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GENERAL BIOLOGY

Unconsidered Sporadic Sources of Carbon Dioxide Emission from Soils in Taiga Forests

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Abstract—Long-term monitoring in the Russian taiga zone has shown that all known extreme destructive effects resulting in the weakening and death of tree stands (windfalls, pest attacks, drought events, etc.) can be sporadic, but significant sources of CO_2 soil emission. Among them are (i) a recently found effect of the multiyear CO_2 emission from soil at the bottom of deadwood of spruce trees that died due to climate warming and subsequent pest outbreaks, (ii) increased soil CO_2 emissions due to to the fall of tree trunks during massive windfalls, and (iii) pulse CO_2 emission as a result of the so-called Birch effect after drought events in the taiga zone. According to the modeling, while depending on the spatial and temporal scales of their manifestation, the impact of these sporadic effects on the regional and global soil respiration fluxes could be significant and should be taken into consideration. This is due to continuing Climate Change, and further increase of local, regional and Global human impacts on the atmospheric greenhouse gases balance, and land use, as well.

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In the field of global ecology growing attention continues to be focused on the refinement of estimates of the fluxes of carbon dioxide and methane that compose the carbon cycle between the land and the atmosphere due to anthropogenic trends and natural cyclicity of climate [1]. In particular, during the past three decades, it has been possible to identify an increase in net primary production resulting in the increase in leaf area index in 1982–2009 [2] and to detect the increase in global soil respiration at the rate of 0.1 Gt C per year [3] in 1970–2009. These parallel trends of two main carbon fluxes, opposite in direction, are explained by overall response of terrestrial vegetation to the increasing CO_2 concentration in atmosphere [2] and increasing temperature [3]. At the same time, the study of episodic and irregular or small-area components of the atmospheric fluxes of carbon, related mainly to extreme weather or anthropogenic factors whose contribution is evident at small spatial and/or temporal scales, is no less important [4]. Indeed, many of the modern global components of the greenhouse gas fluxes have recently been their small anthropogenic sinks and sources (settlement and mining areas, transportation, arable lands, rice fields, farming, forest fires, etc.).

In this study, based on chamber and eddy covariance measurements in 2009–2016 in the ecosystems of the taiga zone (research site of the VF GGI of the Rosgidromet of the Russian Federation, Valdai raion, Novgorod oblast), we identified three forms of little known impulse (or small in area) components of CO_2 soil emission that can have a broad regional significance.

Additional emission of CO_2 from the soil as a result of pathogenic (climatogenic) dying of the tree stand. During long-term observations of soil CO_2 emission in old spruce stands of southern taiga we discovered a local (within 1–2 m^2 around the trunks) but significant (three times higher than the background rate) and continuous (year-round, no less than five years) increase in the emission in the near-root zone of the dry spruce trees killed by drought and subsequent epidemics caused by the root fungus and xylofagous beetles (Fig. 1). The most likely reason for this phenomenon is activation of pathogenic fungal flora respiration in the rhizosphere of dead roots. The effect found is an additional factor of the significant increase (by 20–25%) of CO_2 emission from soil for spruce forest areas with a collapse of stands at the density of trunks typical for the mature southern taiga. This is important in considering the influence of mass climate-driven windfalls (when roots remain in the ground) or biogenic

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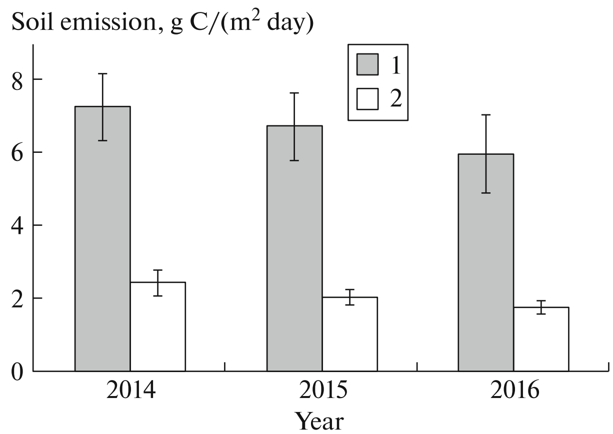

Fig. 1. Changes in (1) the CO_2 soil emission from the areas near trunks of dead spruce trees and (2) the background soil emission level in 2014–2016. We used measurements in the same localities of the sampling plot with decomposition of trees. Observations for April–November; $M \pm m$, $n = 10$ for each locality.

destruction of the tree stand. In Russia, the area of forest stands died off from different causes (fires, windfalls, droughts, pest attacks, etc.) is now about 11×10^6 ha [5].

Pulse release of CO_2 resulting from the so-called Birch effect. This CO_2 emission is characteristic of ecosystems with a pronounced dry seasons. However, our studies have shown that the phenomenon of pulse CO_2 release is much more widespread than it was previously thought, and it can be also observed in humid forest ecosystems in the periods following short-term droughts. In the season of 2010, the first rain (2.3 mm) after 34 days of abnormal drought and heat, which just moistened the upper layer of litter, caused a strong pulsed emission of CO_2 that continued for several hours and exceeded the current level of NEE (Net Ecosystem Exchange, net carbon flux) of the whole spruce forest from of –0.81 to 89.1 g C/(m^2 day). This corresponds to the increase in the night NEE for these days by a factor of 30 (Fig. 2). We attribute this to the Birch effect [6], based on the emergence of available carbon and nitrogen for microorganisms in the moistened soil [7]. The fact that this pulse was caused by soil respiration is confirmed by its proportion in the growing period being changed from 61.6 to 90.2% of Gross Respiration estimated by the night rate of NEE. Furthermore, in our case, this is not the artifact of the influence of precipitation on measured fluxes [8] due to the limitations of the open-path method of eddy covarience technique. Our experiments on the artificial induce of the Birch effect by addition of standard quantities of distilled water to the soil already parched by drought showed similar rates of the pulse emission. The regional input of CO_2 emission from soil due to the Birch effect can be enormous. For example, during the summer anticyclone in 2010 the whole territory of the European Russia was under the influence of the extreme drought. Therefore, according to our calculations, the total additional emissions in 2010 due to the Birch effect could increase the mean annual soil emission in European Russia by 22% (!).

Increase in the soil CO_2 emission in response to the fall of large trunks during windfalls. This phenomenon is the least studied, although windfalls weakening forest stands are common in boreal forests. They start at wind speed exceeding 8 m/s; at wind speed more than 20 m/s, massive windfalls begin [9]. In the season of 2012, we performed the first instrumental recording of CO_2 emission from soil in response to the fall of a large spruce in the period of windfall on August 13–14. This emission (Fig. 3), lasted for at least five days, exceeded fourfold the normal rate of soil CO_2 flux during the growth season. The area of emission corresponded to the area covered with the fallen trunk (10–30 m^2). In this connection, we know now that we should carefully evaluate the results of major seasonal windfalls for estimation of the CO_2 emissions. Most likely, this is due to the physical release of CO_2 from the soil resulting from physical desorption [10] and/or the stimulation of microorganisms due to increased aeration through soil pores, which then leads to depletion of the substrate. This phenomenon should be regarded as an extremely local (tens of square meters), caused by direct impact of tree trunk fall and limited in time (up to several days), as in the case of the Birch effect. Given the subsequent decrease of the emissions below background rate, this effect is likely to be compensated within the annual flux but it can be important at the regional scale in certain periods. For example, during the strong hurricanes in 2009–2010, the areas of complete windfalls in the forest zone of European Russia reached tens of millions of hectares per year [9]. In the period of Global Warming, the area of windfalls increased [11].

The compensation of small components of ecosystem respiration flux at annual balance of carbon evidences against the necessity of taking them into consideration, because additional carbon incoming to the atmosphere by emission is used primarily for local photosynthesis. However, this is true only if intra-annual frequency of such infrequent events is not changing significantly or remains small by area. In particular, the Birch effect depends not only on the genetic characteristics of zonal soils in European Russia, but also on the frequency of summer droughts [12]. The frequency and area of windfalls are directly related to the frequency of extreme (primarily wind) phenomena that are directly proportional to temperature to the fourth power [13]. On the other hand, the rise of temperature leads to weakening of the immunity of a tree stand and its subsequent destruction by phytophagous and pathogenic microorganisms, as well as to change in the local rainfall regime. These

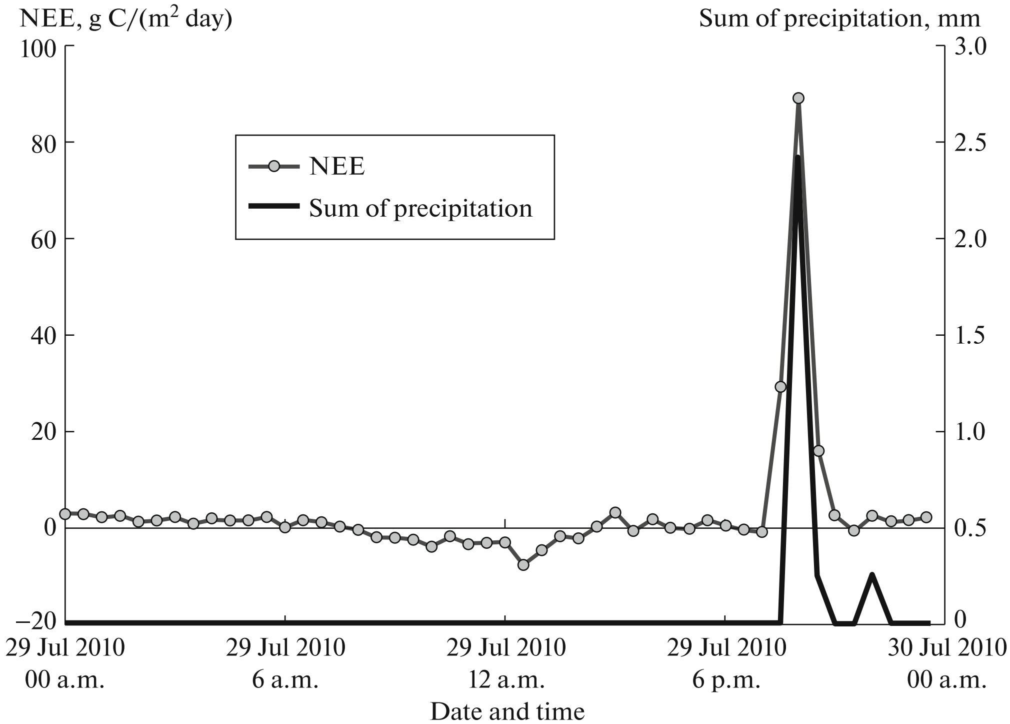

Fig. 2. Pulse emission of CO_2 on July 29, 2010, during 2–3 h resulting from 2.3-mm precipitation after a monthly drought, during which volumetric soil moisture in spruce forest in the layer of 0–6 cm has decreased from 18 to 4% (Taezhnyi Log research station of the Valdai Branch of the State Meteorological Committee of the Russian Federation). Negative values of the net carbon flux designate its sink to the ecosystem from the atmosphere.

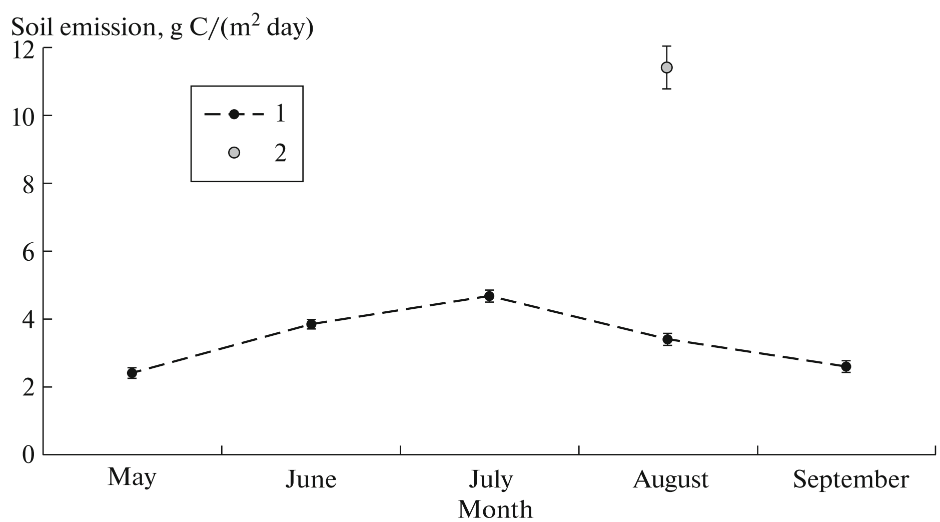

Fig. 3. Variation of the soil emission of CO_2, according to observations in May–September 2009–2012 in the spruce–shamrock forest in southern taiga, Taezhnyi Log research station of the Valdai Branch of the State Meteorological Committee of the Russian Federation. (1) Background mean monthly values and (2) five-day desorption emission of CO_2 caused by a spruce fall during the windfall in August 13–14, 2012; $M \pm m$, $n = 4$–32.

interrelated factors ultimately depend on the growing anthropogenic impact at all scales. In addition, it is important which particular carbon comes from the ecosystem to the atmosphere during year. It may be "older" than the carbon in CO_2 desorbed from the soil as a result of tree falling, or relatively "new" carbon coming to the atmosphere as a result of oxidation of the substance of fresh litter of roots or through acceleration of the carbon turnover of dead microbiota.

Thus, all known external destructive factors resulting in the death of trees: windfalls, attacks of phytophages and microparasites, as well as droughts leading to their weakening, are additional sources of CO_2 accelerating the carbon cycle in boreal forest ecosystems. The contribution of the discussed effects into the Gross respiration flux depend on the spatial and temporal scales of their manifestation, which, in turn, is determined by increasing local, regional, and global anthropogenic impacts and natural climate change.

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