Effects of climatic changes on carbon dioxide and water vapor fluxes in boreal forest ecosystems of European part of Russia

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Abstract
Effects of possible climatic and vegetation changes on H\textsubscript{2}O and CO\textsubscript{2} fluxes in boreal forest ecosystems of the central part of European Russia were quantified using modeling and experimental data. The future pattern of climatic conditions for the period up to 2100 was derived using the global climatic model ECHAM5 (Roeckner et al 2003 The Atmospheric General Circulation Model ECHAM 5. PART I: Model Description, Report 349 (Hamburg: Max-Planck Institute for Meteorology) p 127) with the A1B emission scenario. The possible trends of future vegetation changes were obtained by reconstructions of vegetation cover and paleoclimatic conditions in the Late Pleistocene and Holocene, as provided from pollen and plant macrofossil analysis of profiles in the Central Forest State Natural Biosphere Reserve (CFSNBR). Applying the method of paleoanalogues demonstrates that increasing the mean annual temperature, even by 1–2°C, could result in reducing the proportion of spruce in boreal forest stands by up to 40%. Modeling experiments, carried out using a process-based Mixfor-SVAT model, show that the expected future climatic and vegetation changes lead to a significant increase of net ecosystem exchange (NEE) and gross primary productivity (GPP) of the boreal forests. Despite the expected warming and moistening of the climate, the modeling experiments indicate a relatively weak increase of annual evapotranspiration (ET) and even a reduction of transpiration (TR) rates of forest ecosystems compared to present conditions.

Keywords: SVAT model, H\textsubscript{2}O and CO\textsubscript{2} fluxes, boreal forest ecosystem, climate and vegetation changes, paleoclimatic reconstructions

Introduction

Most scenarios of future climate changes assume a significant increase of global air temperature within the next century, mainly due to increased concentration of greenhouse gases in the atmosphere. The expected warming will be accompanied by changes in precipitation and solar radiation regimes, as well as by an increase in the frequency of extreme weather events (IPCC 2007).

It is obvious that such changes may have a significant impact on forest ecosystems in different latitudinal zones. They could result in changes of tree species dominance and...
diversity, the seasonality of biotic and abiotic processes and events, the structure of plant communities, net primary (NPP) and net ecosystem productivities (NEP), carbon and nutrient cycling, ET and water-use efficiency.

Since the expected climatic changes will be significantly larger in areas with polar and temperate climates than e.g. in tropics, a boreal forest community will obviously be more strongly affected by climate warming than forests in other latitudinal zones (e.g. Prentice 1992, IPCC 2007). The greatest vegetation changes may occur at the southern boundary of the boreal forest zone, where coniferous trees are likely to give way to broadleaf species (Velichko et al 2004).

To predict the possible impacts of these vegetation changes on the water and carbon budgets of the land surface, complex experimental and modeling studies are obviously required. A global FLUXNET network provides measurements of CO2, H2O and energy fluxes between the terrestrial ecosystems and the atmosphere (Baldocchi et al 2001, Valentini 2003) allowing us to determine flux differences between various forest types, and to validate and parameterize the soil–vegetation–atmosphere transfer (SVAT) models. Falge et al (2002) made a comparative analysis of NEE of CO2 for several forest types in the different climatic zones and found that the length and timing of the growing season are very important factors in explaining differences in the CO2 exchange of ecosystems. Comparisons of GPP and NEP of various forest ecosystems showed a relatively large variability even between forests of the same latitudinal zone. The mean differences between GPP and NEP of CO2 of temperate coniferous and temperate broadleaf forest ecosystems were found, however, to be relatively small (Valentini 2003). Analysis of spatial and temporal patterns of H2O fluxes at FLUXNET sites also indicates their very large spatial heterogeneity (Wilson et al 2002). Mean daily H2O fluxes in broadleaf forest ecosystems are somewhat larger than in boreal and temperate coniferous forests. The Bowen ratios range between 0.5 and 1.0 for coniferous forests, whereas for deciduous forests they did not exceed 0.6–0.7.

The very high variability of H2O and CO2 fluxes between forest sites (including forests of the same forest zone) makes it very difficult to obtain an accurate estimation of the possible effects of vegetation changes on H2O and CO2 fluxes. However, these data can be used for validation and calibration of SVAT models that may be very effective tools for climate and vegetation change studies. During the last decades many SVAT models of varying degrees of complexity and temporal (e.g. hour, day, month, year) and spatial (e.g. ecosystem, region) scales were developed and applied (e.g. Sellers et al 1997, Pitman and Henderson-Sellers 1998). The complexity of the applied SVAT model should be closely dependent on the required temporal and spatial resolution, as well as on the regional and local features of forest stands. For estimations of the possible impact of changes in vegetation and tree species composition on H2O and CO2 fluxes, applied SVAT models should be sophisticated enough to take into account both the individual structure of different tree species in a forest stand and their individual responses to environmental changes. The models have to be able to describe both total ecosystem fluxes and flux partitioning between tree species and canopy layers.

To describe possible dynamics of the vegetation cover, paleoclimatic and paleoenvironmental reconstructions of the past epochs are used as analogues for future projections. Nowadays, many global and regional paleoclimatic reconstructions have been compiled for various warming and cooling periods of the Late Pleistocene and Holocene (Velichko 2002). Two situations, assuming increases of global temperature by 1 and 2 °C, are usually considered to describe the proposed global warming in the XXI century. According to data of paleogeographic investigations, the thermal maximum of the Holocene (about 6–5.5 ka BP) corresponds well to the first situation; the optimum of the last Interglacial (Mikulino–Eemian–Sangamon, stage 5e of the deep-sea oxygen curve, about 125 ka BP) period that could be considered as a paleoanalogue for the second one (Velichko et al 2004).

Within the framework of this study, effects of species composition on CO2 and H2O fluxes of boreal forest ecosystems will be analyzed using a process-based one-dimensional SVAT model Mixfor-SVAT (Oltchev et al 2002). The key scientific questions of this study are to estimate: (i) what kind of vegetation changes in the boreal forest zone may be occurring due to modern climatic changes, (ii) how sensitive are the main components of CO2 and H2O fluxes of boreal forest ecosystems to changes of climatic parameters and tree species composition, and (iii) what are the possible trends of the CO2 and H2O flux changes for the period up to 2100.

1. Study area

The area selected for the study is located in the CFSNBR (56°30’N, 325°0’E), in the southern part of Valday hills in Russia, at the watershed of two large European rivers: the Volga (flowing into the Caspian Sea) and the Daugava (flowing into the Baltic Sea). The relief of the area is characterized by a relatively flat topography with gentle slopes that usually do not exceed 2–4°. The area elevation varies between 230 and 270 m above sea level. High precipitation and clay soils with low hydraulic conductivity result in intensive processes of paludification of this territory. The climate is temperate, and moderately continental with an annual precipitation of 700 mm, a mean annual temperature of 3.8 °C and average temperatures in January and July of −10 °C and 17 °C, respectively. The vegetation cover of the CFSNBR is represented by a primary boreal forest of the southern taiga type. Boreal forest stands are composed mostly of Norway spruce with some admixture (~5%) of broadleaf species (lime, elm and maple) in drier habitats. The secondary deciduous forests (birch and aspen) cover about 40%, black alder—1–2%, mires—6% and swamp pine forests—10% of the area.

2. Paleoenographical data

The paleoenvironmental reconstructions in the CFSNBR are based on pollen, plant macrofossil and radiocarbon data from several profiles of both buried organic sediments and modern raised bogs (Novenko et al 2008, 2009). Palynological studies of 40 surface samples in the different plant communities of the CFSNBR have shown that the percentage composition of the
main components of pollen assemblages describes the type of plant cover well for the study area. The proportions of spruce, lime and elm in the forest stands were underrepresented, while the amount of pine and birch there was strongly overrepresented. It was assumed that the share of tree species in the forest stand is linearly dependent on its pollen amount in a spore–pollen spectrum (Grichuk and Zaklinskaya 1948). The coefficients of proportionality in the linear model were: 2.7—for spruce, 2.8—for lime, 3.8—for elm, and 0.1—for birch.

The quantitative characteristics of the Holocene climate (temperature of warmest and coldest months, mean annual temperature and precipitation) were calculated using the information-statistical method developed by Klimanov (1984). The temperatures of the last Interglacial (in January and July) were reconstructed by Grichuk’s method of climagrams (Grichuk 1985).

The paleobotanical records of the buried organic deposits indicate that broadleaf forest dominated by oak and elm, with the participation of lime, maple and ash and a high proportion of hornbeam were widespread over the study area in the warmest phases of the Mikulino (Eemian) Interglacial. Nuts of European hornbeam (it is absent in the modern flora in the territory) and remains of numerous thermophilic water plants have been found there (Novenko et al. 2008). In the optimum of the interglacial the January temperature exceeded the present temperature by 5–8 °C, and for July—for 2–4 °C. During the second half of warm period, the gradual cooling and moistening of the climate resulted in the development of dark-coniferous forest communities.

Since 8000 14C years BP the area of the CFSNBR has been characterized by a rapid expansion of mixed coniferous broadleaf forest with oak, lime, ash and elm. In the middle Holocene the environmental conditions were the most favorable for warm-demanding tree species, the proportion of elm reached 30–40% and proportion of lime was about 10% (figure 1). The proportion of spruce did not exceed 10% in the middle Atlantic warm phase (6000–5500 14C years BP) and only increased to 20–40% in the latest cold phase (5500–4500 14C years PB). The Holocene optimum was followed by a gradual cooling and moistening of the climate resulting in a greater abundance of spruce (up to 60–80% in forest stands) (Novenko et al. 2009).

The climatic reconstructions based on pollen records suggest a significant temperature fluctuation in the late glacial and the early Holocene (in time interval 12000–8000 14C years BP). Several warming periods in the second part of the Holocene have been identified: Late Atlantic (4800–4500 14C years BP), the Middle Subboreal (at c. 3500 14C years BP),
Early Subatlantic (at 2500 $^{14}$C years BP) and the Mediaeval Warm Period (MWP, IX–XII centuries). The cooling of the Little Ice Age, LIA (XV–XVII centuries) is also well manifested in the trend of January temperatures.

The climate of warm periods is characterized mainly by an increase in winter temperatures of 1–4 $^\circ$C above modern values. The mean annual and summer temperatures exceeded their present values by 1–3 $^\circ$C. Precipitation amounts were 600–800 mm year$^{-1}$ (close to modern climate). Pollen data indicate that during the Middle Subboreal and the Early Subatlantic warm phases the role of the spruce was significantly reduced by 40–50%, while broadleaf trees and birch became more abundant (figure 1). The MWP was characterized mainly by spreading of secondary birch forests, probably induced by human impact. During the cold phases the share of spruce was raised up to 80–85%. The cooling in the LIA, together with human impact, resulted in the disappearance of oak and in a significant reduction of the elm and lime populations in the CFSNBR.

3. Model description

Mixfor-SVAT is a one-dimensional process-based SVAT model for the description of the energy, $H_2O$ and $CO_2$ exchange between vertically structured mono- and multi-specific forest stands and the atmosphere (Oltchev et al. 2002, Oltchev et al. 2008a). The main concept used in the Mixfor-SVAT model is an aggregated description of the physical and biological processes in a forest ecosystem on different spatial scales: individual leaf, individual tree and entire ecosystem. For the description of the different scale processes Mixfor-SVAT uses both species specific and species averaged input parameters. For description of the processes occurring inside an individual leaf or tree (e.g. TR, water uptake, precipitation interception (IP), water storage, photosynthesis, respiration) the model uses individual species specific input parameters. For description of exchange processes between different tree species within each sub-layer, as well as for description of the processes at the ecosystem scale (e.g. turbulent exchange, radiative transfer) the model uses species averaged parameters. This approach allows the description of both entire ecosystem $H_2O$ and $CO_2$ fluxes, and also flux partitioning among different tree species and canopy layers in the forest stand.

The main assumptions of the model are that all trees of the different species are evenly distributed over the homogeneous ground surface area (at least 1 ha), and there are no differences between trees of the same species (i.e. each tree of the same species is characterized by the same height, LAI, PAI, root depth, biophysical properties of the leaves, etc and these parameters may differ from properties of other tree species in the forest stand). Also, horizontal advection of energy, water and $CO_2$ through the boundaries of the modeled forest plot is not taken into account. The required meteorological information is hourly air temperature and humidity, wind speed, global radiation, precipitation rate and $CO_2$ concentration data at some height above the forest canopy.

For modeling of the leaf stomatal conductance for each tree species and each canopy sub-layer, Mixfor-SVAT uses a modified multiplicative empirical approach suggested by Jarvis (1976). Leaf water stress is derived taking into account water potentials of the stem water storages of individual tree species, their xylem conductivity and soil moisture. For modeling of the net photosynthesis of the leaves for each tree species and each canopy sub-layer, a Farquhar approach (Farquhar et al. 1980, 2001) is used.

Mixfor-SVAT was validated using long-term results of flux measurements in two unmanaged boreal forest ecosystems in the CFSNBR and agreed well with annual and daily patterns of modeled and measured fluxes, especially for periods with well developed turbulent conditions (Oltchev et al. 2008b).

4. Scenarios of climate and vegetation changes

To describe possible climate changes in the study area for the period up to 2100, the modeling results provided by the ECHAM5 global model (MPI Hamburg, Germany) were used (Rocekner et al. 2003). The ECHAM5 reanalysis dataset (Rocekner 2004a, 2004b, 2004c) was used to quantify the present climate conditions. To generate the future meteorological conditions the moderate A1B emission scenario (IPCC 2007) was selected. In the first step, the possible century trends of the air temperature, air humidity, solar radiation, precipitation and wind speed for the CFSNBR were obtained as a difference between the predicted values for period 2080–2100 (Rocekner et al. 2006a, 2006b, 2006c) and the values taken for period 1980–2000 from reanalysis datasets (Rocekner 2004a, 2004b, 2004c). The trends were calculated using average values from 3 model runs for a grid point (56.89°N, 33.75°E) located close to the CFSNBR area. In the second step, the future annual pattern of meteorological conditions (with 1 h time resolution) for the area was generated from the data set of 1999 (taken as reference) using the obtained climatic trends. Analysis of the trend for our study area shows that the proposed climatic changes under A1B scenario could result in a significant increase of annual air temperature (about 3.4 °C), precipitation (up to 20%), specific humidity (up to 21%) and atmospheric $CO_2$ concentration, as well as in some reduction of the annual global solar radiation by 14% (figure 2).

Possible scenarios of vegetation changes were derived from analysis of vegetation changes in the Late Pleistocene and the Holocene. It was assumed that the proposed climate warming in the next 100 years will not result in a very fast and wide expansion of broadleaf species in the area. However, the role of spruce will be gradually reduced and the abundance of broadleaf species (elm, lime and maple) and the proportion of secondary deciduous tree species (mainly birch and aspen) will be increased. $H_2O$ and $CO_2$ fluxes were modeled, first of all, for a mono-specific spruce forest stand which was classified in our study as a reference. After that, fluxes were also modeled for forest stands with different proportions of deciduous species (broadleaf, birch, aspen) in total leaf area index (LAI)—from 20% to 100%.

It was assumed that the change of species composition does not lead to changes of LAI, tree density and mean tree height of spruce and deciduous trees. Physical soil properties
Figure 2. Annual mean patterns of air temperature (T), precipitation (p), water vapor pressure (e), solar radiation (Q) and their expected changes (∆T, ∆p, ∆e and ∆Q) for the period from 1980–2000 to 2080–2100, proposed by the ECHAM5 model according to the A1B climatic scenario for the CFSNBR area.

...do not alter with changes of forest species composition either. It was also assumed that a foliage appearance in spring, and autumn fall of the leaves, for the study area occur after the mean daily air temperature crosses the threshold value 5°C. Biophysical parameters of different tree species required for modeling experiments were obtained during recent experimental studies in the field. Maximal leaf stomatal conductance (gMAX) for spruce trees in all modeling scenarios was taken to be equal 92 mmol m⁻² s⁻¹, and gMAX for birch and aspen trees—126 mmol m⁻² s⁻¹. Maximal rates of carboxylation at 25°C (Vc MAX) at the top of the canopy for spruce and all broadleaf species were equal to 31.4 and 48.2 μmol m⁻² s⁻¹, and maximal rates of electron transport at 25°C (JMAX)—to 52.4 and 80.2 μmol m⁻² s⁻¹, respectively.

5. Sensitivity of CO₂ and H₂O fluxes to climatic and vegetation changes

To derive the influence of species composition changes on H₂O and CO₂ fluxes, meteorological data obtained during 1999 in the CFSNBR were used. The year 1999 was relatively warm with very changeable weather conditions. The mean annual temperature was about 6.0°C. The mean daily air temperature ranged between −16°C in February and 24°C—in June and July. Annual precipitation was about 650 mm. Spring and early summer were characterized by a relatively small amount of precipitation that resulted in insufficient soil moisture in July. Annual global radiation was relatively high and exceeded 3600 MJ m⁻² year⁻¹.

Most attention in the study was paid to the comparison of ET, TR, IP, NEE, GPP, NPP, ecosystem (RE) and soil (RS) respiration of the forests with different species composition under present and future climatic conditions.

In the first step, the sensitivity of H₂O and CO₂ fluxes to species composition changes was analyzed. It was shown that even small changes of species composition resulted in a change of annual patterns of TR, ET, NEE, NPP and GPP, as well as their total annual sums (figure 3). Two main factors influencing these changes are different rates of TR and photosynthesis for coniferous and deciduous species and the different duration of their growing periods. Some differences can be also explained by the varying interception capacities of spruce and deciduous trees. Annual ET, GPP, NPP, RE and NEE of CO₂ in a deciduous forest is actually slightly higher than in a spruce forest. Although summer TR of a deciduous forest is higher than for spruce, the annual TR of mono-specific forests are nearly the same. ET and TR of a mixed forest are higher than in mono-specific stands by up to 10%. Understory and soil evaporation (ES) is minimal in a spruce forest and it gradually increases with an increase in the proportion of deciduous trees in a forest stand (α). Such an effect can be explained, first of all, by higher turbulent exchange within a deciduous forest stand, especially in spring prior to the beginning of the active growing period.
Figure 3. The differences between modeled annual H2O and CO2 fluxes in mixed and reference mono-specific spruce forests normalized by the annual fluxes in the reference spruce forest \((F_{\text{mixed,}\alpha = 0\text{–}100\%} - F_{\text{spruce}})/F_{\text{spruce}}\) as a function of the proportion of deciduous trees in the forest stand \((\alpha)\) under present climatic conditions. \(\alpha\) is derived as a ratio of plant area indexes (PAI) of deciduous and all trees in the forest stand in summer \((\alpha = \text{PAI}_{\text{deciduous}}/\text{PAI}_{\text{total}} \times 100\%)\).

Figure 4. Modeled annual patterns of NEE and ET for present and proposed future (2080–2100) climatic conditions under different \(\beta\). The modeling results indicate a slight decrease of ET together with a reduction of TR and interception (6–12%) rates, even if there are no vegetation changes in the modeled forest stands (figure 5). Modeled increases of understory and soil evaporation vary between 10 and 20% depending on changes of the deciduous tree proportion in forest stands and the initial tree species composition.

Results of the modeling experiments show quite varied patterns of possible changes of CO2 and H2O fluxes caused by climatic and vegetation changes. They vary significantly over the year and they are sensitive to possible changes of species composition (figures 4 and 5). The modeled decrease of annual TR (down to 12%) for all variety of species composition changes can be explained mainly by reduction of incoming solar radiation, resulting in decreasing the canopy stomatal conductance, and by an increase of the specific humidity of the air.

In the second step, the effect of climatic and vegetation changes on H2O and CO2 fluxes was quantified using the proposed trends of meteorological parameters and species composition changes for period 2080–2100. Three types of modern boreal forest stands were considered: mono-specific spruce \((\alpha = 0\%)\) forest and spruce forests with a 20 and 40% admixture of deciduous tree species \((\alpha = 20, 40\%)\). It was assumed that the forest stands grow in similar soil moisture conditions. Using the results of paleoclimatic reconstructions it was suggested that the possible increase in the proportion of broadleaf and secondary deciduous species in the forest stands \((\beta)\) for period from the present to 2100 could range between 0 and 60%.

Despite the proposed reduction of incoming solar radiation in 2080–2100, the modeling results indicate an increase in the GPP (up to 30% for period from April to September) and the NPP (up to 80%) of forest ecosystems under the A1B emission scenario, mainly due to a significant increase of atmospheric CO2 concentration (figure 5). GPP is quite linearly dependent on \(\beta\) and it is almost insensitive to the initial (present) forest structure.

The expected warming is obviously the main factor that is responsible for the increase of annual RE (up to 20%) for...
Figure 5. Relative changes of ET, TR, GPP and RE, for the period from 1980–2000 to 2080–2100 under the A1B climatic scenario, as a function of $\beta$, in the forest stand in %. The relative changes were estimated for different periods (entire year and growing season for broadleaf trees from April to September) as differences between ET, TR, GPP and RE modeled for future ($F_{A1B}$) and present climatic conditions ($F_{\text{present}}$) and normalized by $F_{\text{present}}$ for forest stands with different $\alpha$ ($(F_{A1B} - F_{\text{present}, a=0-40%})/F_{\text{present}, a=0-40%}$).

Forest ecosystems with different species composition. Higher temperatures and moisture content in the soil result in an increase of annual autotrophic ($R_A$) and heterotrophic ($R_H$) soil respiration, by up to 36% and 52%, respectively. For the period from April to September the modeled increases of RE, $R_A$ and $R_H$ are slightly smaller, and do not exceed 15, 30 and 35%, respectively.

The modeled increase of NEE of forest ecosystems due to climatic and vegetation changes is relatively small and does not exceed 10 mol CO$_2$ m$^{-2}$ year$^{-1}$ whereas its relative changes are significantly larger, mainly because the reference annual NEE values estimated under present conditions are very small and close to zero.

Finally, it should be stressed that all provided modeling experiments are based on fixed parameters describing photosynthesis, respiration and stomatal regulation of forest vegetation. The possible adaptation of plants to environmental conditions and the changes in their biochemical processes is not taken into account in the study. These processes must be obviously carefully investigated in future studies in the field in order to avoid possible uncertainties in such model projections.

6. Conclusion

The results of this study show that the expected future climatic changes may lead to significant changes of species composition and CO$_2$ and H$_2$O budgets of boreal forest ecosystems. It was shown that the expected increase of mean annual temperature, even by 1–2 °C, in the future may result in a decrease in the proportion of spruce trees in forest stands by up to 40%. Increases of CO$_2$ concentration, air temperature and precipitation are the main factors responsible for future increases in the NEE, GPP, NPP and RE of boreal forests. Despite the expected warming and moistening of the climate, the modeling experiments indicate a relatively weak increase of the annual ET and a decrease of the TR of forest ecosystems, probably due to the expected reduction of incoming solar radiation. The annual ET and TR of mixed forests may be up to 10% higher than the ET and TR of mono-specific forest stands. Seasonal patterns of the predicted changes of H$_2$O and CO$_2$ fluxes are very different. They depend on meteorological conditions and are also influenced by the variety of specific biophysical parameters of the coniferous and deciduous tree species in the forest stands.

These modeling experiments may be very useful for the solution of different theoretical and applied tasks, e.g. forecasting of the future dynamics of vegetation cover, forest canopy, water and carbon cycles, and ecological expertise.

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