Modeling of the carbon dioxide fluxes in European Russia peat bogs

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Abstract
A process-based model (Forest-DNDC) was applied to describe the possible impacts of climate change on carbon dioxide (CO₂) fluxes from a peat bog in European Russia. In the first step, Forest-DNDC was tested against CO₂ fluxes measured by the eddy covariance method on an oligotrophic bog in a representative region of the southern taiga (56°N 33°E). The results of model validations show that Forest-DNDC is capable of quantifying the CO₂ fluxes from the bog ecosystem. In the second step, the validated model was used to estimate how the expected future changes of the air temperature and water table depth could affect the C dynamics in the bogs. It was shown that a decrease in the water table and an increase in temperature influence significantly the CO₂ exchange between our bog ecosystem and the atmosphere. Under elevated temperature and deepened water table the bog ecosystems could become a significant source of atmospheric CO₂.

Keywords: CO₂ fluxes, eddy covariance flux measurements, Forest-DNDC model, bog ecosystem

Introduction
Carbon balance in mires or paludified peatlands is one of the scientific focuses in contemporary ecosystem studies. Various types of peatland cover about 3.5 × 10⁶ km² of Northern Hemisphere sub-arctic zones, Northern American boreal and Eurasian taiga zones and store 220–460 Pg of carbon (1 Pg C = 10¹⁵ g C; Minayeva et al 2006). This is about 60% of the C pool in the atmosphere and 30% of the total C stored in soils of the world (Joosten and Clarke 2002). Carbon storage in boreal and other northern peatlands is estimated at 114–882 Pg C (Post et al 1982, Armentano and Menges 1986, Gorham 1991, Zoltai and Martikainen 1996). Russia possesses large areas (about 369 × 10⁶ ha) of bogs, which occupy more than 20% of its territory (Vompersky et al 1999). Russian peatlands alone are estimated to contain between 113.5 Pg C (Vompersky et al 1996) and more than 200 Pg C (Botch et al 1995). It is from 20–50% of the carbon stored in the world’s peat. Thus mires and peatlands play a weighty role in the natural carbon (C) balance in Russia. The recent estimation of net primary productivity (NPP) of Russian bogs was about 0.22 tC ha⁻² yr⁻¹ (Shvidenko et al 2001). However, our knowledge about the C dynamics in the peatlands remains relatively poor (Alm et al 1997, Schulze et al 2002). Most investigations connected with the forecasting of global responses of the biosphere to climate change focus on oceans and forests (Fan et al 1998) and the role of peatlands is underestimated (Ramsar Resolution 2006). Unlike many other types of ecosystems, peatlands have the ability to store carbon for long periods of time but their ability to store carbon is being influenced by climate change (Minayeva et al 2006). The investigations have confirmed that peatlands can be a source of CO₂ for the atmosphere during limited periods of time (Alm et al 1997, Arndt et al 2002).
During the past few decades, the eddy covariance method has been widely applied for terrestrial ecosystem studies in many regions of the world. The eddy flux tower networks have produced rich datasets on the net ecosystem exchange of CO$_2$ (NEE) for a number of natural ecosystems at site scale (Valentini 2003). In this method, NEE is defined as the difference between measured gross primary production (GPP) and ecosystem respiration ($R_e$) which consists of the plant autotrophic respiration and the soil microbial heterotrophic respiration. In particular, the long-term measurements of CO$_2$ fluxes carried out with the eddy covariance technique offer an ideal opportunity to quantify C sequestration rates for the terrestrial ecosystems at the local scale. Among the numerous observations across the regions of the world, the bog ecosystems showed significant heterogeneity in NPP or NEE driven by the variability of the local microlandscape within the mires (Alm et al 1997, Talanov et al 2000). However, the relationships between the environmental parameters and the bog responses are so complex that it is hard to reveal the mechanisms controlling the wetland C dynamics solely relying on the observed CO$_2$ fluxes. Process-based models have been developed to fill the gaps in our knowledge (Bohn et al 2007, Kurbatova et al 2008). With detailed physiological, biochemical and geochemical processes embedded in the modeling framework, this kind of model is capable of simulating photosynthesis and various respirations for wetland ecosystems and hence provides an ideal tool for interpreting, integrating and extrapolating field observations. This letter reports a case study on wetland C dynamics by integration of field observations with a modeling approach for a southern European oligotrophic bog in Russia. The main objectives of this letter were (i) to compare the simulated CO$_2$ fluxes with eddy covariance flux measurements especially under a drought and (ii) to predict possible CO$_2$ exchange of oligotrophic bog under temperature and water table changes in future.

1. Site description and field experiments

The experimental site is within the Central Forest State Biosphere Natural Reserve (CFSBNR; 56°27′N, 32°55′E) located in the Southern Valdai area on the main watershed of the Russian Plain. The climate of the area is temperate and moderately continental with an annual mean temperature of 3.8 °C and annual precipitation of 731 mm. The precipitation mainly occurs during the May–September period, accounting for 381 ± 101.5 mm (Minayeva et al 2001). The frost-free period is 111 days on average. In the bogs, the mosses and vascular plants with dicyclic and polycyclic shoots start growing when the mean daily temperature exceeds 0 °C. The growing period of the plants with monocyclic shoots is started when the mean temperature reaches 10 °C.

The bog under investigation (‘Staroselsky Moch’) covers 617 ha including several typical domed bogs, at one of which was located the eddy tower for CO$_2$ flux measurements. The average peat depth at the site is approximately 3.9 m, with a maximum depth of 5.8 m dated to 8900 yr BP. The bog under study has a typical concentric structure with a forested hollow–hummock complex on the top, a non-forested hollow–hummock complex on the gentle southern slope and a typical consequence of Pinus sylvestris oligotrophic communities on the slope.

Measurements of ecosystem CO$_2$ fluxes and associated climatic variables were conducted over three growing seasons of 1998–2000. The eddy covariance system employed at the experimental site consisted of a three-axis sonic anemometer with omnidirectional head (Solent R3, Gill Instruments, Lymington, UK) combined with a closed-path infrared gas analyzer (IRGA; Li-Cor 6262, Lincoln, NE, USA) that was similar to that used in the Euroflux project (Aubinet et al 2000). The anemometer was installed atop a 6 m high aluminum tower. Details of the observation program were provided by Kurbatova et al (2002) and Arneth et al (2002).

For this investigation only the results of eddy flux measurements in the year 1999 were selected. This period was selected because: (i) a number of measurements of CO$_2$ fluxes in 1999 were uninterrupted and continuous and (ii) in 1999 the bog ecosystem was a source of CO$_2$ for the atmosphere that can serve as a good example for describing the response of the bog to elevated temperatures and to a deepened water table in the future.

In general the year 1999 was relatively warm with very changeable weather conditions. Mean annual temperature was about 6.0 °C. Mean daily air temperature ranged from −16 °C in February to 24 °C in June and July. Annual precipitation was about 650 mm, but June and July precipitation was 30.9 and 47.6 mm, respectively, versus 74 and 87 mm for the climatic averages. The level of groundwater was below 25 cm (figure 1). Annual global radiation was relatively high and exceeded 3600 MJ m$^{-2}$ yr$^{-1}$.

2. The Forest-DNDC model

A process-based model, Forest-DNDC (Forest Denitrification–Decomposition model), was used to analyze the impacts of temperature and groundwater level on CO$_2$ fluxes from the bog ecosystems at the experimental site. Forest-DNDC (www.dndc.sr.unh.edu) is a computer simulation model of water, carbon and nitrogen exchange for forest and wetland ecosystems and hence provides an ideal tool for interpreting, simulating photosynthesis and various respirations for wetland ecosystems. This kind of model is capable of biochemical and geochemical processes embedded in the modeling framework, hence it can be used to analyze the impacts of temperature and groundwater level on CO$_2$ fluxes from the bog ecosystems at the experimental site. Forest-DNDC (www.dndc.sr.unh.edu) is a computer simulation model of water, carbon and nitrogen exchange for forest and wetland ecosystems.
3. Model simulations

In our study, first of all Forest-DNDC was tested against a dataset obtained with the eddy covariance method at the experimental bog site during the field campaigns in the year 1999 (figure 2). In the test run, actual weather data, soil properties and vegetation conditions at the site were used as input data. Daily weather data (i.e. maximum and minimum air temperatures, precipitation and radiation) were collected from the nearest climatic station located in the territory of CFSBNR, about 5 km from the experimental site. The validated model was then applied to estimate the impacts of temperature and water table changes on CO₂ fluxes. The simulated soil profile is 1.5 m deep and contains peat organic matter. The bulk density of peat soil is 0.1 g cm⁻³, porosity 0.8, field capacity 0.35 and wilting point 0.2 as water-filled porosity. The total C content in the 1.5 m soil profile was 313 300 kg C ha⁻¹. The vegetation consisted of mosses (3000 kg C ha⁻¹) and vascular plants (sedge) (3000 kg C ha⁻¹). The set of physiological parameters for moss and vascular plants is listed in the table 1. The water table data measured at the bog site in 1999 were used as input data for model calculations.

To describe the possible response of the peat bog to possible future changes of the air temperature and moistening conditions five alternative scenarios assuming a decrease of the water table depth by 10 or 20 cm and an increase of the air temperatures by 2 or 4 °C were generated (figures 2–4). Air temperature and water table depth are key parameters influencing the carbon budget of the peat bogs. Moreover, a choice of these scenarios is based also on the hypothesis that proposed future warming will be accompanied by an increase in the frequency of extreme weather events including droughts in the European part of Russia.

4. Results and conclusions

Figure 2 and table 2 present the measured and modeled daily NEE fluxes for the growing season of 1999. The patterns and
magnitude of the modeled daily NEE fluxes were basically in good agreement with observational data. However, comparison of modeled and observed results has showed that the model has a significant high bias in the months April–July and a low bias in the months August–October. The discrepancy shown in the pattern of monthly NEE fluxes (figure 2) was caused by the phenological parameters adopted for the simulated species, moss and vascular plants. It is connected with the absence of field-measured physiological or phenological data to support parameterization of the wetland plants, so the set of values of photosynthesis efficiency, maximum photosynthesis rate, minimum, maximum and optimum temperature for photosynthesis, etc (see details in table 1) from the available literature sources was used. As these parameters explicitly control the relation between plant photosynthesis and air temperature, the bias of the parameters would certainly have affected the modeled seasonality of photosynthesis. Equipped with the roughly estimated parameters, the photosynthesis rates were apparently underestimated for the months May–July and overestimated for the months August–October in comparison with observations.

Both the measured and modeled daily NEE fluxes showed a clear dependence of NEE on weather conditions including air temperature and soil moisture in 1999 (Arneth et al 2002). The modeled seasonal pattern of NEE fluxes is in relatively good agreement with observational data. Minimal NEE is observed in May. It is in good correspondence with uptake CO$_2$ from the atmosphere. Maximal values of NEE (the bog is the source CO$_2$ for the atmosphere) are observed in July, in the period with the lowest water table depth and maximal air temperatures. The highest loss of CO$_2$ occurred in 1999 in the period with the lowest precipitation and with the groundwater below 20 cm.

Modeled photosynthesis, plant autotrophic respiration and soil heterotrophic respiration of the bog ecosystem during the measurement period (27 March–19 November in 1999) were 1992, 1212 and 1065 kg C ha$^{-1}$, respectively. The seasonal patterns of heterotrophic soil and autotrophic plant respirations are quite similar, except at the end of spring and autumn. In April and October the heterotrophic respiration is significantly larger than autotrophic respiration whereas in summer it is, in contrast, smaller. Such dynamics may be explained by the phenology of bog vegetation. The modeled NEE flux for the same time period was 284 kg C ha$^{-1}$ and it is comparable with the observed NEE flux, 258 kg C ha$^{-1}$.

Simulation results obtained under the alternative scenarios showed that both increasing temperature and decreasing water table depth can have a significant impact on NEE fluxes. Increase of the air temperature by 2 or 4 °C results in increasing the annual NEE flux from the bog ecosystem from 432 to 876 or to 1429 kg C ha$^{-1}$, respectively (figure 4). Decrease in the water table depth by 10 or 20 cm can increase the annual NEE flux from the ecosystem from 432 to 1040 or 1577 kg C ha$^{-1}$, respectively (figures 3 and 4). If the air temperature increased by 4 °C meanwhile the water table depth decreased by 20 cm and the annual NEE flux from the bog increased from the present 432 to 3828 kg C ha$^{-1}$ (figure 3).

Russia has large areas located at high latitudes with various wetland ecosystems, which contain long-term accumulated organic carbon in the soil profiles and which are highly vulnerable to climate change. Temperature and water table depth are two major factors that directly link the soil C dynamics to climate change. In this study, we investigated a rich dataset of CO$_2$ fluxes measured in an oligotrophic bog in European Russia to test a process-based biogeochemistry model, Forest-DNDC, and then we used the model to estimate the possible impacts of changes in air temperature and water table depth on the C dynamics in the bog ecosystem. The modeled results were encouraging, with positive output from the validation tests as well as the predicted impacts of climate change on the seasonal pattern of CO$_2$ fluxes from the tested site. The results showed that the water table depth and air temperature could play a key role in C gain or loss in wetland ecosystems such as the bog ecosystem reported in this study.

**Table 2.** Monthly modeled fluxes in kg C ha$^{-1}$ m$^{-2}$: NEE, photosynthesis (GPP), plant autotrophic respiration (Ra) and soil heterotrophic respiration (Rh) at the bog in 1999. The ‘−’ corresponds to uptake of CO$_2$ from the atmosphere.

|        | Apr     | May     | June    | July    | Aug     | Sept    | Oct    |
|--------|---------|---------|---------|---------|---------|---------|--------|
| NEE    | 29.4    | −48.7   | 53.8    | 182.3   | 21.3    | −7.37   | 41.65  |
| GPP    | 0.82    | 176.8   | 567.7   | 621.3   | 391.2   | 191.1   | 41.4   |
| Ra     | 1.38    | 93.45   | 377.6   | 404.9   | 210.5   | 98.1    | 24.7   |
| Rh     | 28.9    | 34.7    | 244.0   | 398.6   | 202.0   | 85.6    | 58.4   |

**Figure 3.** Impact of water table and temperature changes on NEE fluxes from the bog ecosystem.

**Figure 4.** Impact of water table change on NEE fluxes from the bog ecosystem.
study. To upscale such a prediction to regional scales, the researchers would need to put more effort into the fusion of biogeochemical modeling with hydrological studies.

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