{global} reaches 2.0 °C (11-yr mean).