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GEOGRAPHY

The Long-Term Effect of Ongoing Spruce Decay on Carbon Exchange in Taiga Forests

D. V. Karelin[a,b,*], D. G. Zamolodchikov[b], A. V. Shilkin[c], A. S. Kumanyaev[d], S. Yu. Popov[d], N. O. Tel'nova[a], and M. L. Gitarskiy[e]

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Abstract—The long-term effect of spruce stand decay on the CO_2 balance was studied in the taiga of Valdai (Russia, Novgorod oblast). The CO_2 emission from soil, the respiration of coarse wood debris, the total respiration, and the net fluxes of CO_2 and water vapor were evaluated. In areas of dead spruce forest affected by xylophages and saprotrophs, as well as by windfall, a noticeable decrease in specific gross respiration is absent. This is related to the fact that reduced CO_2 respiration of living trees is compensated by emission from coarse wood debris and a sharp (3- to 3.5-fold) and long-term (no less than six years long) rise in soil respiration (hotspots) under dead-standing spruce trees. The contribution to carbon emission from soil hotspots per unit area in dead spruce stands under dry standing trees is greater than the role of decomposition of coarse wood debris (14.4 and 9%, respectively). The observation period is characterized by a significant decrease in the annual net CO_2 sink in the area studied: from –300 to –95 g C m^{-2} $year^{-1}$, which is followed by reduced evapotranspiration (0.0116 g H_2O m^{-2} s^{-1} in May–October 2018 as compared to 0.0142 g H_2O m^{-2} s^{-1} in the same period of 2010). We assume that the observed decrease in carbon uptake is related both to the reduction in the primary spruce productivity and to an increase in gross respiration from larger areas of decomposed spruce trees. The calculations show that if the area of the dead spruce stands is further increased to 27%, the resulting net balance of the territory will switch to a CO_2 source for the atmosphere. This should be taken into account for remote forecasting.

Keywords: taiga, *Picea abies*, CO_2 efflux from the soil, carbon net balance, deadwood, coarse wood debris, windfall, xylophages, extreme weather events, climate change

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Despite the increasing anthropogenic impact related to land use, forests remain one of the most important regulators of the composition of atmospheric gas and the albedo in the modern biosphere and exert a direct effect on the climate [1]. The tree stand is the most important structural–functional component of forests, including boreal ones, the phytomass of which comprises 14.9% of the world forests [2]. It determines the typical rates of production and decomposition of organic substances in forested areas and the content of organic carbon in soils of the forest ecosystem. Therefore, the effect of climate (including the anthropogenic effect) or the direct anthropogenic impact on the status of trees and, hence, on the carbon balance of forest ecosystems is among the most important problems of the global ecology.

This research is based on a series of long-term (from 2009 to the present time) observations of taiga ecosystems at the Valdai Branch of the State Hydrological Institute of Rosgidromet (Russia, Novgorod oblast, 57°57′43.0″ N, 33°20′19.4″ E, 225.8 m above sea level). The ecosystems studied and the research methods are described in detail in the collective monograph [3]. The area is dominated by overmature high-quality spruce forests on moraine deposits with pine and birch with a maximal tree canopy height of 40 m. The studied area is characterized by numerous windfalls of dry spruce trees, which died in 2010–2013 as a result of attacks by xylophages (*Ips typographus* L in particular) and fungal rot. This is assigned to the last

[a] *Institute of Geography, Russian Academy of Sciences, Moscow, 119017 Russia*
[b] *Center for Problems of Forest Ecology and Productivity, Russian Academy of Sciences, Moscow, 117997 Russia*
[c] *Taifun Research and Production Association, Rosgidromet, Obninsk, Kaluga Region, 249038 Russia*
[d] *Moscow State University, Moscow, 119991 Russia*
[e] *Dubna State University, Dubna, Moscow Region, 141982 Russia*
**e-mail: dkarelin7@gmail.com*

pan-European large-scale loss of spruce trees [4]. The most significant thinning of the tree stand occurred after an abnormal summer drought in 2010, which is often considered as a manifestation of global climate warming [5, 6]. In the period of 2009–2016, the reserve of coarse wood debris on the plot increased by three times, while the pool of living wood decreased from 572 to 312 m^3 ha^{-1} [3].

We have evaluated the effect of increasing degradation of the tree layer on the main parameters of the carbon cycle in the taiga, and on soil emission, gross respiration, and net CO_2 fluxes in particular. The area of the footprint of eddy covariance instrumentation (EC) for measuring CO_2 and water vapor fluxes was used for the evaluation of these parameters per unit area. The height of the equipment location was 42 m above the soil surface and 5 m above the forest canopy; the maximum radius of the footprint under these conditions was 500 m with an area of 0.785 km^2 [3, 7]. The main reserves of wood and aboveground phytomass, as well as the CO_2 fluxes from coarse wood debris (dead wood and dead standing trees) and from the soil, were measured on permanent test plots and transects.

The 11-yr observation period was characterized by an increase of forest area with weakened or dead spruce trees from 5 to 30% and in a rise of CO_2 soil efflux at the sites with forest decline: by 16.5% in 2014 and by 19% in 2017. Additional emission is related to increased carbon dioxide flux from the soil around dead standing spruce trees at a distance of no more than 0.5 m from the stems [8, 9]. This effect is seen one to two years after tree death and remains constant for at least six years. The increase in CO_2 emission near dead-standing trees relatively to inter-stem areas is high and rather constant (3–3.5 times) and does not change much from year to year. The mechanism of this phenomenon is still unclear. It is most obviously related to the increased activity of xylotrophic fungi and to easier gas transportation in the soil in the zone near the trunk base of the dead tree. The release of CO_2 as a result of decomposition of the increasing reserve of dead wood is the second component of the gas emission in the areas of forest decline. The gross respiration (GR) in these areas may include respiration of preserved living trees. We have compared the GR of a forest without dead trees with the GR in areas with a completely dead tree stand. For this, we calculated the main components of the GR, including emission from the soil (with forest litter) under the of dead trees, from coarse wood debris, and from living trees. In areas of forest stand decline with a total flux of 815 ± 24.6 g C m^{-2} $year^{-1}$, the greatest contribution belongs to the soil of the inter-stem areas (76.6%), the second place is occupied by soil zones under dead-standing trees (14.4%), and emission from dead wood (9%) is in the third place. In the unaffected spruce forest, the contribution of respiration of living trees is second after emission from the soil. According to the block model, the total GR flow in the undamaged forest varies within 922.1–970.7 g C m^{-2} $year^{-1}$. In areas with a totally dead forest stand, the impact of emission from debris depends significantly on its amount. According to our estimations, the GR on model plots with the dead tree stand was 1480 g C m^{-2} $year^{-1}$ [3] in 2013. Therefore, the obtained difference between the GR in areas with a dead spruce canopy and a sound spruce forest cannot be considered significant. The decrease in respiration of autotrophs during forest decline is compensated by an equal increase in the respiration of heterotrophs.

It is important for the carbon balance of the forest in general that plots of the dying forest function as carbon source for a long time and occupy a significant area. Their impact over a larger area may be evaluated by the EC method. The comparison of data on the annual net carbon balance during the period of the most active degradation of spruce forests shows that, in 2010–2011, the net balance in the ecosystem was –300 g C-CO_2 m^{-2} $year^{-1}$ (the sink of C from the atmosphere), while in 2018, the sink decreased to –95 g C-CO_2 m^{-2} $year^{-1}$. This was caused not only by an increase in the gross respiration, but also by a decrease in the primary production of weakened spruce stands, which is confirmed by a significant drop in evapotranspiration in May–October of the compared years: 0.0142 ± 0.0003 g H_2O m^{-2} s^{-1} (n = 6475) in 2010 and 0.0116 ± 0.0002 g H_2O m^{-2} s^{-1} (n = 7677) in 2018 (the median test shows that the differences are significant, $p = 0.027$).

Using the EC data from May until October 2010 and 2018, we have compared the mean values of net C fluxes in sectors of wind directions, which include various biotopes. The comparison has shown that the positive correlation between the average net carbon flux and areas under dead standing spruce stands and treeless areas is maximal at a distance within the range from 30–40 to 300–350 m from the EC instrumentation (Figs. 1, 2). This correlation became significant in 2018 ($r_p = +0.77$, $p = 0.026$).

Thus, the increasing weakening and death of spruce trees most likely attributed to modern climate warming have resulted in a threefold decrease in the carbon sink in large areas despite the accompanying regeneration successions. This is related to the preservation of the gross respiration against the background of smaller production. Calculations show that when the area of the total forest decline rises to 27%, the surface under the boreal forest is transformed into a source of CO_2 for the atmosphere. This should be used for remote assessments of the climatic or anthropogenic impacts on the carbon balance of forests.

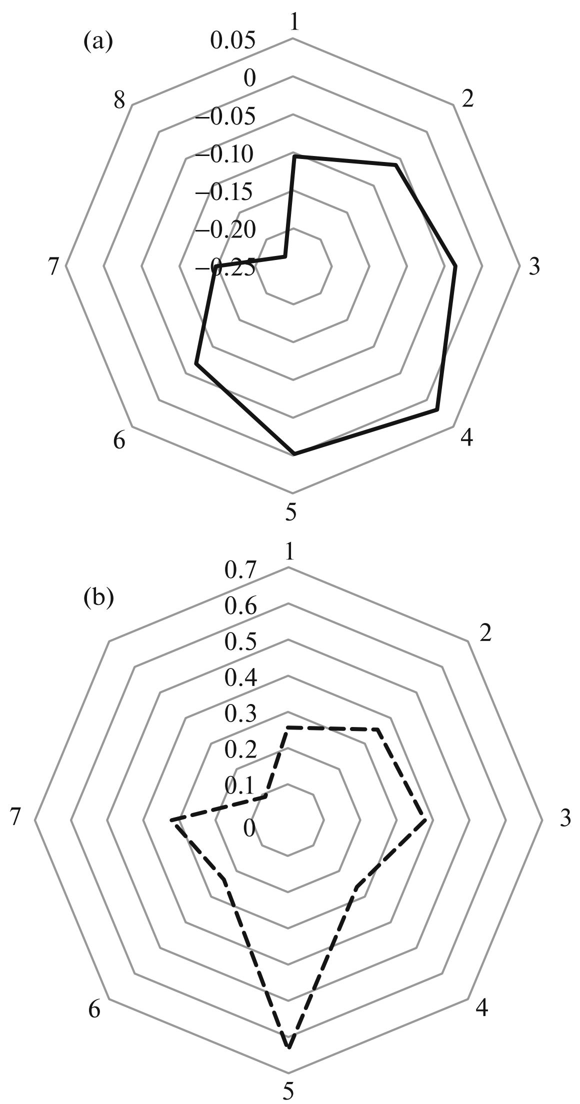

Fig. 1. (A) Mean net carbon flux (mg C-CO_2 m^{-2} s^{-1}, N = 6475) from May till October 2010 and (B)the portion of area occupied by drying spruce stands and forestless areas with respect to wind directions (1, north; 2, northeast; ...; 8, northwest) in the zone from 40 to 300 m from the eddy covariance instrumentation. Negative values of the net flux indicate a sink of C-CO_2 from the atmosphere, and positive values show the source.

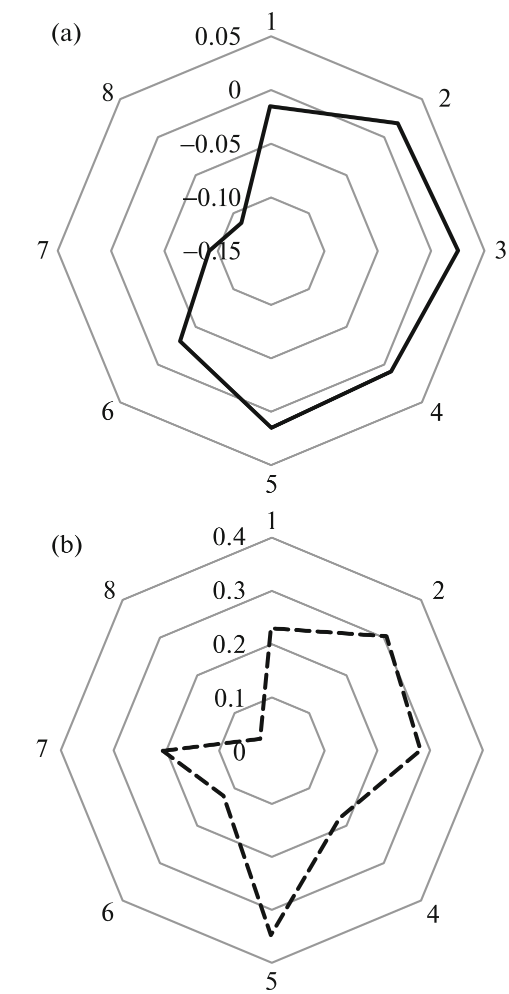

Fig. 2. (A) Mean net carbon flux (mg C-CO_2 m^{-2} s^{-1}, N = 7677) from May until October 2018 and the portion of area occupied by drying spruce stands and forestless areas in the zone from 30 to 350 m from the eddy covariance instrumentation. Negative values of the net flow indicate the sink of C-CO_2 from the atmosphere, and positive values show the source.

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REFERENCES

1. G. B. Bonan, Science **320**, 1444–1449 (2008).

2. Y. Pan, R. A. Birdsey, O. Phillips, and R. B. Jackson, Ann. Rev. Ecol. Evol. Syst. **44**, 593–622 (2013).
3. *Monitoring of Greenhouse Gases Fluxes in Natural Ecosystems,* Ed. by D. G. Zamolodchikov, D. V. Karelin, M. L. Gitarskii, and V. G. Blinov (Amirit, Saratov, 2017) [in Russian].
4. M. Štursová, J. Šnajdr, T. Cajthaml, J. Bárta, H. Šantrůčková, and P. Baldrian, ISME J. **8**, 1920–1931 (2014).
5. V. I. Danilov-Danielyan, Ekol. Zhizn', No. 10, 20–27 (2010).
6. I. I. Mokhov and V. A. Semenov, Russ. Meteorol. Hydrol. **41** (2), 84–93 (2016).
7. D. G. Zamolodchikov, M. L. Gitarskii, A. V. Shilkin, A. S. Marunich, D. V. Karelin, V. G. Blinov, and A. I. Ivashchenko, Fundam. Prikl. Klimatol., No. 1, 54–68 (2017).
8. D. V. Karelin, D. G. Zamolodchikov, and A. S. Isaev, Dokl. Biol. Sci. **475** (4), 165–169 (2017).
9. D. V. Karelin, A. V. Pochikalov, and D. G. Zamolodchikov, Izv. Ross. Akad. Nauk., Ser. Geogr., No. 2, 60–68 (2017).

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