Modeling the Dynamics of Natural Forest Ecosystems in the Northeast of European Russia under Climate Change and Forest Fires

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Modeling the dynamics of natural forest ecosystems in the northeast of European Russia under climate change and forest fires [1]

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Abstract: The individual-based EFIMOD simulation model was used for regional-scale assessments of the dynamics of basic characteristics of the carbon and nitrogen balance in the forest ecosystems of north central Russia. Two forest strict nature reserves were chosen as case studies. Data from the National Forest Inventory were used for model initialization. Initial soil data were taken from a soil survey database containing data on soil organic matter and nitrogen content in the organic layer and mineral soil for different forest types and regions of European Russia. Standard meteorological data were used as climatic inputs. Two simulation scenarios (without disturbances and with forest fires) were coupled with 2 climatic ones (actual climate and the scenario of climate change). The main sources of uncertainty were analyzed and the model parameters were evaluated. A Monte Carlo procedure was applied for evaluation of the robustness of coefficients. Simulation results showed that the greatest carbon accumulation occurred in the scenario without disturbances. Fires resulted in significant losses in soil organic matter and tree biomass through direct and indirect carbon dioxide emissions. Simulated climate change led to an increased decomposition rate of soil organic matter and a related increase in the productivity of vegetation; however, for this region, the carbon balance was positive. This was primarily because young and middle-aged stands are prevalent in the region modeled. A full analysis would require analytical data on the possible dynamics of mature and over-mature forests in the same scenarios of climate change and forest fires.

Keywords: boreal ecosystems, carbon balance, carbon turnover, climate change, forest fires, forest types.

Résumé : Le modèle de simulation EFIMOD basé sur l'individu a été utilisé pour évaluer à l'échelle régionale la dynamique des caractéristiques de base des bilans de carbone et d'azote dans les écosystèmes forestiers du nord de la Russie centrale. Deux forêts situées dans des réserves naturelles strictes ont été choisies pour les études de cas. Les données de l'inventaire forestier national ont été utilisées pour initialiser le modèle. Les données initiales des sols proviennent de la base de données des relevés de sols contenant des données sur la quantité de matière organique et d'azote dans la couche organique et le sol minéral pour divers types de forêts et différentes régions de la partie européenne de la Russie. Des données météorologiques standards ont été utilisées comme intrants climatiques. Deux scénarios de simulation (un sans perturbation et l'autre avec feux de forêt) combinés à 2 scénarios climatiques (le climat actuel et un scénario avec changement climatique) ont été appliqués. Les principales sources d'incertitudes ont été analysées et les paramètres du modèle évalués. Une procédure de Monte-Carlo a été utilisée pour évaluer la robustesse des coefficients. Les résultats des simulations ont montré que la plus grande accumulation de carbone était observée avec le scénario sans perturbation. Le scénario avec feux a mené à des pertes significatives de matière organique du sol et de biomasse des arbres avec des émissions de dioxyde de carbone directes et indirectes. Le scénario avec changement climatique a mené à des taux plus élevés de décomposition de la matière organique du sol ainsi qu'à une augmentation conséquente de la productivité végétale; cependant, pour cette région, le bilan de carbone était positif. Il est à noter que la cause principale de ce résultat est que la modélisation a été effectuée pour des régions dominées par des peuplements jeunes et d'âge moyen. Une analyse complète exigerait d'examiner les possibles dynamiques de forêts matures et surannées en utilisant les mêmes scénarios de changement climatique et de feux de forêt.

Mots-clés : bilan de carbone, changement climatique, écosystèmes boréaux, feux de forêt, renouvellement du carbone, types de forêts.

Nomenclature: BSBI, 2007.

Introduction

In recent decades, the use of mathematical modeling to make dynamic predictions concerning the organic matter pools in forest ecosystems has advanced considerably (Kellomäki & Kolström, 1994; Kurz *et al.*, 2009; Liu *et al.*, 2009; Larocque *et al.*, 2011 etc.), including in Russia (Verkerk *et al.*, 2006; Shvidenko *et al.*, 2007; Palosuo *et al.*, 2008; Zamolodchikov *et al.*, 2008; Shanin *et al.*, 2011; Komarov & Shanin, 2012).

There are a wide variety of natural ecosystems in Northern European Russia; determining the role of this region in the carbon cycle of the biosphere is of

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considerable scientific and practical interest. Estimates of the main carbon pools and the rates of their transformation are available for several strict nature reserves in this territory (Bobkova & Zagirova, 2014). The age structure of these untouched territories makes them of particular interest: the forests are mostly mature or over-mature, providing an opportunity to analyze the main tendencies of such forests at natural development and to evaluate possible losses of carbon resulting from natural disturbances such as climate change and forest fires. We selected 2 forest reserves with different yet typical for this territory forest types and site conditions. Both reserves contain boreal forests with a small number of tree species. These forests are characterized by low activity among the microbiota, mainly different groups of fungi, that break down dead organic matter. The soil of the forest floor is acidic, poor in nitrogen, and up to 20–25 cm thick. Litter flow is greater than the decomposition processes in the soil, leading to the accumulation of large carbon pools (Bobkova & Zagirova, 2014). In addition, one of the selected reserves has very wet site conditions, providing the opportunity to study a site that has not suffered forest fires in the recent past.

Because of a lack of permanent sample plots extending over a period of several decades, it was necessary to use mathematical modeling to do the analysis. An existing mathematical modeling system describing the carbon and nitrogen cycle in forest ecosystems, EFIMOD-ROMUL (Chertov *et al.*, 2001; Komarov *et al.*, 2003), was used to predict the dynamics of forest ecosystems under climate change. The system was modified to work in batch mode (Shanin *et al.*, 2011; Komarov & Shanin, 2012), enabling prediction of carbon balance dynamics over large areas using standard forestry data.

The forested area of the Komi Republic is 36 Mha, which amounts to 79% of the total area of the region (Bobkova & Zagirova, 2014). The computer-simulated experiment was conducted for 2 areas (the Lyalskiy and Beliy reserves), using 2 forestry and 2 climate scenarios (stationary climate and possible warming). The results were then analyzed based on several key variables (carbon supply in the stand, deadwood, forest floor, and soil; carbon dioxide emission; net primary production; species composition of the forest stand). Comparison of the results from the different scenarios revealed the main trends in the carbon and nitrogen balance in these forest ecosystems under possible climate changes.

Methods

STUDY AREA

The study took place in the Komi Republic (Russian Federation) in the middle taiga subzone (Figure 1). The forest lands of the Komi Republic play a significant role in the carbon cycle in the European North. Siberian spruce (*Picea obovata*) accounts for 55% of the forest, making it one of the major forest-forming species. Another 24% and 15%, respectively, are covered by Scots pine (*Pinus sylvestris*) and birch (*Betula pendula*, *B. pubescens*); the presence of cedar, larch, fir, and aspen species is insignificant. The average annual temperature in the study region is 0.1 °C. The average air temperature during the growing season is 11.6 °C. Temperatures higher than 5 °C last for 142 d on average. Total precipitation is 693 mm, with uneven distribution over the year. Most (442 mm) falls from April to October; 332 mm of that amount falls during the growing season. Approximately 40% of annual precipitation falls as snow; the solid snow cover lasts for 6 months.

The forested area of the Beliy reserve (62°05'N, 50°25'E) accounts for 7329 ha, or 95%, of the total area of the reserve. The major forest-forming species is Scots pine (*Pinus sylvestris*), comprising 88%, while Norway spruce (*Picea abies*) covers 9%, and silver and white birch (*Betula pendula*, *B. pubescens*) account for 3% of the forested area. The pine forest mainly consists of ripening (35%) and middle-aged (28%) forests. The share of the young stands is 20%, with mature and over-mature stands accounting for 17%. Spruce covers 635 ha, with mostly mature and over-mature forests. Deciduous species cover 227 ha, mainly with mature and ripening stands.

The area of the Lyalskiy forest reserve (62°17'N, 50°40'E) is 700 ha. Forests cover 96% of the reserve. Coniferous stands are prevalent, with pine accounting for 57% and spruce covering 19% of the area of the reserve. Deciduous species are represented mostly by birch and cover 24%. The age structure is complex: 43% of the stands are mature and over-mature, 23% are middle-aged, 18% are young, and 16% are ripening stands (Bobkova & Zagirova, 2014).

PARAMETERIZATION OF THE EFIMOD MODEL

SHORT DESCRIPTION OF THE EFIMOD MODEL

The EFIMOD modeling system is an individual-based model for the biological cycle of elements in forest ecosystems. The unique structural feature of the EFIMOD model system is its treatment of a mixed forest as an assembly of separate, interacting trees of different species with accurate spatial positions inside the stand and detailed simulation of both the stand dynamics and the organic matter pools in the soil.

The simulated stand consists of separate trees that are located on a square lattice. The annual growth increment of each tree is distributed among 5 compartments (stem, branches, leaves/needles, fine roots, and coarse roots). The forest growth sub-model is linked to the ROMUL model, which describes the dynamics of soil carbon and nitrogen (Chertov *et al.*, 2001) and returns available nitrogen for tree growth. Each tree forms a shadow zone and an area of nutrition the size of which depends on the size of the tree. Areas of nutrition for neighbouring trees can overlap, and available nitrogen is consumed in proportion to the mass of fine roots of the neighbouring trees in these overlap areas. Belowground competition is thus species-specific and depends on the spread of the roots and their density per square unit, which are different for different species. Two types of tree increment can be calculated, that due to light and that due to soil nitrogen. These calculations require species-specific estimates of the biomasses of leaves/needles and fine roots, the maximal biological productivity of leaves/needles, and the specific consumption

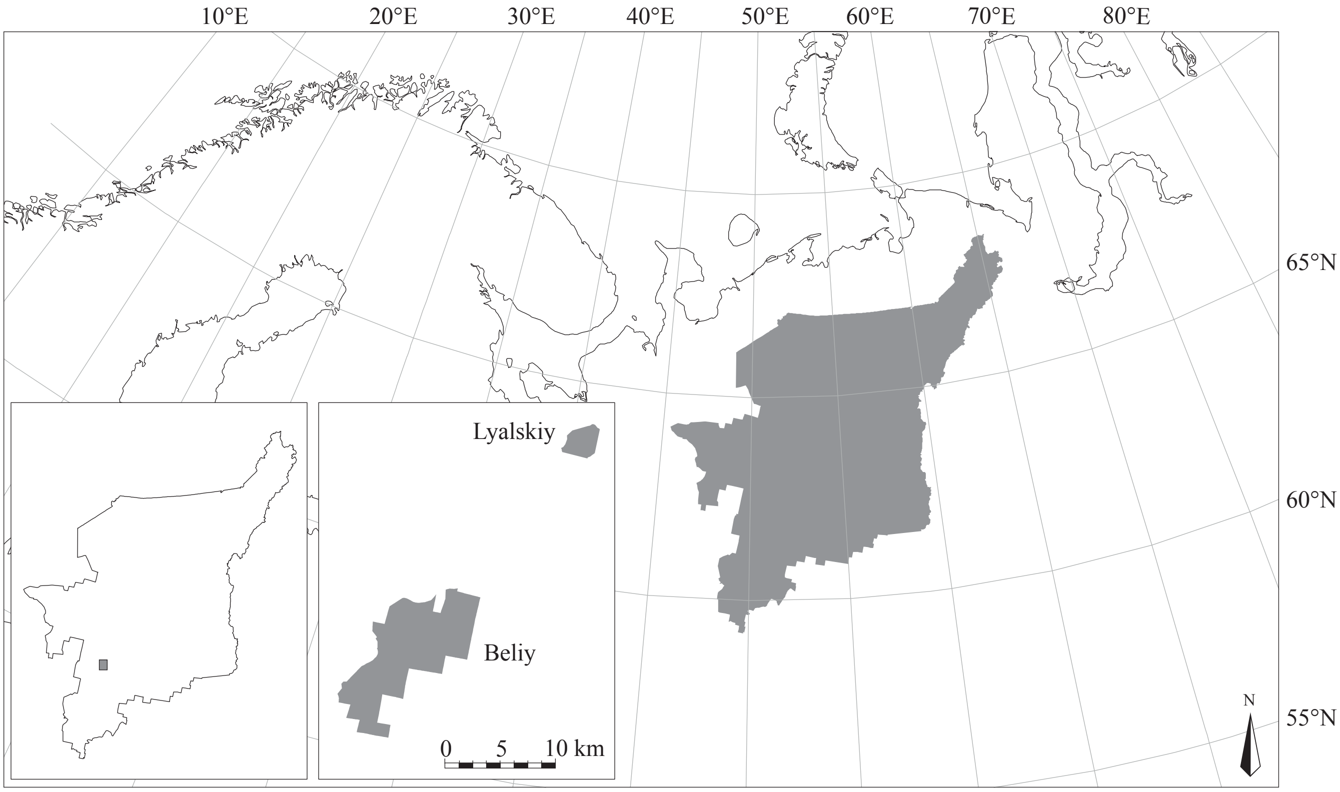

FIGURE 1. Study region. Grey area on large map delineates the Komi Republic. The boundaries of the Lyalskiy and Beliy reserves are presented on the inset at right.

rate of nitrogen. The smaller of the 2 types of increment is taken as the annual increment, following Liebig's principle.

The model has species-specific parameters describing crown opacity, shade tolerance, the size of zones of soil nutrition, and nitrogen consumption. Therefore, it is able to simulate species-specific responses to competition and environmental changes and, consequently, the dynamics of species composition.

A more detailed description of the model can be found in Komarov *et al.* (2003). It should be mentioned that the EFIMOD-ROMUL system of models has also been applied to Canadian BFTCS sites (Shaw *et al.*, 2006; Chertov *et al.*, 2009).

PARAMETERIZATION OF THE SOIL CHARACTERISTICS

Modeling requires initial values for each soil organic horizon and for the total mineral layer up to a depth of 1 m with respect to the amount of soil organic matter and the corresponding amount of total nitrogen (Komarov *et al.*, 2003).

Since the forest inventory data do not include soil characteristics, they are estimated based on 2 parameters, site conditions related to forest type and dominant soil type, using regional databases and expert assessments (Chertov *et al.*, 2002; Chestnykh, Zamolodchikov & Utkin, 2004; Chertov *et al.*, 2006; Bobkova & Zagirova, 2014).

The initial variables of the ROMUL model are the characteristics of fresh litter pools, the humus of the forest floor (organic horizons), and the humus of the mineral horizons in the soil, namely the content of organic matter and nitrogen. It should be noted that only organic matter pools are meant, not analytically definable carbon.

The amount of soil organic matter per soil horizon was estimated using volumetric density and the depth of the horizon obtained from soil surveys. The same procedure was used for the estimation of nitrogen pools in the soil. More details can be found in Bobkova and Zagirova (2014).

CONVERSION OF FOREST INVENTORY DATA INTO MODEL INPUTS

We used the latest databases of the National Forest Inventory as the source of the model inputs. During such inventories (usually carried out every 10 y), all forested areas are divided into small and relatively homogenous sites (in terms of canopy species composition, stand age, and environmental conditions).

The description of the forest stand on each site consists of a set of forest elements, *i.e.*, even-aged cohorts of 1 species with similar characteristics: age, mean height, diameter at breast height, the number of trees per hectare.

Along with the detailed characteristics of the forest stand itself, the forest management data include the relative density of the stand, its total growing stock, and site conditions, *i.e.*, characteristics of soil moisture and soil fertility expressed via a generalized index (more detail is provided in Shanin *et al.*, 2011).

From the forest inventory data, we obtained the characteristics of 723 sites in the Beliy forest reserve and 42 sites in the Lyalskiy forest reserve. In order to apply the individual-based model to simulations of large forest areas while maintaining a high level of detail, we ran the simulations for each site using a special extension of the model for batch processing (Shanin *et al.*, 2011). After the simulations, the averaged dynamics of the basic carbon pools were calculated.

MODEL VALIDATION AND SENSITIVITY ANALYSIS

The model was verified using forest inventory data. The number of samplings was increased by adding data from the Zheleznodorozhnoe forestry (Komarov & Shanin, 2012) for the territories under investigation. The stands used for validation were chosen because they feature the most widespread dominant species in the area and the type of site conditions pertinent to the species. Scatter plots displaying the relation of the height and diameter of a tree to its age were compiled using the forest inventory data. Due to the large number of stands, between 500 and 3000 measurements were taken for each of the studied species.

To eliminate the fluctuation in model outputs related to uncertainty in model inputs, a validation experiment was conducted using the Monte Carlo method (Komarov *et al.*, 2003). We assumed 20% variation from the average value (in terms of standard deviation) of the initial parameters on soil carbon stocks. The number of Monte Carlo runs was set to 100. The initial stand data were taken from the corresponding species- and site-specific yield tables (Shvidenko *et al.*, 2006). The test showed that the EFIMOD model predicted outputs close to the measured data (Figure 2).

Although this study focused on carbon stocks in soil and vegetation, we mainly used measured data on the height and diameter at breast height (DBH) of trees for the model validation because data on carbon stocks are extremely sparse for the studied areas. We assume that predictions of stand density, species composition, and size of trees provide sufficient information for accurate estimation of basic carbon stocks. Measured values of basic carbon stocks were only available for 3 sample plots (Bobkova & Osipov, 2012; Kuznetsov & Bobkova, 2014); however, these plots did represent the most common types of forest in the studied areas.

We compared measured data with simulation results averaged over the whole simulation period and over all of the simulated sites of the same forest type. The data from empirical observations of the main carbon pools for wet and bog spruce and pine forests (Bobkova & Osipov, 2012; Kuznetsov & Bobkova, 2014) were fairly consistent with the modeling results (Table I). Some differences were seen in the simulated values for carbon pools in vegetation, net primary production (NPP), and carbon dioxide emission (20%, 12%, and 20% lower than the empirical data, respectively). This is explainable by the model's structure, which

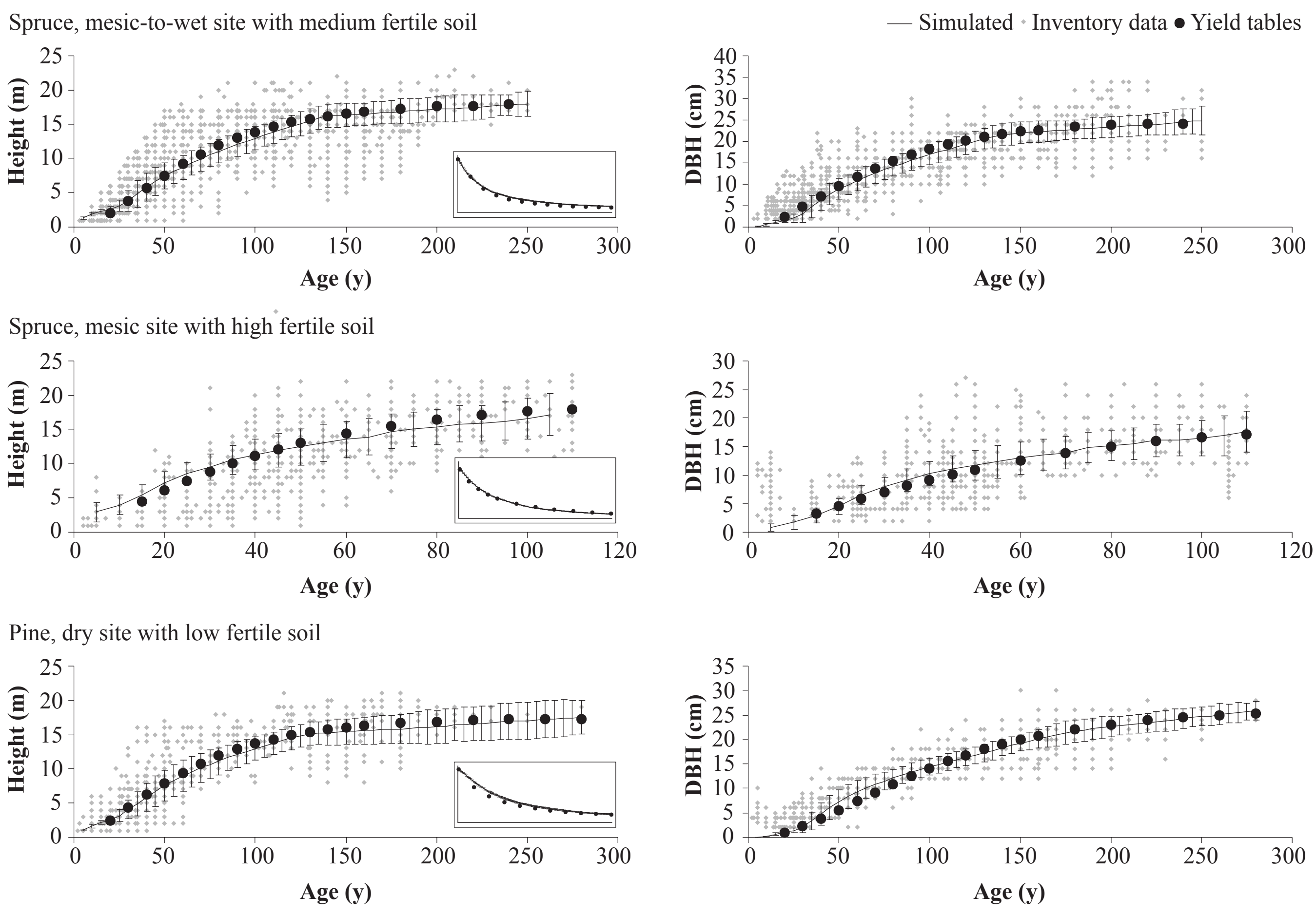

FIGURE 2. Comparison of model outputs with measured data on height, diameter at breast height (DBH), and stand density (insets). Whiskers represent the confidence interval for simulated data.

TABLE I. Measured and simulated data on carbon stocks in main pools and fluxes (t·ha^{-1}).

Pools and fluxes	Spruce forest with dwarf shrubs and *Sphagnum* in ground cover		Spruce forest with *Polytrichum* and *Sphagnum* in ground cover		Pine forest with dwarf shrubs and *Sphagnum* in ground cover	
	Measured	Simulated	Measured	Simulated	Measured	Simulated
Phytomass	88.1	64.6	77.1	67.3	60.5	47.9
Mineral soil	54.7	58.9	38.7	61.4	32.9	36.8
Forest floor	26.6	27.1	25.5	27.7	33.5	34.8
Coarse woody debris	7.5	9.3	1.9	12.2	2.3	4.1
NPP (annual)	3.1	2.5	2.8	2.5	3.0	2.8
Emission (annual)	2.7	1.8	2.4	2.1	1.3	1.1

simulates only tree vegetation dynamics and does not take into account undergrowth and ground vegetation. It is thus unsurprising that this modeling approach underestimates productivity and the carbon pool in biomass, and therefore underestimates the flow of debris onto the soil, resulting in lower estimated carbon dioxide emission values. Another discrepancy is caused by the limitations of the current version of the model, which calculates the rate of decomposition of coarse woody debris in the same way as for other litter fractions. This results in underestimation of the decomposition rate and thus greater estimated accumulation of carbon in this stock.

SIMULATION SCENARIOS

Two simulation scenarios were prepared to determine the effect of forest management type on forest ecosystems.

The "NAT_" scenario simulates the development of the forest without external influence. Undergrowth appearing under the forest canopy is simulated as 1000 trees·ha^{-1} every 15 y, with species composition proportional to the existing composition of mature stands (in terms of growing stock).

The "FIR_" scenario assumes that the ecosystem develops without logging but with possible forest fires. The frequency of fires in northeast European boreal forests is estimated to be once every 60–100 y (Engelmark, 1984; Gromtsev, 1993). More detailed data on the frequency of fires and annually burned areas were taken from Bobkova and Zagirova (2014). The simulations assume that the following proportions of biomass burn (percent of the respective carbon pool): foliage, 10%; branches, 5%; trunks, 5%; fine roots, 25%; forest floor, 100%; and organic soil horizons, 25% (according to Goldammer & Furyaev, 1996); with 25% variation in the parameters. Forest wildfires are assumed to be stronger with climate change (Flannigan *et al.*, 2009). Thus, based on data from Korovin and Zukert (2003), we set the frequency and severity of fires in the version of the scenario with climate change (FIR_C) to be 30% higher than in the version without (FIR_S). Simulation of fire events in EFIMOD includes the simulation of losses in carbon pools and calculation of the corresponding amount of carbon dioxide. Trees are assumed to have died due to fire if losses of foliage biomass make them unable to maintain production higher than the species- and age-specific threshold value.

It is assumed that unburned tree parts remain in the plot and are involved in the decomposition process. One limitation of the model is that the rate of decomposition of charred organic material is considered to be the same as for other debris. Another limitation is that the model ignores the effects of fire-induced stress on soil biota. These limitations most likely result in overestimation of the decomposition rate and overlook the very stable "black carbon" stock in soil. However, data on the amount of phytoleims after fire and their decomposition rates are extremely rare, making it impossible at the moment to include more accurate simulation of the decomposition of charred material in the model.

Fire spread is highly unlikely in the Lyalskiy reserve, as it features only bog forests. For this reason, scenarios with fire simulation (FIR_S and FIR_C) were analyzed only for the Beliy reserve.

The species composition of regeneration in both simulation scenarios was determined by forest type and dominant species on the basis of data provided by K. S. Bobkova (Bobkova & Galenko, 2001; Bobkova, 2006).

Since data on the stock of deadwood (snags and fallen trees) are generally absent from the forestry records, the initial deadwood values to initialize the runs were estimated using the ratio between the coarse debris pool and the wood pool based on data from Shvidenko, Shepashenko, and Nilsson (2009) and Zamolodchikov (2009).

CLIMATE SCENARIOS

For this project, the simulation scenarios accounting for anticipated climate change used air temperature and precipitation ranges over the 20th century interpolated into grid nodes of 0.5° × 0.5° (CRU TS 2.0) and global climate change scenarios for the 21st century (TYN SC 2.0) calculated for the same grid (Mitchell *et al.*, 2004).

Two climate scenarios were used to determine the maximum possible range for the ecosystem parameters in the 21st century: "extreme" climate change (_C), based on the A1Fi greenhouse gas emission scenario and the HadCM3 global circulation model , and "actual" climate (_S).

In the "extreme" scenario, annual average temperature rises by 7.2 °C by the end of the 21st century and annual total precipitation increases by 8%, mainly due to an increase in precipitation during the winter months. The "actual" scenario (_S) assumes that the 21st century retains the climate conditions of the second half of the 20th century. For the initial characteristics of the scenarios, see Table II.

TABLE II. Climatic data for grid point with coordinates 62°45'N, 51°45'E (Zheleznodoroznoe forestry) during 1961–1990 and assumed data for years 2071–2100 under conditions of "extreme" climate change (global air circulation model HadCM3 and emission scenario A1Fi) (Mitchell *et al*., 2004).

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Mean values 1961–1990													
Air temperature (°C)	–17.5	–14.6	–7	–0.1	7	13.3	16.8	13.3	7.6	–0.1	–7.2	–13.1	–0.1
Precipitation (mm)	36	27	28	35	45	59	75	67	60	61	50	43	585
Assumed means for 2071–2100													
Air temperature (°C)	–6.2	–7.6	–1.5	4.8	13.6	18.8	24.5	19.9	14.4	6.4	1.5	–0.9	7.3
Change (°C)	11.3	7	5.5	4.9	6.6	5.5	7.7	6.6	6.8	6.5	8.7	12.2	7.4
Precipitation (mm)	59	35	29	43	54	77	81	67	66	73	70	66	720
Change (mm)	23	8	1	8	9	18	6	0	6	13	20	23	135
Change (%)	63%	29%	5%	23%	21%	31%	8%	–1%	10%	21%	40%	55%	23%

Results

DYNAMICS OF MAJOR CARBON POOLS

The carbon pool of forest stands in the NAT_S scenario (no influences, actual climate) grew continuously (Figure 3a, b), and by the end of the simulation period reached values of 70 t·ha^{-1} for all territories under investigation, with a confidence interval of 6.1%. Under climate change, the corresponding carbon pool reached approximately 80 t·ha^{-1} by the end of the period.

The FIR_S scenario (with forest fires and actual climate) also predicted an increase in the carbon pool in forest stands, but the increase was considerably smaller than in the previous scenario: the maximum reserve capacity reached approximately 62 t·ha^{-1} (Figure 3a). Carbon pool growth in the stand under climate change (FIR_C scenario) was slightly lower than in the "actual climate" scenario.

The soil carbon pool in the Beliy reserve (NAT_S scenario) grew from 50 to 56 t·ha^{-1} (Figure 3c). The value for the Lyalskiy reserve had almost stabilized at 82 t·ha^{-1} by the second half of the modeling period (Figure 3d).

The impact of fires on the soil carbon pool dynamics was noticeably less significant than on the carbon pool in trees (Figure 3c), and the litter pool predictably suffered the most damage.

The scenario without influences (NAT_S) saw the accumulation of carbon in the deadwood pool in both habitats during the first half of the modeling period, which was associated with the processes of natural tree mortality, followed by stabilization of this value at 12–14 t·ha^{-1}. Climate change (NAT_C scenario) had a significant impact on the accumulation of carbon in the pool; in this case it stabilized at approximately 10–11 t·ha^{-1} (Figure 3e, f).

PECULIARITIES OF CARBON POOL DYNAMICS IN DIFFERENT FOREST TYPES

Carbon pool dynamics differed significantly in relation to forest types. In order to determine these differences, the modeling results were arranged by forest type, following V. N. Sukachev's classification of forest types (Zheldak & Atrokhin, 2002). The differences (in %) between the initial and simulated final values for carbon pools in the soil and the stand were calculated to analyze the effects of climate change on carbon pool dynamics in different forest types (Table III).

In general, the biggest response of carbon pools to climate change was observed for dry sites with poor soils, and the smallest was in bog sites with rich soils, which was especially notable in the case of stable carbon pools in mineral soil (Table III).

NET PRIMARY PRODUCTION (NPP) AND CARBON DIOXIDE EMISSION

The value of NPP of an ecosystem reflects the accumulation of carbon dioxide and is an asset in the carbon balance. This characteristic undergoes major variations over time, both from climate change variations and from forest succession processes. Therefore, mean net primary production over the whole modeling period rather than NPP value at any particular time was used to compare the scenarios.

In the actual climate scenario without influences (NAT_S), mean NPP reached 1.61 t·ha^{-1}·y^{-1} in the Lyalskiy reserve and 1.81 t·ha^{-1}·y^{-1} in the Beliy reserve (Table IV). The mean net primary production value in the FIR_S actual climate scenario was 1.77 t·ha^{-1}·y^{-1}, or 2% lower than in the scenario without influences.

The scenario without influences showed carbon emissions of 1.46 t·ha^{-1}·y^{-1} for the Beliy reserve and 1.19 t·ha^{-1}·y^{-1} for the Lyalskiy reserve. Forest fires caused additional direct carbon dioxide emission as a result of the burning of organic compounds; these totaled 0.045 t·ha^{-1}·y^{-1} in the actual climate and 0.064 t·ha^{-1}·y^{-1} in the climate change scenario. As a result, total carbon dioxide emission was higher in the scenarios with forest fires.

CHANGES IN SPECIES COMPOSITION

The different simulation scenarios resulted in different dynamics of species composition. In the scenario without disturbances, the proportion of conifers (pine and spruce) increased by the end of the simulation period for the Beliy reserve and the proportion of spruce increased for the Lyalskiy reserve in comparison to the initial values (Figure 4a, b). Forest fires led to a slight increase in the proportion of pine and birch, which are typical species of post-fire succession, while the proportion of spruce decreased insignificantly.

Discussion

MAJOR CARBON POOLS DYNAMICS AND THE IMPACT OF CLIMATE CHANGE

Growth in the carbon pool in trees is determined by the accumulation of carbon in the biomass of growing trees and

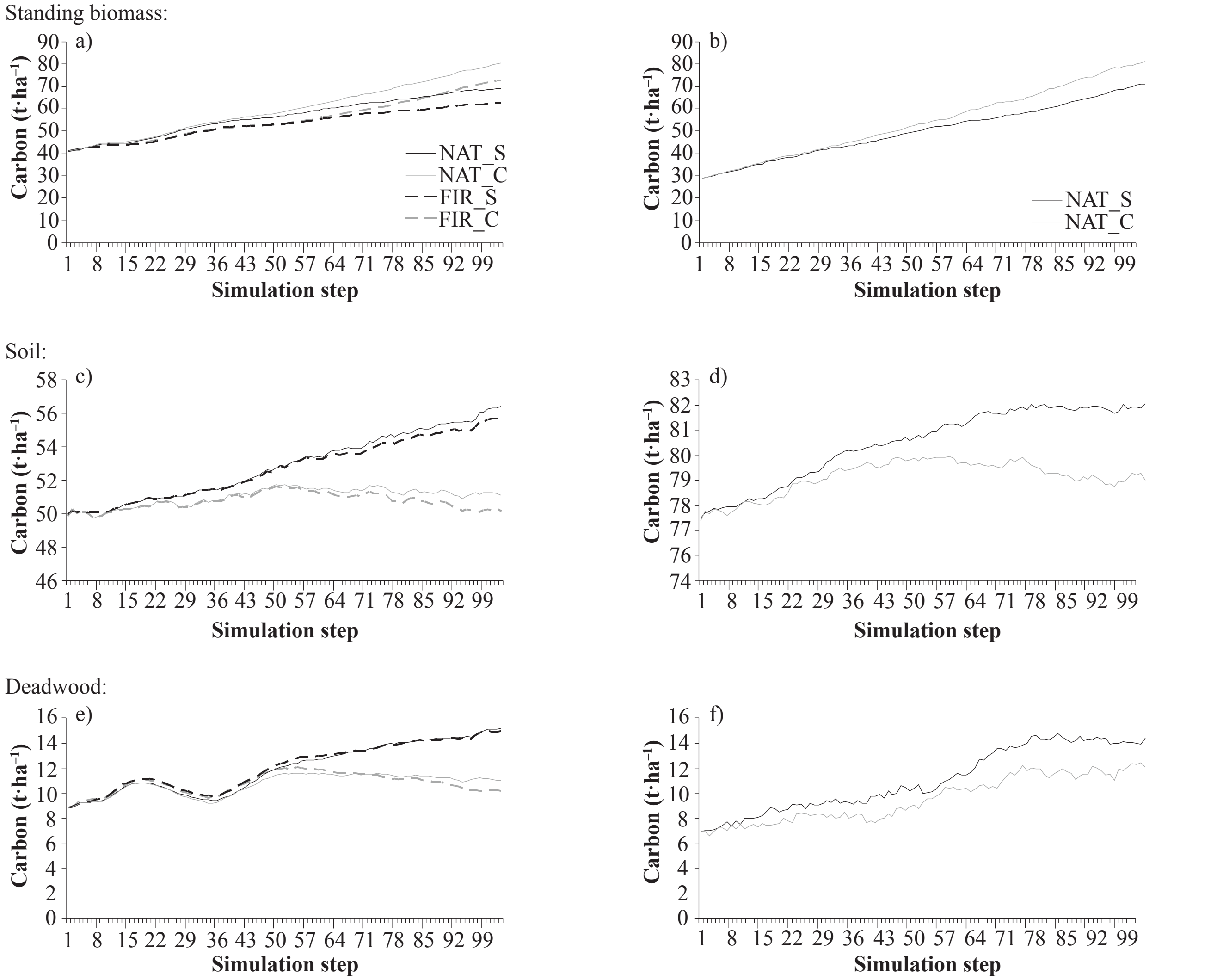

FIGURE 3. The dynamics of carbon stocks in standing biomass (a, b), soil (c, d), and deadwood (e, f) for different simulation scenarios for the Beliy (left column) and Lyalskiy (right column) reserves. NAT_S,– scenario without any influences; NAT_C, no influences, climate change; FIR_S, scenario assuming forest fires; FIR_C, forest fires + climate change.

was thus more noticeable in the Lyalskiy reserve, in which young and middle-aged stands, which have greater potential to accumulate carbon, are more prevalent, than in the Beliy reserve (Figure 3a, b). In the case of climate change (NAT_C scenario), monthly average temperatures and precipitation increase and the accumulation of carbon in the trees intensifies. The predicted increase in carbon stock in forest vegetation was about 2% per decade, which is lower than earlier estimates based on measured data (Lopatin, Kolström & Spiecker, 2006). However, the lower relative gain seen in our results can be explained by the lower productivity of northern forests.

The relative carbon gain in the FIR_C scenario in comparison to the FIR_S scenario is slightly lower than that in the NAT_S scenario in comparison to the NAT_C scenario, since the increase in stand productivity is partially negated by rising losses due to the higher fire rate. However, the productivity gain due to climate change outperforms the carbon loss caused by fires. Theoretically, the territory of the Lyalskiy reserve might become fire-prone as a result of a decrease of forest floor moisture due to climate change. However, even in the dry and hot summer of 2010, the gravimetric water content of the forest floor measured on permanent sample plots in the Lyalskiy reserve was never less than 100% (Osipov, 2013). As the climate change scenario chosen for the simulations predicts increased precipitation along with temperature growth (Table II), we postulate that the increased evapotranspiration will be offset by higher precipitation.

The accumulation of carbon in the soil can be explained by higher litterfall due to the growth and development of the stands without any external influences. Carbon accumulation in the organic horizons was slower for the Lyalskiy reserve (Figure 3c, d), with its relatively moister sites and soil types richer in organic compounds, because the rate of decomposition in such bog habitats is slower and, consequently, relative nitrogen content is lower.

Note that we calculate soil carbon supply as the sum of organic matter in the forest floor and in the mineral soil. All

Table III. Predicted changes in basic carbon pools during the simulation period due to climate change (difference between the corresponding carbon pools by the end of simulation period for NAT_C and NAT_S scenarios). Combined results for the Beliy and Lyalskiy reserves are shown.

Site type [a] (based on dominating species in ground layer vegetation)	Change (%) in: Organic layer	Stable humus	Total SOM	Standing biomass
Increasing soil fertility [b] ↓				
Cladina type	–28.7	–10.4	–17.0	14.2
Moss-*Cladina* type	–32.3	–11.7	–19.2	23.0
Vaccinium type	–32.4	–9.5	–17.0	14.7
Sphagnum type	–31.4	–5.2	–9.6	17.1
Dwarf shrubs type	–24.4	–3.8	–6.4	17.3
Ledum type	–32.8	–5.8	–10.2	16.2
Herb-*Sphagnum* type	–34.1	–3.5	–7.9	15.7
Polytrichum type	–34.1	–3.9	–8.6	20.6
Herb-grasses type	–32.7	–4.6	–10.7	17.1
Myrtillus type	–30.2	–4.1	–8.8	15.3
Oxalis type	–35.5	–6.2	–14.0	26.6

[a] Classification of forest types is based on composition of ground layer vegetation, which is related to site environmental conditions (humidity and fertility); this approach is similar to Cajander's (Cajander, 1926; 1949; Hotanen *et al*., 2008). A more detailed explanation is presented in Shanin *et al*. (2011).

[b] Corresponding range of site types in terms of humidity is *Cladina* type > moss–*Cladina* type > *Vaccinium* type > *Myrtillus* type = *Oxalis* type > herb–grasses type > *Polytrichum* type > dwarf shrubs type > herb–*Sphagnum* type > *Ledum* type > *Sphagnum* type.

Table IV. Predicted net primary production (NPP), soil heterotrophic respiration (R_h), fire-induced emission, and carbon balance for different simulation scenarios for the Beliy and Lyalskiy reserves ($t \cdot ha^{-1} \cdot y^{-1}$) mean values for the whole simulation period. Carbon balance was calculated as NPP minus R_h and fire-induced emission of carbon dioxide. NAT_S, scenario without any influences; NAT_C, no influences, climate change; FIR_S, scenario assuming forest fires; FIR_C, forest fires + climate change.

Simulation scenario	NPP	R_h	Fire-induced emission	Balance
Beliy reserve				
NAT_S	1.812	–1.458	0	0.354
NAT_C	2.071	–1.699	0	0.372
FIR_S	1.773	–1.445	–0.045	0.283
FIR_C	2.015	–1.671	–0.064	0.280
Lyalskiy reserve				
NAT_S	1.650	–1.193	0	0.457
NAT_C	1.918	–1.408	0	0.510

of the modeled areas undergoing "undisturbed" development showed both a slight increase in organic matter in the forest floor and a reduction of the stable humus stock. Apparently, in the absence of logging, the constant flow of sub- and top-soil litter involved in decomposition results in significantly greater forest floor and humus pools.

Note also that the impact of climate change on organic matter pool dynamics in the soil, and on their individual components, is much greater than the impact of forest fires, which affect relatively small areas.

Our previous investigations (Shanin *et al.*, 2011; Shanin, Komarov & Bykhovets, 2012) showed that different organic matter fractions in forest soils react differently to simulation scenarios: the humus in mineral horizons, being a kind of buffer with a long life and low decomposition rate, reacts slowly to external influences and climate change; the forest floor, as a labile fraction, is quick to react to changing external conditions, and its amount may undergo both severe short-term variations caused by fires and long-term variations with changing climate parameters.

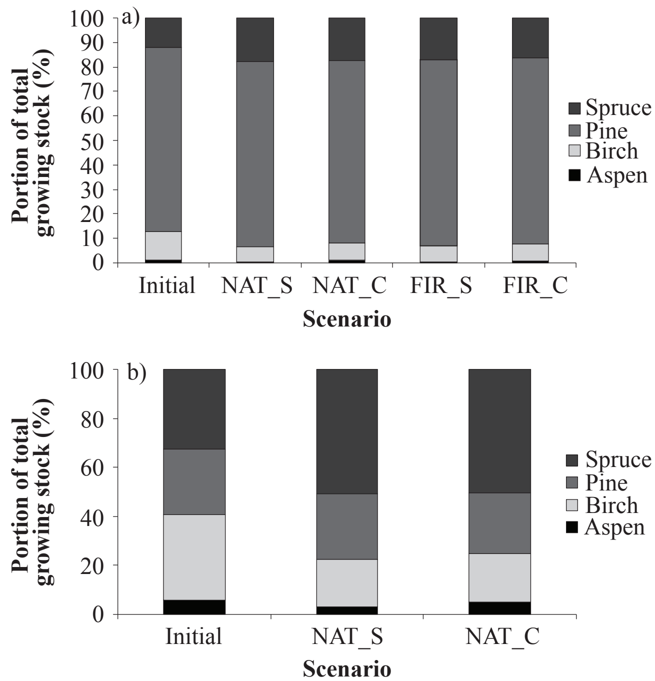

Figure 4. Initial species composition and species composition by the end of the simulation for different simulation scenarios for the Beliy (a) and Lyalskiy (b) reserves. NAT_S, scenario without any influences; NAT_C, no influences, climate change; FIR_S, scenario assuming forest fires; FIR_C, forest fires + climate change.

The carbon pool in deadwood shows slight fluctuations caused by 2 opposing processes: on the one hand, the pool is constantly renewed with dying trees damaged by fires, while, on the other hand, the fires partially burn the snag and debris pools and consequently cause additional carbon dioxide emission into the atmosphere (Figure 3e, f).

The conspicuous fluctuations in the deadwood stocks of the Beliy reserve at the beginning of the simulation period were observed in all simulation scenarios (Figure 3e). This was probably the result of the specific features of the stand age structure in the reserve. More specifically, a lot of over-mature stands in this area begin to decline just after the beginning of the simulation period, producing a large amount of deadwood. The low proportion of mature stands in the study area (see STUDY AREA, above) then leads to a decline in the mortality rate, resulting in a corresponding decrease in deadwood stock.

The current version of the model does not address the specific characteristics of snags and fallen trees, simulating them like wood residuals, with relatively slow rates of mineralization (Tarasov, 2002; Zavarzin, 2007).

Comparison of the reactions of different carbon pools under the 2 climate scenarios used in the study shows elevated (when compared to actual climate) accumulation of carbon in biomass under climate change (Figure 3a, b). The carbon pools of deadwood and soil are lower under climate change than a stable climate (Figure 3c-f). The lower proportion of litter in the total organic matter pool in soil under climate change could be caused by the higher average monthly temperatures combined with slightly higher precipitation (and thus moister litter and soil), increasing the organic matter decomposition rate more than for the labile pool of the litter.

The increased rates of decomposition in soil resulted in a lower carbon pool in deadwood. Increased activity of soil decomposers and higher mineralization rates have been noted in many previous studies (*e.g.*, Rustad *et al.*, 2001; Vetter *et al.*, 2005). The positive relationship between warming and the productivity of forest ecosystems is generally more noticeable in forests of colder climate zones (Strömgren & Linder, 2002). Unfortunately, due to a number of restrictions, the model cannot account for certain negative effects of climate change on the physiological traits of plants, *e.g.*, thermal stress, decrease of photosynthetically active radiation owing to increasing cloudiness, and reaction to a change in the hydrologic regime (Breshears *et al.*, 2009; Johnston *et al.*, 2009). This is a drawback of the simplified productivity model used in the modeling system; the advantages of the model are its high performance and the small number of parameters that are required for initialization. The model can be easily swapped for a detailed ecophysiological productivity model. However, the deviation from the precipitation norm is minor and positive, and therefore this factor is negligible when modeling for relatively short periods (matching the lifespan of a generation of trees), if any effect is noticeable at all. The EFIMOD model is also unable to simulate the effect of carbon dioxide “fertilization”. However, the extent of this effect is still a subject of discussion (Kurz, Stinson & Rampley, 2007), as some studies (Percy *et al.*, 2002; Bond-Lamberty *et al.*, 2007) have failed to observe any increase in productivity.

Comparison of the dynamics of the basic carbon pools among the different forest types (Table III) showed that sites with soil of low fertility are more sensitive to changes in the environment due to the low “buffer capacity” of their organic matter pools. This trend was most noticeable when considering changes in the pool of stable humus in mineral soil. The differences between forest types in terms of changes in the soil organic layer stock were not as significant, but the general trend was that wet sites with a thick forest floor showed a greater decrease under climate change. A possible explanation is that decomposition rates were higher in those cases due to drying of the forest floor. The increase in standing biomass was closely related to changes in the soil pools because higher rates of soil organic matter decomposition could result in higher availability of inorganic nitrogen compounds in the soil. There is also some evidence that dry habitats may be more sensitive to climate change than wet ones (Kang, Kimball & Running, 2006).

In addition to the increase in standing biomass pools resulting from the undisturbed development of stands in the NAT_S and NAT_C scenarios, changes in species composition can also have an effect on the accumulation of carbon: in our simulations, sparse birch stands were partially replaced by more productive, dense, and long-living spruce stands. Domination by species with high competitive ability is consistent with modern concepts of the development of forest ecosystems (Chumachenko & Smirnova, 2009). Climate change did not significantly influence the species composition at the modeled sites because it was affected by stronger impacts, such as fires. However, some climate change effects can be seen when comparing the NAT_S and NAT_C scenarios. In particular, climate change led to an increase in the proportion of birch and aspen (Figure 4a, b). This was the result of an increase in soil organic matter decomposition rates, and thus faster turnover, which favours pioneer species.

Carbon balance

The decrease of NPP in scenarios with fires can be attributed to forest fires damaging trees and the forest floor, thus affecting the productivity of the stand. Note that the actual NPP levels could be lower, since some natural damage sources (*e.g.*, windfall, parasitic infestation) were excluded from the scenarios addressed in this work. This allowance could lead to NPP being overestimated (Li *et al.*, 2003). Climate change also has a substantial influence over the productivity of an ecosystem; in this case, the difference between the 2 climate scenarios is greater than that between the undisturbed and the forest fire scenario, amounting to 14–16% (Table IV).

Carbon dioxide emission from soil as a consequence of mineralization depends on the amount of plant residues incorporated into the soil and subsequent decomposition processes, and on the decomposition rate. The emission rate for bilberry–sphagnum pine forests in the Lyalskiy forest reserve was reported by Osipov (2013) to be 0.7–0.9 $t \cdot ha^{-1} \cdot y^{-1}$, but this value applied only to the vegetative season. Comparison of the climate scenarios indicates that carbon dioxide emissions increase (by approximately 16%) under climate change, since increased temperature and precipitation values lead to accelerated mineralization processes for organic matter in the soil. Forest fires, on the other hand, reduce decomposable mortmass and consequently slightly reduce emissions when compared to scenarios without disturbances.

The carbon balance for each simulation scenario was calculated as the total net primary production of trees over the modeling period minus carbon dioxide emission from the soil, large decomposing plant residues, and carbon losses from the organic matter burned in forest fires. The ecosystems functioned as sinks in all scenarios, but the absolute carbon balance values were higher in the scenarios without disturbances than in the scenarios with fires.The carbon balance in the warming scenarios exceeded in absolute value that in the actual climate scenarios (the increased productivity of trees under warming conditions exceeded the increase in carbon dioxide emission), and the difference was greatest between the climate scenarios that did not include disturbances; in the climate change scenario with fires (FIR_C), additional losses of carbon occured due to higher fire activity (Table IV).

Conclusion

Analysis of the results of the simulation experiment shows that an increase in average annual temperatures and precipitation affects the distribution of the organic carbon supply. The increase in average annual temperatures causes biomass to increase and carbon in the forest litter to shrink, increasing the amount of carbon that accumulates in the organic matter of the mineral soil horizons.

As our previous studies showed (Chertov *et al.*, 2006; Shanin *et al.*, 2011; Komarov & Shanin, 2012), an increase in decomposition rates raises the amount of nitrogen in the soil that is available for plants to consume, which causes a productivity increase for trees. The greatest growth in the carbon pool occurs in the scenario without disturbances, accompanied by the development of highly productive, uneven-aged coniferous stands. This scenario also produces the maximum flow of carbon into forest ecosystems.

It is worth noting that all of the modeled forests and scenarios showed a positive carbon balance, probably because the territories modeled consisted mostly of young and middle-aged stands. A full analysis would require analytical data on the possible dynamics of mature and over-mature forests in the same scenarios of climate change and forest fires. The net ecosystem productivity of forests between 15 and 800 y of age (net carbon balance of the forest, including soil) is usually positive (Luyssaert *et al.*, 2008), despite the longstanding view, originating with Odum (1969) and continuing into recent decades (Gower, McMurtrie & Murty, 1996, etc.), that old-growth forests are carbon neutral. It is sometimes argued that increased nitrogen deposition will increase forest growth in Central Europe (Högberg, 2007; Janssens *et al.*, 2010; Högberg, 2012). We found that the low level of nitrogen deposition in the Komi Republic in comparison with Central Europe (Komarov & Shanin, 2012) would lead to a negligible effect on forest growth in this territory. Climate change could be more influential. Nevertheless, further research is needed to determine the overall carbon balance of forests in the north-east of European Russia.

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