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Comparative analysis of the influence of climate change and nitrogen deposition on carbon sequestration in forest ecosystems in European Russia: simulation modelling approach

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Abstract

An individual-based simulation model, EFIMOD, was used to simulate the response of forest ecosystems to additional nitrogen deposition. The general scheme of the model includes forest growth depending on nitrogen uptake by plants and mineralization of soil organic matter. The mineralization rate is dependent on nitrogen content in litter and forest floor horizons. Three large forest areas in Central European Russia with a total area of about 17 000 km^2 in distinct environmental conditions were chosen. Simulations were carried out with two climatic scenarios (stable climate and climate change) and different levels of nitrogen deposition. The simulations showed that increased nitrogen deposition leads to increased productivity of trees, increased organic matter content in organic soil horizons, and an increased portion of deciduous tree species. For the climate change scenario, the same effects on productivity and shifts in species composition were predicted but there was a negative effect on the accumulation of organic matter in soil.

1 Introduction

There is a growing research interest in the effects of nitrogen deposition on carbon sequestration in forest ecosystems in different regions (Högberg, 2012; Magnani et al., 2007; Thomas et al., 2010). It is well known that nitrogen is a limiting nutrient for tree growth and carbon sequestration in boreal and temperate zones linked with nitrogen deposition from the atmosphere (Sutton et al., 2011). At first it was widely held that nitrogen deposition should increase tree growth in the northern hemisphere (e.g. Townsend et al., 1996). Increased nitrogen input through deposition can affect forest ecosystems in different ways. Magnani et al. (2007) found that nitrogen deposition plays a positive role in forest carbon sequestration in boreal and temperate forests. Based on forest inventory data, Thomas et al. (2010) showed that nitrogen deposition within a range of 3 to 11 $kg\,ha^{-1}\,y^{-1}$ increased aboveground biomass by 61 kg C per

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kg N deposited. However, other researchers have shown that increased nitrogen inputs through deposition have almost no effect on carbon sequestration (De Vries et al., 2008; Nadelhoffer et al., 1999). In addition, different tree species may have different responses to nitrogen deposition even in the same region (Thomas et al., 2010). There is evidence of different responses of different species to nitrogen deposition. These conflicting results suggest that the effects of nitrogen deposition on carbon sequestration may be regional or site-specific. In some of the temperate forests of central Europe, nitrogen deposition has already removed limitation by amount of nitrogen. In addition, different tree species may have different responses to nitrogen deposition even in the same region (Komarov et al., 2007; Thomas et al., 2010). These facts highlight the need for more research on the various major forest species in the boreal zone. Russian forests are widespread in the northwest and northeast of European Russia, and their response to nitrogen deposition in different climatic zones has not previously been studied. The effects of both climate change and various management options on forest ecosystem dynamics in Central Russia have been studied using simulation modelling (Mikhailov et al., 2004; Palosuo et al., 2008; Verkerk et al., 2006; Shanin et al., 2010, 2011; Zamolodchikov et al., 2008).

Usually models used in regional studies, such as semi-empirical models (Shvidenko et al., 2007), ROBUL (Zamolodchikov, 2011), or the CBM-CFS3 model (Kurz et al., 2009), which have been applied for regional carbon assessment in Russia, have simulated not individual species but broad functional groups (i.e. deciduous trees, conifers, etc.). Russian forests are usually mixed and therefore modelling of functional types was not well suited to study the interactions between nitrogen deposition and forest management, which are dependent on species composition. To avoid these issues, an ecosystem-level individual-based and spatially explicit forest management model is more suitable.

The model EFIMOD has been used as a management evaluation tool in many types of world forest ecosystems (Chertov et al., 2009; Kahle et al., 2008; Larocque et al., 2008; Shaw et al., 2006). The model is specially designed to examine the impacts

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of different management strategies or natural disturbance regimes on long-term site productivity and carbon sequestration. A detailed description of the EFIMOD model can be found in Komarov et al. (2003) and a brief description of the algorithms simulating carbon sequestration and nitrogen limitation will be presented in the next section.

The objective of this paper was to evaluate the effects of various levels of nitrogen deposition on carbon sequestration capacity in the mixed forest ecosystems of Central European Russia in different climatic zones and site conditions. Moreover we carried out simulations with different climate scenarios (Shanin et al., 2011).

2 Materials and methods

2.1 Model and initialization

The system of models EFIMOD (Komarov et al., 2003) has been used for the analysis of soil and stand dynamics in forest ecosystems of the boreal and temperate zones. The system of models is of the individual-based type. A simulated stand is arranged on a square lattice, and the size of the cells allows only one tree to be located in a cell. The biomass of five compartments (stem, branches, leaves/needles, fine roots, and coarse roots) is calculated for each tree. There are two types of interactions between trees in a stand: competition for available photosynthetically active radiation (PAR) and competition for nitrogen available to plants. Each tree forms a shadow zone and an area of nutrition whose size depends on the tree diameter. Shadowing reduces production proportionally. Areas of nutrition of neighbouring trees overlap, and competition consists of the consumption of different amounts of available nitrogen by fine roots, which are evenly distributed in the tree's area of nutrition. In overlapping areas, available nitrogen is consumed proportionally to the mass of corresponding fine roots. Consideration of belowground competition is a considerable distinction from some other models, where competition for light is a main ecosystem driver. It should be noted that for boreal and partially temperate forests in Central European Russia, which are nitrogen limited,

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competition for nitrogen (and other elements of nutrition, i.e. basic cations, etc.) has larger priority than competition for light.

The system of models consists of four main blocks (sub-models): (1) a model of individual tree growth; (2) a spatially explicit stand model; (3) a model of soil organic matter (SOM) dynamics, ROMUL (Chertov et al., 2001); and (4) a statistical climate generator which converts changes in climatic variables, including air temperature, precipitation onto the forest floor, soil temperature, and moisture, on a monthly basis (Bykhovets and Komarov, 2002). Each compartment is characterized by biomass, nitrogen, and ash contents. Initialization of biomasses is done using Marklund equations (Marklund, 1988). Biomasses of compartments in the annual modelling step have been calculated using allocation coefficients which are derived from data on different tree species' productivity (Komarov et al., 2003, 2007). Each tree compartment has species-specific nitrogen and ash contents depending on forest type. Forest types have been adjusted with Cajander forest types (Cajander, 1926). Thereby nitrogen turnover has been simulated through corresponding litter fall onto/into soil and the return of available nitrogen from the ROMUL model. Nitrogen deposition has been added to the pool of available nitrogen. The flowchart of EFIMOD is shown in Fig. 1.

ROMUL is a model of SOM dynamics based on the assumption that there is a consequent change in the communities of destructors in the course of SOM decomposition and humification (Chertov et al., 2001). The amount and species composition of destructors depend on the biochemical properties of organic residues, hydrothermic conditions, and soil texture. Thus, it is possible to calculate the decomposition and humification rates as functions of biochemical properties of litterfall, soil temperature, and moisture.

It is assumed that nutrients released due to mineralization are completely absorbed by plants. ROMUL describes the dynamics of the three main pools of SOM and corresponding pools of nitrogen: total SOM of the forest floor, labile humus of mineral horizons (originating from decomposing root litter), and stable humus of mineral soil consisting of SOM combined with mineral particles with a slow rate of decomposition.

Additionally, ROMUL delivers a pool of mineral nitrogen available for plant nutrition. It is assumed that this pool is fully consumed for forest growth and surplus nitrogen is immobilized in soil. A simple procedure of leaching nitrogen from soil to ground water is also included in the nitrogen cycle of the model (Chertov et al., 2001).

As mentioned above, the system of models EFIMOD is an individual-based one and is intended for the assessment of forest ecosystem dynamics on a local (stand) scale. Advantages and special features of applications of the individual-based model at regional scale are described in detail in previous publications (Shanin et al., 2010, 2011, 2012).

The following input parameters are necessary to run the model: the species composition of the mixed forest stand which consists of forest elements (a "forest element" is an even-aged group of trees of the same species with similar stem heights and diameters); accordingly we need the average height of trees, the average stem diameter at breast height, the number of trees per hectare, and the age of trees for each forest element.

The characteristics of SOM pools have been taken from a special database (Alexeev and Birdsey, 1998; Chestnykh et al., 1999; Komarov et al., 2007). Most stand information is available from forest inventory databases. Absent data have been calculated on the basis of available data: growing stock, site area, relative stand density, stand composition, site class, and tree species. Absent characteristics of SOM pools have been estimated from two available parameters: forest site class and dominant species in the overstorey, with the use of regional databases and expert estimations (Komarov et al., 2007).

EFIMOD uncertainties and predictions were thoroughly verified against field measurements (Shanin et al., 2011, 2012).

2.2 Management and climate scenarios

Simulations were done for 100 yr starting in the 1990s using corresponding forest inventory data for all stands of case studies. The forest growth scenario assumed that

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mixed tree stands are conserved as a forest reserve without any silvicultural operations. The natural regeneration by seeds was modelled every 15 yr in the specific proportions of the tree species depending on the forest site types and dominant trees (Shanin et al., 2011). The density after regeneration was 2000 trees ha^{-1}.

We took the set of climatic scenarios compiled by Mitchell et al. (2004) which are available at the Climate Research Unit of the University of East Anglia website (http://www.cru.uea.ac.uk/cru/data/hrg.htm). This set includes a gridded ($0.5^\circ \times 0.5^\circ$) climatic dataset for the 20th century, CRU TS 2.0, and a set of climate change scenarios for the 21st century, TYN SC 2.0.

From the resulting set of 16 climate change scenarios we took the "most dramatic" one (_C) to estimate the maximum possible changes in ecosystem parameters during the 21st century. The "stationary climate" (_S) was taken as the second scenario. Both scenarios were taken for the dataset grid boxes which were the closest to the study areas.

The _S climatic scenario was compiled on the dataset CRU TS 2.0 from 1951 to 2000. The _S scenario is similar in average values to the "standard" of 1961–1990 during the whole simulation span. The _C scenario from 2001 to 2100 was chosen as the most "extreme" scenario of warming to show the widest range of possible climatic conditions. It was based on the HadCM3 model and the A1Fi emission scenario. According to the scenario, average annual air temperature increases by 7.4 °C in the Dankovskoe forest area, 7.2 °C in the Manturovskoe forest area, and 7.3 °C in the Zheleznodorozhnoe forest area. Corresponding total changes in precipitation are not so significant: −1 % in the Dankovskoe forest area, 8 % in the Manturovskoe forest area, and 5 % in the Zheleznodorozhnoe forest area), mostly due to the increased monthly totals in winter.

How plausible such a temperature increase is and what climate change scenario is better are highly debatable, but this paper considers not an accurate quantitative forecast but the qualitative behaviour of the warming effect on the main carbon fluxes in the forest ecosystem under climate change and different nitrogen deposition scenarios.

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2.3 Nitrogen deposition scenarios

To assess the effect of additional nitrogen on forest ecosystems, three levels of nitrogen deposition were proposed. The current level was taken as a baseline. It was 13.2 kg [N] ha^{-1} yr^{-1} for Dankovskoe forest area, 7.2 kg [N] ha^{-1} yr^{-1} for Manturovskoe forest area, and 4.8 kg [N] ha^{-1} yr^{-1} for Zheleznodorozhnoe forest area (State report, 1998, 2011). We also used two levels of probable increases in nitrogen inputs. The first one assumed an increase in deposition of 6 kg [N] ha^{-1} yr^{-1} in comparison to the current level, and the second simulated an increase of 12 kg [N] ha^{-1} yr^{-1}. Such scenarios were first proposed for Manturovskoe forest area as two- and three-fold increases in current anthropogenic inputs and were then used for all areas under study to keep the same values of absolute increase.

2.4 Areas under study

Three study areas in different parts of European Russia were chosen for the simulation experiments (Fig. 2). These areas have distinct environmental conditions, soil cover, and vegetation. They were selected to present a latitudinal gradient of climatic conditions. The Dankovskoe forest area (total area 69 200 ha) in the Moscow region consists of middle-aged pine and birch stands on weak podzolic soils. The Manturovskoe forest area (180 600 ha) in Kostroma region consists of middle-aged pine, birch, and aspen stands as the most common species. Soil cover is formed by sandy and loamy-sandy, podzolic, sod-podzolic, and peaty-gley soils, with an underlying moraine. The Zheleznodorozhnoe forest area (in the Komi Republic), with an area of about 1 445 000 ha, consists of young and old-growth stands; the prevailing tree species are Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). Soil cover is presented by podzolic, swamp-podzolic, and peat-bog soils (Zaboeva, 1975). Annual average temperature varies from 5.0 °C in the Moscow region to 0.1 °C in the Komi Republic (3.0 °C in the Kostroma region); annual total precipitation is 634 mm in the Dankovskoe forest

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area, 621 mm in the Manturovskoe forest area, and 585 mm in the Zheleznodorozhnoe forest area.

The areas under study have different environmental conditions. Moderately wet habitats prevail in the Dankovskoe forest area, while in the Manturovskoe and Zheleznodorozhnoe forest areas a considerable part of the total area is covered by habitats with lean soils. Also, the Zheleznodorozhnoe forest area is characterized by excessive moisture in nearly the entire territory. As such, distinct dynamics of forest ecosystems can be expected in these areas. Modelling carried out for three areas with different climatic conditions will allow us to construct a latitude transect and to extrapolate the results of these simulations to larger areas.

3 Results

As seen from Fig. 3, the increase in nitrogen input with atmospheric precipitation resulted in a predicted increase in the productivity of stands. This increase led to increased litter production and to a higher rate of SOM decomposition and corresponding carbon dioxide emission. Climate change also resulted in an increase in rate of decomposition in the soil. This, on the one hand, led to an increase in the release of inorganic nitrogen compounds which are available for plants and resulted in a productivity gain. But, on the other hand, the increased rate of destruction negatively affected the total balance of carbon, which was calculated as net primary production (NPP) minus respiration of plants and soil biota. As a result, the carbon balance in a climate change scenario could be almost equal to or even lower (in the case of Dankovskoe forest area, Fig. 3a) than this one under a stable climate for all levels of nitrogen deposition. Comparison of the simulation result for 100-yr simulations for the different areas under study shows that net primary production decreased from south (Dankovskoe forest area with average value of NPP among all scenarios of 553.6 t ha^{-1}) to north (Zheleznodorozhnoe forest area, 423.9 t ha^{-1}). The average value of NPP in Manturovskoe forest area was 482.5 t ha^{-1}. The same pattern was observed for carbon dioxide emission

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(343.3 t ha^{-1} in Dankovskoe forest area, 331.7 t ha^{-1} in Manturovskoe forest area, and 307.8 t ha^{-1} in Zheleznodorozhnoe forest area) and total carbon balance (210.3 t ha^{-1} in Dankovskoe forest area, 150.8 t ha^{-1} in Manturovskoe forest area, and 63.9 t ha^{-1} in Zheleznodorozhnoe forest area).

The dynamics of different constituents of SOM in different scenarios are shown in Fig. 4. The first trend which could be observed is an increase in SOM stock with increased nitrogen input (Table 1). Climate change leads to the opposite effect. Higher levels of nitrogen deposition result in a significant increase in the portion of organic layer in the total SOM pool while the portion of the mineral horizons in total SOM stock decreased. However, with the same level of nitrogen deposition, the portion of organic layer in the total SOM stock under the climate change scenario was lower than that under a stable climate because the decomposition rates of this fraction are much more affected by changes in temperature and moisture. It should also be noted that differences between climatic scenarios in terms of both total carbon stock in soil and portions of different SOM fractions were most significant for the more southern Dankovskoe forest area (Fig. 4a) and least significant for the northern Zheleznodorozhnoe forest area (Fig. 4c). The effect of increasing nitrogen deposition on the increase in the total carbon stock in soil and the portion of organic layer in different areas showed a similar pattern: it was more significant in Dankovskoe and Manturovskoe forest areas in comparison with Zheleznodorozhnoe forest area.

Figure 5 reveals the dynamics of different nitrogen pools. Obviously, the total nitrogen stock in an ecosystem increases with increasing nitrogen deposition. The dynamics of different pools of nitrogen are closely related to the dynamics of corresponding carbon pools (soil, stand, organic debris). Both climate change and increased nitrogen deposition resulted in increases in the amount of available nitrogen. The nitrogen pool in tree biomass grew and the portion of nitrogen pool in soil fell correspondingly.

The effects of warming and nitrogen deposition on the dynamics of species composition are shown in Fig. 6. All tree species were split into three groups. The first group consists of so-called parvifoliate tree species, which are pioneer species with

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fast growth and high demand for nutrients: silver birch (*Betula pendula* Roth) and European aspen (*Populus tremula* L.). The second group includes small-leaved lime (*Tilia cordata* Mill.) and pedunculate oak (*Quercus robur* L.), which are tolerant species with highly competitive capacities which also require fertile soil but have lower metabolic rates than the previous group. Both groups are rich in nitrogen contents in compartments. The third group includes coniferous species whose needs for soil nutrition are lower than those of parvifoliate and broadleaved species: Norway spruce (*Picea abies* (L.) H. Karst.) and Scots pine (*Pinus sylvestris* L.).

The increase in nitrogen deposition led to increasing portions of parvifoliate and broadleaved tree species, which require more nutrients for growth than coniferous species. The effect of climate change was generally the same but with some exceptions. The effect of nitrogen deposition on species composition was the most significant in the warmer Dankovskoe forest area. The territory of Zheleznodorozhnoe forest area is beyond the geographic range of broadleaved tree species; the relative increase in the share of parvifoliate species in this case was rather low.

4 Discussion

The EFIMOD model analyses the common dynamics of carbon and nitrogen in forest ecosystems. The principal peculiarity of the model consists in its structure, which not only describes flows between model compartments but also includes competition for light (controlling the binding of carbon due to the tree's position in a mixed stand) and for soil nutrition (controlling production by nitrogen deficit) as the main mechanisms. It should be noted that the case studies under investigation are limited by nitrogen although to different extents. The competition mechanisms acting together and depending on climatic factors and nitrogen deposition show distinctive results.

A positive effect of climate change on forest productivity, particularly for boreal forests of the northern hemisphere, was noted in many studies (Lopatin et al., 2006; Myneni et al., 1997; Shanin et al., 2010, 2011; Spiecker, 1999). Authors usually mention

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increased carbon dioxide concentration as a possible source of positive influence (Boisvenue and Running, 2006; Cole et al., 2010; Coops and Waring, 2001; Ellsworth et al., 2012; Moore et al., 2006) and increased input of nitrogen compounds with precipitation (Callahan et al., 2008; Högberg, 2012; Vetter et al., 2005). A significant increase in biomass is noted for fine roots (Pritchard et al., 2001; Rasse, 2002).

An increase in nitrogen deposition from the atmosphere also leads to an increase in forest growth and corresponding increase in litter flow on or in the soil. Nevertheless it is known that in temperate forest soils where nitrogen does not limit microbial growth, nitrogen deposition could impede the decomposition of organic matter and thus stimulate carbon sequestration (Janssens et al., 2010). At the same time, increases in forest floor temperature due to climate change lead to increased rates of SOM decomposition (Rustad et al., 2001; Vetter et al., 2005). EFIMOD can take into account both of these processes in detail. However, in some studies (Ramirez et al., 2010) the inhibition of decomposition processes due to nitrogen fertilization was noted.

The analysis of results is clearer if we calculate the values of relative carbon accumulation, in terms of kilograms of carbon accumulated in the forest ecosystem (ha^{-1} yr^{-1}) per kilogramme of deposited nitrogen (ha^{-1} yr^{-1}). The results are shown in Table 1. First, there was a significant decrease of this characteristic from south (Dankovskoe forest area) to north (Zheleznodorozhnoe forest area). Second, the so-called "saturation effect" could be observed, where the value of relative carbon accumulation per kilogramme of nitrogen decreased with increases in the amount of deposited nitrogen. All of these values are in good agreement with data reported by Högberg (2012).

Increments due to the current level (CL) of nitrogen deposition decrease from south to north. A higher productivity gain was predicted for Dankovskoe and Manturovskoe forest areas (Fig. 3a and b) than for Zheleznodorozhnoe forest area (Fig. 3c). There is a non-linear saturation in relation to nitrogen additions: the more nitrogen is added, the lower the sequestration of carbon. Climate change increases the relative sequestration of carbon except in southern Dankovskoe forest area. We will try to explain this exception later in the description of changes of species composition. The rate of

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carbon sequestration decreases from south to north. The lower forest growth is the main reason for this decrease.

Increased nitrogen deposition resulted in an increased growth rate of trees and, therefore, in an increased litter flow. The higher nitrogen content in litter had an additional positive effect on the mineralization rate. Climate change also accelerates the decomposition processes in soil and leads to increased carbon dioxide emissions. The increased input of plant residues to soil resulted in increased SOM content at different levels of nitrogen deposition, mainly in the forest floor. Conversely, climate change led to a decrease in the relative SOM content in organic soil horizons. The net effect of these processes was an increase in total SOM (Fig. 4).

It is known from repeated measurements of permanent plots that forest floor accumulates soil carbon in the middle-aged stands, which is in good agreement with chronosequence studies and flux measurements of eddy sites (Hakkinen et al., 2011). Our case studies are mostly middle-aged after strong cuttings in the 1940s.

The total amount of nitrogen in all ecosystems is growing but it is reallocated in different ways in the more southern and more northern case studies. In all cases nitrogen is accumulating in stands due to increased forest growth. In the north, leaching decreases the total nitrogen amount, mostly due to climate change, which speeds up decomposition processes and releases movable nitrogen, which is then leached.

Additional nitrogen deposition also affected the species composition: the portion of deciduous tree species increased. The most considerable changes are in the south. Here coniferous species are changing to parvifoliate and deciduous trees. This results in a decreasing rate of sequestration of carbon per nitrogen unit because the nitrogen content in compartments of those species is much higher and is a reason for decreases in relative carbon sequestration. Moreover, climate changes accelerate species changes. The geographical ranges of species may move northward, with the estimated migration rate being within the range of approximately 1000 to 200 $\mathrm{m\,yr^{-1}}$ (Iverson and Prasad, 1998; Johnston et al., 2009; Pearson, 2006) or even 5000 $\mathrm{m\,yr^{-1}}$ (Thuiller, 2007) due to the predicted increase in the mean annual temperature and

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associated alterations in precipitation patterns. The replacement of coniferous species by broadleaved ones has been shown using both paleoecological (Overpeck et al., 1991) and simulation methods (Iverson and Prasad, 1998, 2001; Sykes et al., 1996). This is why corresponding values for Dankovskoe forest area given in Table 1 show a difference in relation to northern sites. Manturovskoe forest area has an intermediate position, and Zheleznodorozhnoe forest area does not demonstrate this effect because it has no deciduous species.

5 Conclusions

In the forest lands of Central European Russia, warming leads to: (1) relative increases in forest productivity from south to north (the maximum increase is in the north); (2) increases in carbon dioxide emissions from the soil; (3) decreases in carbon in the forest floor; (4) increases in the proportion of broadleaf species (except in the most northern area under study).

Based on the simulations, we conclude that nitrogen deposition plays a positive role in carbon sequestration in mixed forests in Central European Russia at the current average levels of nitrogen deposition.

The most important consequence of common impacts of warming and nitrogen deposition is that they both change species composition for the benefit of deciduous species which require more nitrogen for growth. Warming controls this process.

Because of these important effects, the effect of nitrogen deposition must be considered when evaluating forest carbon potentials under various future management and climate change scenarios.

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Table 1. Carbon accumulation (NEP), kg [C] ha^{-1} yr^{-1} per 1 kg [N] ha^{-1} yr^{-1} deposited with different levels of deposition of nitrogen compounds (CL – current level, I06 – increase of 6 kg [N] ha^{-1} yr^{-1}, I12 – increase of 12 kg [N] ha^{-1} yr^{-1}) and climatic scenarios (_S – stable climate, _C – climate change).

	Scenario of nitrogen deposition					
Forest area under study	CL_S	CL_C	I-06_S	I06_C	I12_S	I12_C
Dankovskoe	30.9	22.4	18.6	17.1	16.2	12.8
Manturovskoe	16.2	17.8	13.2	13.7	11.9	12.7
Zheleznodorozhnoe	9.6	11.1	6.3	7.3	5.4	5.7

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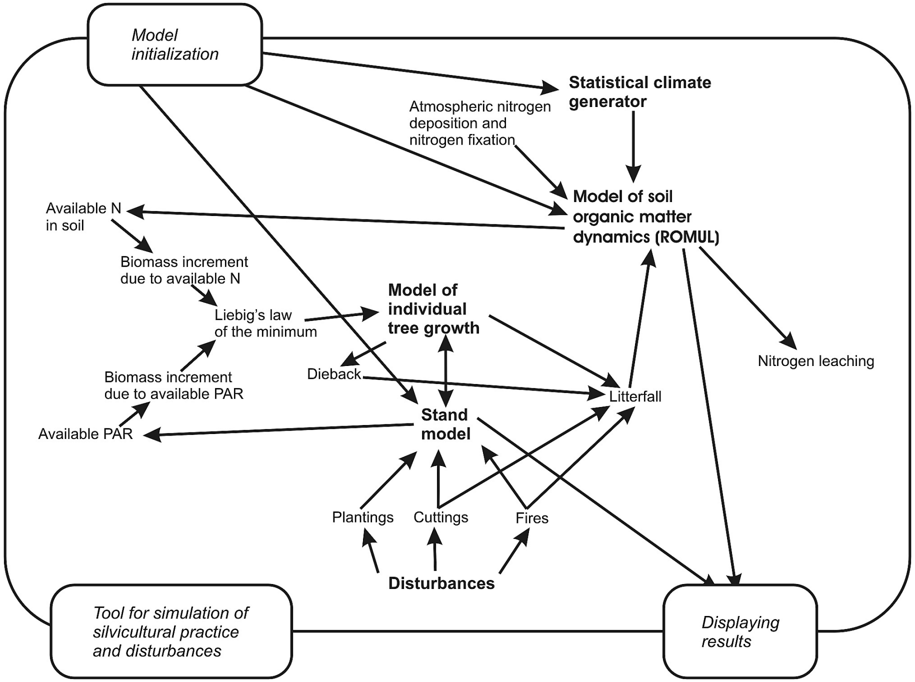

Fig. 1. The flowchart of the EFIMOD model.

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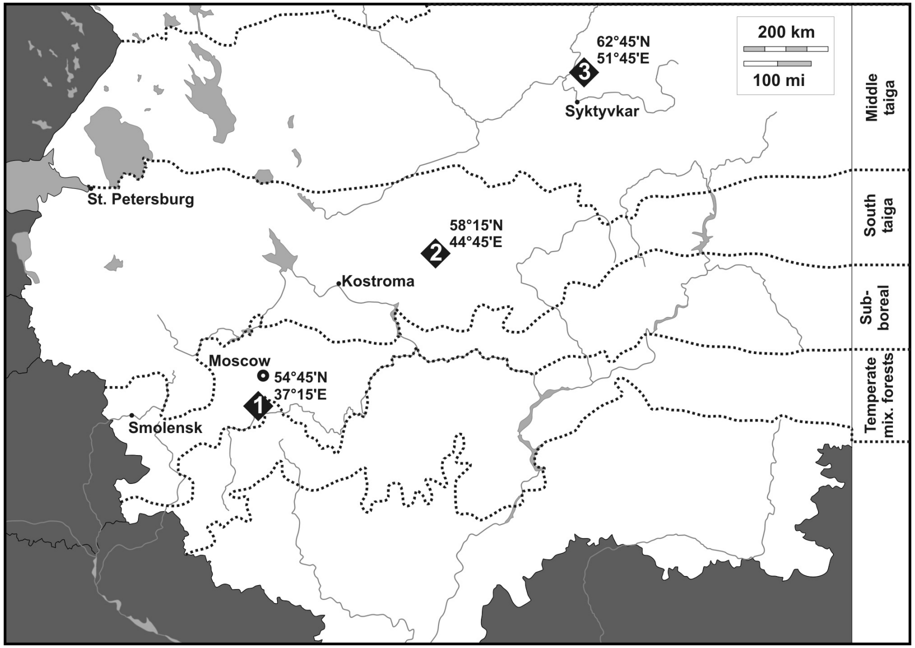

Fig. 2. Areas under study: 1 – Dankovskoe forest area; 2 – Manturovskoe forest area; 3 – Zheleznodorozhnoe forest area. Dashed lines delineate approximate borders of vegetation subzones. Geographic coordinates for the CRU TS 2.0 dataset grid box closest to the corresponding area under study are shown. Based on a map by Daniel Dalet (d-maps.com).

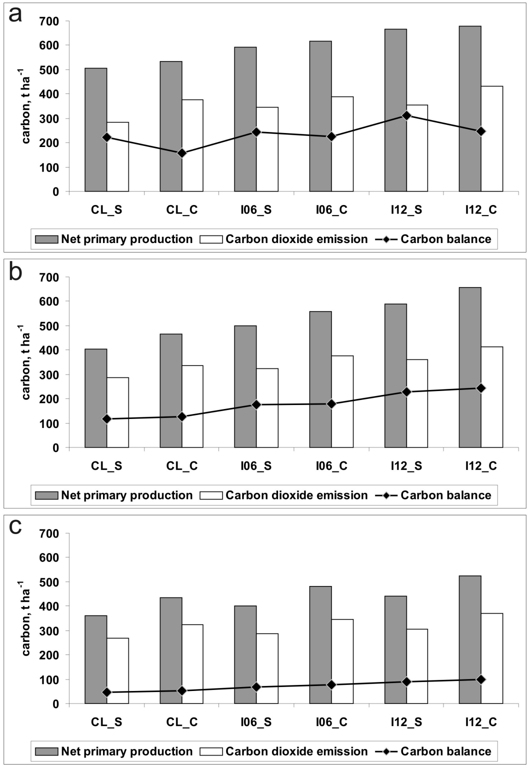

Fig. 3. NPP, emission of CO_2, and carbon balance (sum for 100 yr of simulation) with different levels of deposition of nitrogen compounds (CL – current level, I06 – increase of 6 kg [N] ha^{-1} yr^{-1}, I12 – increase of 12 kg [N] ha^{-1} yr^{-1}) and climatic scenarios (_S – stable climate, _C – climate change) for the different areas under study (**a** – Dankovskoe forest area, **b** – Manturovskoe forest area, **c** – Zheleznodorozhnoe forest area).

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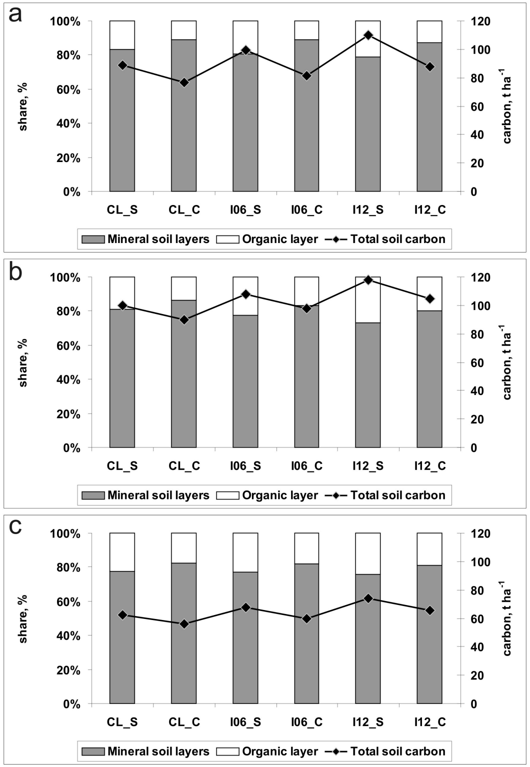

Fig. 4. Shares of different fractions of SOM and total carbon stock in soil by the end of simulation with different levels of deposition of nitrogen compounds (CL – current level, I06 – increase of 6 kg [N] ha^{-1} yr^{-1}, I12 – increase of 12 kg [N] ha^{-1} yr^{-1}) and climatic scenarios (_S – stable climate, _C – climate change) for the different areas under study (**a** – Dankovskoe forest area, **b** – Manturovskoe forest area, **c** – Zheleznodorozhnoe forest area).

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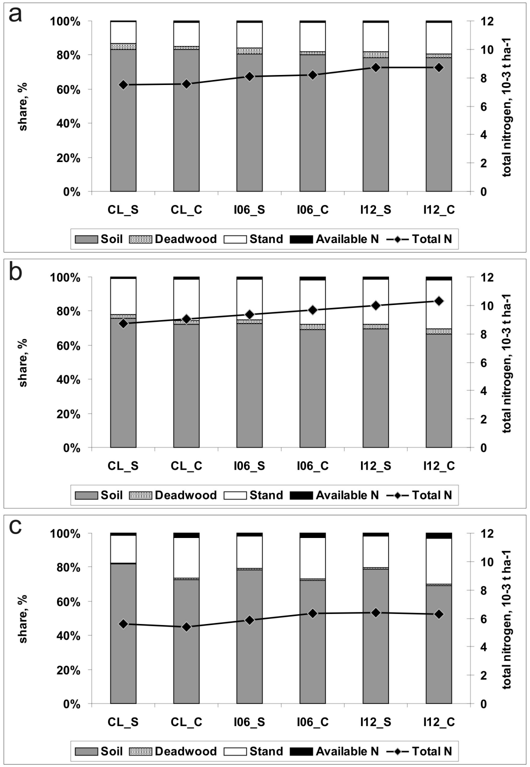

Fig. 5. Nitrogen stocks in different pools by the end of simulation with different levels of deposition of nitrogen compounds (CL – current level, I06 – increase of 6 kg [N] ha^{-1} yr^{-1}, I12 – increase of 12 kg [N] ha^{-1} yr^{-1}) and climatic scenarios (_S – stable climate, _C – climate change) for the different areas under study (**a** – Dankovskoe forest area, **b** – Manturovskoe forest area, **c** – Zheleznodorozhnoe forest area).

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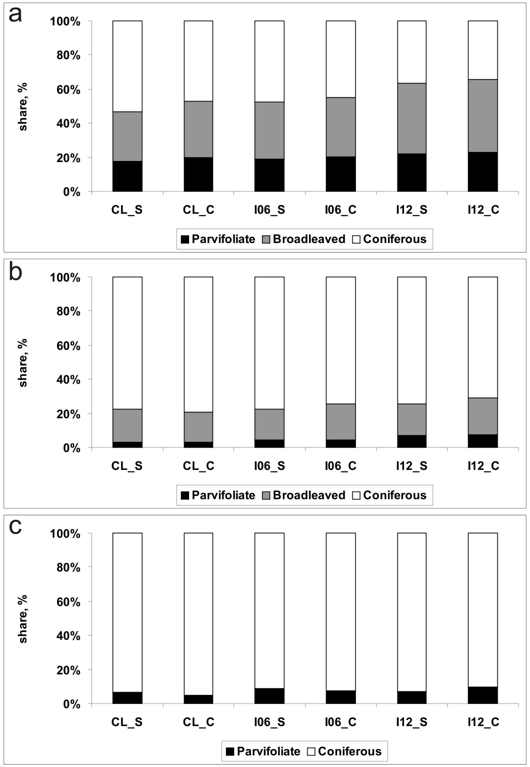

Fig. 6. Shares of different groups of tree species by the end of simulation with different levels of deposition of nitrogen compounds (CL – current level, I06 – increase of 6 kg [N] ha^{-1} yr^{-1}, I12 – increase of 12 kg [N] ha^{-1} yr^{-1}) and climatic scenarios (_S – stable climate, _C – climate change) for the different areas under study (**a** – Dankovskoe forest area, **b** – Manturovskoe forest area, **c** – Zheleznodorozhnoe forest area).