

Dynamics of the larch taiga–permafrost coupled system in Siberia under climate change

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Abstract

Larch taiga, also known as Siberian boreal forest, plays an important role in global and regional water–energy–carbon (WEC) cycles and in the climate system. Recent *in situ* observations have suggested that larch-dominated taiga and permafrost behave as a coupled eco-climate system across a broad boreal zone of Siberia. However, neither field-based observations nor modeling experiments have clarified the synthesized dynamics of this system. Here, using a new dynamic vegetation model coupled with a permafrost model, we reveal the processes of interaction between the taiga and permafrost. The model demonstrates that under the present climate conditions in eastern Siberia, larch trees maintain permafrost by controlling the seasonal thawing of permafrost, which in turn maintains the taiga by providing sufficient water to the larch trees. The experiment without permafrost processes showed that larch would decrease in biomass and be replaced by a dominance of pine and other species that suffer drier hydroclimatic conditions. In the coupled system, fire not only plays a destructive role in the forest, but also, in some cases, preserves larch domination in forests. Climate warming sensitivity experiments show that this coupled system cannot be maintained under warming of about 2 °C or more. Under such conditions, a forest with typical boreal tree species (dark conifer and deciduous species) would become dominant, decoupled from the permafrost processes. This study thus suggests that future global warming could drastically alter the larch-dominated taiga–permafrost coupled system in Siberia, with associated changes of WEC processes and feedback to climate.

Keywords: taiga–permafrost, vegetation model, soil hydrology

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1. Introduction

The world's forests influence planetary energetics, the hydrologic cycle, and atmospheric composition and climate

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through physical and biological processes (Bonan 2008). As one of the largest terrestrial biomes, Siberian boreal forests store huge amounts of carbon in their biomass and soil, and play an important role in climate feedback processes (e.g., lowers surface albedo, masking the high albedo of snow in winter, and large evapotranspiration in summer) (Bonan 2008, Lopez *et al* 2008). Therefore, taiga is thought to play an

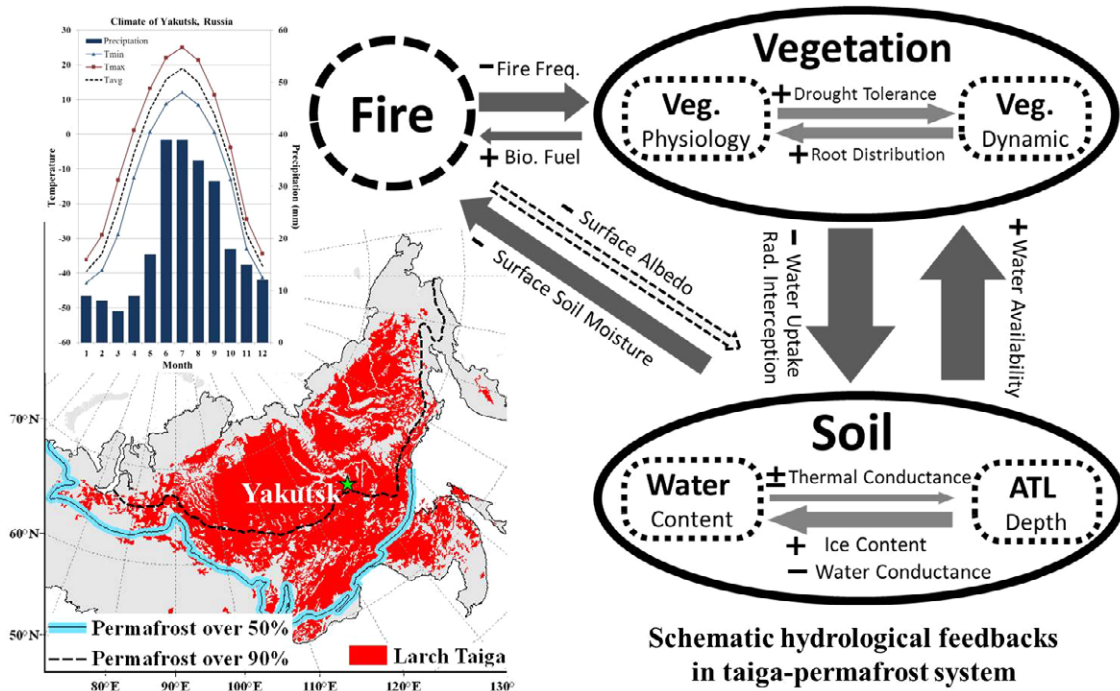


Figure 1. Schematic diagram of feedbacks of soil, vegetation and fire in the Siberian taiga–permafrost system considered in this study (right-side diagram); spatial distribution of larch taiga (left-bottom figure, red area) and boundary of permafrost (left-bottom figure, dashed line and blue line); location (left-bottom figure, green star) and climate of Yakutsk (left-top figure). In the schematic diagram: arrows show force directions between each factor. ‘+’ (‘-’) means the following the forces direction, there is a positive (negative) correlation between two factors, and ‘±’ means the correlation is still not clear. The thicker arrows indicate the processes which were better considered in the model simulation. Dashed arrow indicates the process which is not considered in this study. The words beside each arrow indicate the variables that control such process.

important role in both the global carbon balance (Piao *et al* 2008, Euskirchen *et al* 2006) and regional or continental-scale hydroclimate (Betts 2000, Bonan *et al* 1992, Chapin *et al* 2005, Saito *et al* 2006). Uniquely in eastern Siberia, the distribution of the nearly homogeneous larch-dominated taiga highly coincides with the zones of continuous and discontinuous permafrost (Osawa *et al* 2009, Stolbovoi and McCallum 2002) (figure 1). Unlike other boreal ecosystems, recent *in situ* observations have shown that the larch taiga–permafrost system in Siberia has displayed distinct water–energy–carbon (WEC) exchange characteristics including in its temporal and spatial variations (Tanaka *et al* 2008, Ohta *et al* 2008, Sugimoto *et al* 2002, Maximov *et al* 2008, Ohta *et al* 2001). It suggests that larch has adapted better than other species to the permafrost environment, forming a larch-dominated taiga–permafrost coupled system (Osawa *et al* 2009). Although soil freezing–thawing processes and permafrost have been introduced to a number of vegetation models to improve simulations of fire disturbance, soil respiration, and vegetation dynamics (Beer *et al* 2007, Sato *et al* 2010, Tchebakova *et al* 2009, Wania *et al* 2009), most of these studies focused on carbon exchanges and emphasized vegetation responses to climate variation. In other words, few models have treated ‘larch taiga–permafrost’ as a coupled system in terms of water and energy exchanges, which could be distinctly different from other boreal forest biomes.

2. Methodology

To address this issue, we need to introduce a new scheme that integrates vegetation and permafrost, two major components in the unique taiga–permafrost system, which emphasizes the hydrological feedbacks among these processes (figure 1). Meanwhile, wildfire, as it has strong mutual influence with taiga–permafrost coupled system, is also considered in the scheme (Osawa *et al* 2009) (see supplementary ‘Fire’ available at stacks.iop.org/ERL/6/024003/mmedia). A new dynamic vegetation model DV-FSM, therefore, was developed by coupling two prototype models, vegetation model FAREAST (see supplementary ‘FAREAST’ available at stacks.iop.org/ERL/6/024003/mmedia) (Yan and Shugart 2005, Zhang *et al* 2009, Shuman and Shugart 2009, Shugart *et al* 2006) and frozen soil model FSM (Zhang *et al* 2007). Moreover, we also introduced a new biogeophysical process into DV-FSM in order to simulate the responses of vegetation physiological processes to soil hydrological seasonal and inter-annual variability, which in another sense link the simulation of long-term forest ecological dynamics and short-term soil hydrological processes (see supplementary, ‘Model Description’ available at stacks.iop.org/ERL/6/024003/mmedia). Using the model, this study aimed to prove the importance of the interactions of permafrost and Siberian larch taiga as a coupled system. Meanwhile, we conducted an additional experiment to evaluate the sensitivity of this coupled system to future warming

climate. As a validation of the model experiment, we adopted the observed vegetation–permafrost processes at Spasskaya Pad near Yakutsk in eastern Siberia (Russia), where continuous observations of energy, water, and carbon fluxes of permafrost–vegetation coupled system have been made since 1998 (Ohta *et al* 2008, 2001). We conducted different simulations, all forced by the same 1 year length climate forcing dataset. The dataset is derived from averaged half-hourly observations from 2000–4. Time-integration of 1000 years for each plot-scale simulation started from bare ground condition was repeated eight times and then averaged for broader spatial scale. To clarify the importance of the existence of permafrost for maintaining the Siberian larch taiga–permafrost ecosystem, the following two sets of experiments were conducted.

In the first set of experiments, we introduced four different runs: control run (CNTL, permafrost–vegetation–fire coupled run), no fire run (NF, without consideration of fire disturbance), no permafrost run (NP, without consideration of permafrost effect), and no permafrost and fire run (NPF). In the NP and NPF runs, we kept the soil water freezing–thawing process in the model, but not considering the effect of soil ice blocking the percolation of soil water. This blocking effect was considered to be a unique and essential feature of the permafrost system.

In the second set of experiments, four groups of simulations with different warming intensity were conducted to examine the sensitivity of the taiga–permafrost system to climate warming (see supplementary, ‘Method’ available at stacks.iop.org/ERL/6/024003/mmedia). We set warming intensity of study site to approximate 4.5 °C at the end of the 21st century projected by the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR4). Similar to the previous experiment, each group included two runs in which we turned on/off the permafrost effect. In three groups, summer (JJA) surface air temperature were added by 1.12 °C, 2.25 °C, and 4.5 °C (abbreviated below as, for example, +1.12 °C), respectively, over the original forcing data. In another group, summer surface air temperature of +4.5 °C and precipitation +20% were added to examine the taiga–permafrost sensitivity to precipitation change under the strong warming condition. Hereafter, CNTL_1C represented the control run with temperature of +1.12 °C, and NP_1C was non-permafrost run with temperature of +1.12 °C. Accordingly, CNTL_2C & NP_2C and CNTL_4C & NP_4C represent the runs with temperature of +2.25 °C and +4.5 °C, respectively.

3. Results

The model control (CNTL) run was conducted to reproduce the taiga and permafrost interactions that were observed in long-term field experiments (Osawa *et al* 2009, Ohta *et al* 2008). The model successfully reconstructed the larch-dominated forest in assembled simulation (figure 2) with birch and pine appearing occasionally as sub-dominant or scattered tree species. The simulation result coincides with the *in situ* observation (Osawa *et al* 2009, Ohta *et al* 2008) (also see supplementary ‘Soil Water Content’ available at stacks.iop.org/ERL/6/024003/mmedia) and in the large-scale

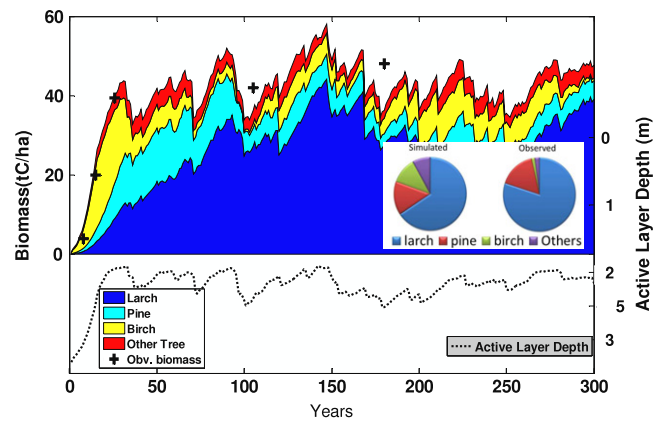


Figure 2. Time sequence of simulated forest succession and ALT of permafrost. Colored areas indicate the assembled simulation of aboveground forest succession from bare ground (first 300 years of 1000 years run); dash line is assembled result of simulated annual maximum ALT; ‘+’ marks are observed aboveground biomass at different forest stages; pies are observed (left) and simulated (right) forest composition.

observation-based semi-empirical model output (Shvidenko *et al* 2007) (figure 2). The modeled fire-return was about 170 year/plot, in accordance with the field observed fire interval of 100–200 years (Shvidenko *et al* 2007, Bonan and Shugart 1989). The model also reproduced well the observed recovering process of forest biomass after fire disturbance (see supplementary, ‘Fire’ and figure 1 available at stacks.iop.org/ERL/6/024003/mmedia). The annual maximum thawed layer thickness (i.e., the active layer is the surficial layer above the permafrost which thaws during the summer (Burn 1998); hereafter abbreviated as ALT) could reach 1.8 m in the model, which is close to the observed depth of 1.5 m. The model also well reflected changes of ALT in accordance with annual aboveground vegetation dynamics and disturbance (see supplementary figure 1 available at stacks.iop.org/ERL/6/024003/mmedia). In the time sequence, ground biomass higher (lower) above intercepts more (less) radiation and therefore shallows (deepens) the ALT depth (figure 2).

To clarify the effect of permafrost on the aboveground vegetation composition and its interaction with soil hydrology, we conducted a model run without permafrost, called the NP run, and compared it with the CNTL run. Although the amount of precipitation in the growing season is very limited (130 mm from May to June in the model forcing data), a wet spring to dry summer soil-moisture pattern appeared in the CNTL run, but in the NP run (see supplementary figures 2(a) and (b) available at stacks.iop.org/ERL/6/024003/mmedia) an overall dry moisture condition appeared in spring through summer. Soil moisture in summer (JJA) of the CNTL run was 3–4% (absolute difference in soil volumetric water content) higher than that of the NP run (figure 4 leftmost square and diamond symbols). Accordingly, throughout the growing season, the CNTL run showed no clear depression in vegetation water uptake associated with the decrease of soil moisture (figure 3(a)). On the other hand, when permafrost was removed (NP run), the model showed less vegetation water

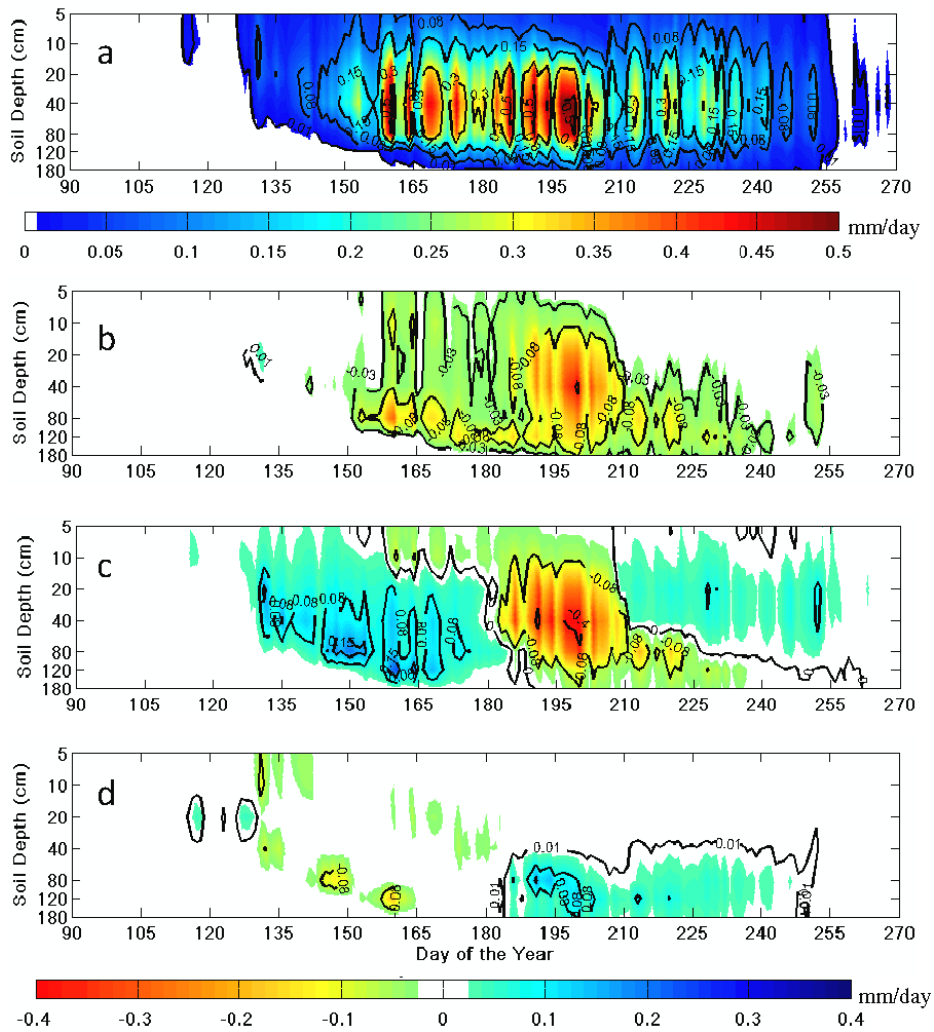


Figure 3. Time sequence of daily vegetation water uptake from different soil depths during the growing season (90–270 days of the year) for (a) CNTL run; (b) difference of NP run from CNTL run; (c) difference of CNTL_4C run from CNTL run; and (d) difference of NP_4C run from CNTL_4C run.

uptake and a resulting soil drought. The decrease in vegetation water uptake was found throughout the summer and peaked in mid-summer, despite the favorable temperature and radiation conditions for vegetation photosynthesis activity. This result suggests that vegetation photosynthesis activities of the taiga–permafrost system might be more vulnerable to mid-summer drought than to the drought occurred in the early growing season.

The above results have proved that the active layer serves as an ‘aquifer’ and the permafrost serves as ‘aquifuge’. To the soil water availability, this ‘aquifer–aquifuge’ system plays a ‘buffer effect’ through which intensive water input (by snow meltwater and summer precipitation) is evened out from early spring over most of the growing season until mid-summer (see supplementary ‘Soil water content’ available at stacks.iop.org/ERL/6/024003/mmedia). By removing the permafrost, incoming water drained much faster because there was no frozen soil to hold the water. For soil moisture, the ‘buffer effect’ was stronger in spring than in summer

due to the shallow ALT and intensive meltwater income (see supplementary figure 2(b) available at stacks.iop.org/ERL/6/024003/mmedia), as for vegetation water uptake. This effect was more obvious in mid-summer than in spring because of the low water supply and high potential vegetation water demand of summer (figure 3(b)). Therefore, the absence of permafrost may lead to a larger summer water deficit.

The inter-seasonal hydrological effect of permafrost may further affect the long-term vegetation dynamics. Model output indicated that the existence of permafrost (CNTL run) helps larch survive the summer drought by providing a continuous supply of water to the top soil layer, whereas the absence of permafrost (NP run) might lead to fatally dry conditions for larch (see supplementary figure 3 available at stacks.iop.org/ERL/6/024003/mmedia). Therefore, in the NP run, larch was eventually replaced by pine and birch as the dominant species, which have more roots in deeper soil and can tolerate extreme drought. Moreover, dry soil induced higher fire frequency in the NP run than in the CNTL run, resulting in a notable

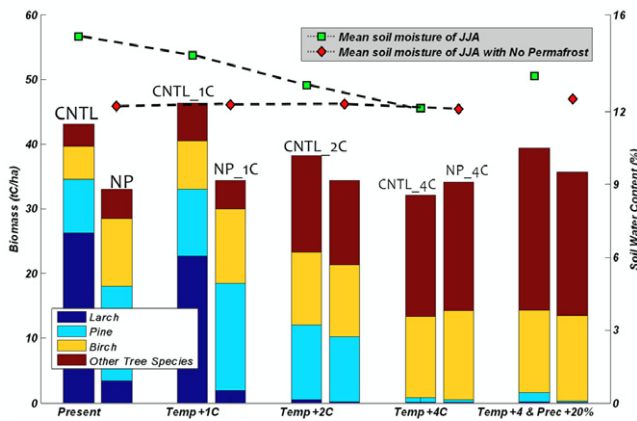


Figure 4. Aboveground total biomass (with fractional components of major species) for CNTLrun (left bar) and NP run (right bar) simulated under five different climate conditions. Five bar groups represent those (from left to right) for the present climate condition; for temperature conditions of +1.12 °C (above the present); +2.25 °C; +4.5 °C, and +4.5 °C plus precipitation +20% (above the present). The name of each experiment was shown on the top of the bar. Two dashed lines in the upper part show changes of summer (JJA) mean soil water for CNTL run (square marks) and NP run (diamond marks), respectively. Note the changes of major species contributing to the total biomass under the different climate conditions.

decrease in aboveground biomass in the NP run (figure 4, leftmost group of bars; see supplementary figure 4 and ‘Fire’ available at stacks.iop.org/ERL/6/024003/mmedia).

The vegetation dynamics and its phenological cycle (i.e., foliation and broadening and falling leaves etc) block radiation to prevent frozen soil from thawing in summer and also suppress the development of other permafrost processes (e.g., thermokarst, soil fluctuation, and thermo-erosion) (Ohta *et al* 2008). The limited ALT in summer, in turn, provides sufficient water for larch trees and lowers the fire frequency to preserve the aboveground taiga composition and its biomass. In this manner, under the present climate condition, the taiga ecosystem is stabilized by coupling with the hydrological process of permafrost. Thus, the taiga (larch)–permafrost system can be interpreted as a self-regulating coupled system.

Is this coupled taiga–permafrost system sustainable under future climate warming? The results of second set of experiments show a drastic change of dominant species and biomass depending on the degree of temperature increase. Under moderate warming (CNTL_1C, figure 4), larch trees were still the dominant species, and aboveground biomass increased. However, under intense warming (CNTL_2C and CNTL_4C), drastic larch extinction occurred, with decreased biomass and decreased soil moisture in mid-summer (figure 4, yellow squares). This drought condition was mainly attributed to the enhanced photosynthesis activity in early summer (figure 3(c)) and advanced thawing processes (see supplementary figure 2(c) available at stacks.iop.org/ERL/6/024003/mmedia), both of which were caused by the temperature increase (see supplementary ‘Warming’ available at stacks.iop.org/ERL/6/024003/mmedia). In contrast, the sensitivity experiments without permafrost (NP_1C, NP_2C,

NP_4C) showed no clear effect of temperature increase on changes in soil moisture and vegetation biomass (figure 4, red diamonds and right bar of each group). These experimental results indicate that the taiga–permafrost coupled system is more sensitive to the future warming compared to the ecosystem without permafrost. Another notable feature under intense warming (+2 °C or more) was the drastic change in biome (forest) composition as well as biomass, as shown in the experiments with the permafrost process (left bars of each experiment in figure 4). The difference between the CNTL_1C and NP_1C run is significant, but less difference between CNTL_4C and NP_4C in terms of forest composition, biomass (figure 4), and soil water uptake (figure 3(d)). This suggests that under intense warming (+2 °C or more), the permafrost effect is drastically weakened, or more realistically, the taiga–permafrost coupled system might no longer exist. However, in the additional experiments, by increasing the precipitation intensity by 20% over the NP_4C and CNTL_4C run, the permafrost effect again came into force (figure 4 rightmost bars), although this precipitation effect was not as remarkable as the temperature effect. That is, the vulnerability of the taiga–permafrost system under future climate conditions depends greatly on the intensity of warming, but additionally on the intensity and temporal distribution of precipitation.

4. Conclusion and discussion

Climate has been considered as the most important driver to control the WEC activities in taiga–permafrost system on large scale. However, in the smaller scale, the lack of a definitive relationship with climate occurs because energy partitioning is strongly controlled by vegetation type and structure rather than directly by climate or latitude (McGuire *et al* 2002, Lopez *et al* 2008). The two sets of numerical experiments using the new dynamic vegetation–frozen soil coupled model have revealed that under the present hydroclimatic condition, the taiga (represented by larch forest) is tightly coupled with the permafrost, forming a taiga–permafrost coupled system. In this system, the permafrost maintains soil water for the taiga by controlling the ALT, while the taiga maintains the permafrost by controlling canopy radiation interception through vegetation long-term succession. Though the active layer seasonal thaw is mainly driven by climate seasonal rotate, its freezing–thawing process may notably controlled (changed) by vegetation dynamic.

The warmer climate runs have shown that this coupled system can be sustained under a temperature increase of about +1 to +2 °C or less. However, under intense warming of +2 to +4 °C or higher, a drastic change of vegetation (extinction of larch and its replacement by other boreal and sub-boreal tree species) is strongly suggested, where the coupling of forest and permafrost would be destroyed or weakened. Moreover, our results have predicted a decrease in biomass and the transpiration rate in mid-summer due to drought conditions in the soil layer under warmer climate (figure 3(c)).

The feedback to climate from the taiga–permafrost system is still not clear. Some modeling studies showed strong continental-scale climate effects through vegetation processes

(Betts 2000, Bonan *et al* 1992, Saito *et al* 2006, Yasunari *et al* 2006) and through soil freezing–thawing processes (Takata and Kimoto 2000), separately. The IPCC-AR4 suggested increasing precipitation in Siberia under the future warmer condition, but none of the models have considered the effects by the taiga–permafrost coupled system in their climate projections. The current study has suggested that decreases in transpiration and biomass might have negative feedback to the regional water cycle, including reduction of precipitation. Future climate prediction studies should, therefore, be conducted incorporating the vegetation–permafrost coupled system demonstrated here, in light of a potentially large impact of this coupled system in the global climate.

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References

- Beer C, Lucht W, Gerten D, Thonicke K and Schmullius C 2007 Effects of soil freezing and thawing on vegetation carbon density in Siberia: a modeling analysis with the Lund–Potsdam–Jena dynamic global vegetation model (LPJ-DGVM) *Glob. Biogeochem. Cycle* **21** GB1012
- Betts R A 2000 Offset of the potential carbon sink from boreal forestation by decreases in surface albedo *Nature* **408** 187–90
- Bonan G B 2008 Forests and climate change: forcings, feedbacks, and the climate benefits of forests *Science* **320** 1444–9
- Bonan G B, Pollard D and Thompson S L 1992 Effects of boreal forest vegetation on global climate *Nature* **359** 716–8
- Bonan G B and Shugart H H 1989 Environmental-factors and ecological processes in boreal forests *Annu. Rev. Ecol. Syst.* **20** 1–28
- Burn C R 1998 The active layer: two contrasting definitions *Permafrost Periglac. Process* **9** 411–6
- Chapin F S *et al* 2005 Role of land-surface changes in Arctic summer warming *Science* **310** 657–60
- Euskirchen E S *et al* 2006 Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems *Global Change Biol* **12** 731–50
- Lopez M L *et al* 2008 Comparison of carbon and water vapor exchange of forest and grassland in permafrost regions, Central Yakutia, Russia *Agric. Forest Meteorol.* **148** 1968–77
- Maximov T, Ohta T and Dolman A J 2008 Water and energy exchange in East Siberian forest: a synthesis *Agric. Forest Meteorol.* **148** 2013–8
- McGuire A D *et al* 2002 Environmental variation, vegetation distribution, carbon dynamics and water/energy exchange at high latitudes *J. Veg. Sci.* **13** 301–14
- Ohta T, Hiyama T, Tanaka H, Kuwada T, Maximov T C, Ohata T and Fukushima Y 2001 Seasonal variation in the energy and water exchanges above and below a larch forest in eastern Siberia *Hydrol. Process* **15** 1459–76
- Ohta T *et al* 2008 Interannual variation of water balance and summer evapotranspiration in an eastern Siberian larch forest over a 7-year period (1998–2006) *Agric. Forest Meteorol.* **148** 1941–53
- Osawa A, Zyryanova O A, Matsuura Y and Kajimoto T 2009 *Permafrost Ecosystems: Siberian Larch Forests* 1st edn (Berlin: Springer) p 502
- Piao S L *et al* 2008 Net carbon dioxide losses of northern ecosystems in response to autumn warming *Nature* **451** 49–U43
- Saito K, Yasunari T and Takata K 2006 Relative roles of large-scale orography and land surface processes in the global hydroclimate. Part II: impacts on hydroclimate over Eurasia *J. Hydrometeorol.* **7** 642–59
- Sato H, Kobayashi H and Delbart N 2010 Simulation study of the vegetation structure and function in eastern Siberian larch forests using the individual-based vegetation model SEIB-DGVM *Forest. Ecol. Manag.* **259** 301–11
- Shugart H H, Shuman J K, Yan X and Zhang N 2006 Eurasian forest cover and climate feedbacks *iLEAPS Newsllett.* **3** 20–1
- Shuman J K and Shugart H H 2009 Evaluating the sensitivity of Eurasian forest biomass to climate change using a dynamic vegetation model *Environ. Res. Lett.* **4** 045024
- Shvidenko A, Schepaschenko D, Nilsson S and Bouloui Y 2007 Semi-empirical models for assessing biological productivity of Northern Eurasian forests *Ecol. Modell.* **204** 163–79
- Stolbovoi V and McCallum I 2002 CD-ROM 'Land Resources of Russia' (Laxenburg, Austria: International Institute for Applied Systems Analysis and the Russian Academy of Science) (available at: www.iiasa.ac.at/Research/FOR/russia_cd/copyr_intro.htm)
- Sugimoto A, Yanagisawa N, Naito D, Fujita N and Maximov T C 2002 Importance of permafrost as a source of water for plants in east Siberian taiga *Ecol. Res.* **17** 493–503
- Takata K and Kimoto M 2000 A numerical study on the impact of soil freezing on the continental-scale seasonal cycle *J. Meteorol. Soc. Japan* **78** 199–221
- Tanaka H, Hiyama T, Kobayashi N, Yabuki H, Ishii Y, Desyatkin R V, Maximov T C and Ohta T 2008 Energy balance and its closure over a young larch forest in eastern Siberia *Agric. Forest Meteorol.* **148** 1954–67
- Tchebakova N M, Parfenova E and Soja A J 2009 The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate *Environ. Res. Lett.* **4** 045013
- Wania R, Ross I and Prentice I C 2009 Integrating peatlands and permafrost into a dynamic global vegetation model: 1. Evaluation and sensitivity of physical land surface processes *Glob. Biogeochem. Cycle* **23** GB3014
- Yan X D and Shugart H H 2005 FAREAST: a forest gap model to simulate dynamics and patterns of eastern Eurasian forests *J. Biogeogr.* **32** 1641–58
- Yasunari T, Saito K and Takata K 2006 Relative roles of large-scale orography and land surface processes in the global hydroclimate. Part I: impacts on monsoon systems and the tropics *J. Hydrometeorol.* **7** 626–41
- Zhang N, Shugart H H and Yan X D 2009 Simulating the effects of climate changes on Eastern Eurasia forests *Clim. Change* **95** 341–61
- Zhang X, Sun S F and Xue Y K 2007 Development and testing of a frozen soil parameterization for cold region studies *J. Hydrometeorol.* **8** 690–701