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Simulation of the Carbon Budget for Different Scenarios of Forest Management

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Abstract—The effect of different scenarios of forest management on the carbon budget in forest ecosystems of the Dankovskii forest (Moscow oblast) is analyzed with the use of the EFIMOD model of the soil–forest vegetation system. Four scenarios of long-term (200 years) forest management have been simulated: (a) natural development, (b) existing practice (business-as-usual), (c) selective cutting, and (d) illegal cutting. The maximum sequestration of carbon in the forest ecosystem is predicted for the scenario of natural development. Forest cutting reduces carbon sequestration in the ecosystem. Only selective cutting ensures a net carbon sink in the ecosystem. Illegal forest cuttings result in a negative carbon budget in the ecosystem.

INTRODUCTION

Mathematical computer-based simulation of various processes is a convenient tool to test our theoretical concepts and make necessary corrections to them. Mathematical simulation is especially promising for studying those objects and processes that cannot be studied through direct experiments because of their spatial dimensions and/or characteristic times. Forest ecosystems are one of such objects. Often, it is impossible to estimate element fluxes in these ecosystems for considerable time spans. In the recent past, the simulation method has been applied widely for studying the carbon budget in forest ecosystems [4, 10, 11, 13, 14]. This is due to an increasing demand for quantitative estimates and forecasts of the carbon budget, which can be obtained only by the simulation method or by the rapid development of information technologies.

MATERIALS AND METHODS

In our study, the EFIMOD model of the forest–soil system has been used [2, 5, 7, 12]. This model belongs to the class of individual-based models; i.e., it simulates a forest stand composed of individual trees. This approach makes it possible to trace population-based mechanisms of the development of forest stands (competition for light and nutrients, tree mortality indices, etc.) and assess the effect of various forest management practices (tree planting, cutting, etc.) taking into account their spatial differentiation. The EFIMOD model includes the ROMUL submodel describing the dynamics of organic matter decomposition in the soil [8]. The ROMUL submodel describes the decomposition of different components of tree falloff (stem wood, branches, roots, and leaves) taking into account the difference in the rates of the corresponding processes. The model structure makes it possible to use information from standard descriptions of forest stands as input variables. The modeling of stand growth is performed with the time step of one year; the modeling of soil processes is performed with the time step of one month. Inputted climatic data are derived from the SCLISS generator of the soil climate [1]. The outputs of the model include standard indices of the assessment of stand quality, data on the pools of carbon and nitrogen in the tree stand and in the soil, data on the CO_2 emission from the soil, etc. The modeling can be performed for short-term and long-term periods; the spatial resolution of the model can vary from a particular forest plot to the entire area of the forest. The results of the modeling can be analyzed with the help of the CommonGIS system for visualization of spatial and temporal data [6, 9]. In this paper, we analyze the dynamics of carbon in the tree stand and soil.

The case study was performed for 104 control plots within four sections of the Dankovskii Forest with a total area of 273.4 ha. The Dankovskii Forest is part of the Russkii Les (Russian Forest) Experimental Forest located on the left bank of the Oka River, 100 km to the south of Moscow. This territory represents an ecotone between coniferous and broad-leaved forests developed on the sandy and loamy soddy-podzolic soils; it belongs to the southwestern subregion of the Atlantic continental forest-climatic region. According to agroclimatic parameters, it is characterized by a moderate heat and water supply [3].

The territory of the forest was actively used in the 17th–20th centuries; at present, it is covered by secondary forests. The species composition and age structure of these forests depend on the time of the last clear cutting and on the character of natural regeneration of the

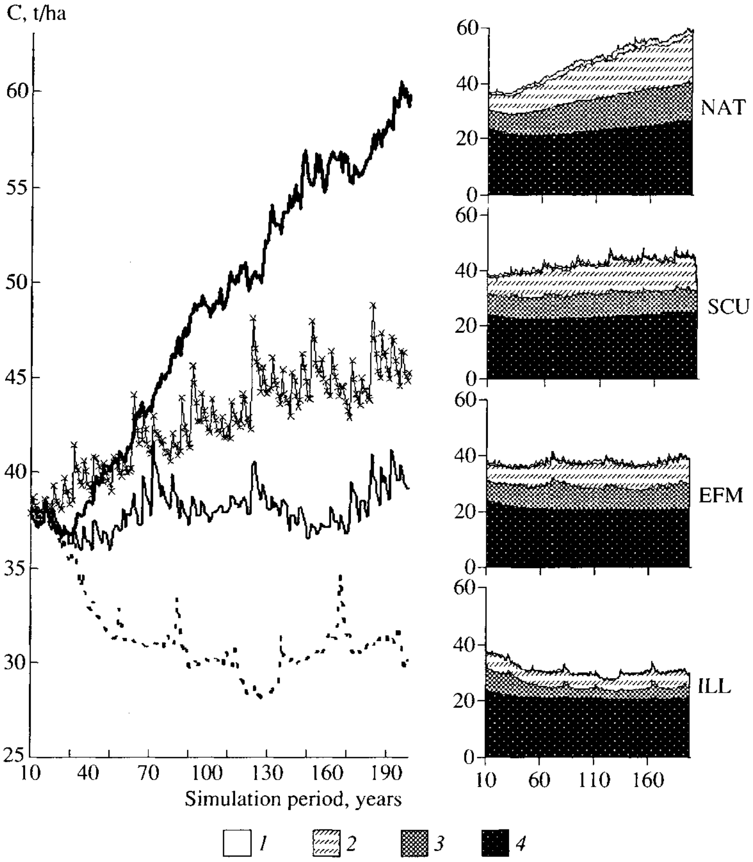

Fig. 1. Soil carbon dynamics from different scenarios of forest management (NAT, natural development; SCU, selective cuttings; EFM, existing practice of forest management; and ILL, illegal practice of forest management). Organic matter pools: (*1*) undecomposed litter, (*2*) semidecomposed litter, (*3*) labile soil humus, and (*4*) stable soil humus.

forest stands. Pine, birch, and lime predominate in the species composition of the stands; in some areas, there is an admixture of spruce, aspen, and oak trees. Young stands (with an age of less than 40 years) occupy 12% of the forestry; medium-age stands (40–60 years) predominate in the area (53%). Ripening stands (60–80 years) occupy 35% of the territory.

The carbon budget in the stand–soil system has been modeled for four different scenarios: (a) natural development, (b) existing practice of forest management, (c) selective cutting, and (d) illegal cutting.

The scenario of natural development (NAT) suggests that the tree stands are not subjected to cutting and other disturbing impacts. To model the natural regeneration of tree stands, artificial planting of the main tree species was performed at cutting places once in 30 years. The density of forest plantations reached 4000 trees/ha. The particular proportion between the planted tree species depended on the site conditions. At the sites with poor soils (habitat of class A according to P.S. Pogrebnyak), the following proportion was used: pine, 30%; birch, 50%; and alder, 20%. At the sites with moderately and highly fertile soils, the proportion between the main tree species was different: pine, 15%; spruce, 20%; birch, 25%; alder, 15%; oak, 10%; and lime, 15%.

The scenario of the existing practice of forest management (EFM) suggests that tree stands are subjected to four tender cuttings and, then, to a clear cutting. Tender cuttings are performed according to the following schedule: on the fifth year (to rarify dense tree plantations and ensure sufficient lighting of the trees), on the tenth year (disengagement cutting), on the twenty-fifth year (severance felling), and in the fiftieth year (advance felling). The clear cutting operation includes the burning of felling debris. The time of the clear cutting depends on the predominant tree species within the given plot. Thus, for the plots with a predominance of birch and lime, the clear cutting is performed in the 80th year; for the plots with a predominance of spruce, in the 100th year; for the plots with a predominance of pine, in the 120th year; and for the plots with a predominance of oak, in the 140th year. In the year after the clear cutting, the artificial planting of trees (10000 trees/ha) is performed at the felling places (to imitate natural regeneration of forest vegetation).

The scenario of selective cutting (SCU) suggests that the tree stands are subjected to two tender cuttings (in the 25th and 50th year) followed by a series of selective cuttings at a rate of 30% of the stand density (the sum of tree sections at the breast height) over a period of 30 years. After the selective cuttings, artificial planting of the trees (4000 trees/ha) is performed.

Finally, the scenario of illegal practices (ILL) suggests that the tree stands are subjected to one intermediate cutting (at the age of 50 years) of the best trees and clear cutting at the age of 80 years, without the preservation of ripening trees and with the burning of felling debris. The artificial planting of trees (imitating the natural regeneration process) is performed on the third year after the clear cutting at a rate of 6000 trees/ha. On poor soils, the species composition of planted trees is as follows: pine, 5%; birch, 70%; and alder, 25%. At the other sites, the species composition of newly created stands is as follows: spruce, 5%; birch, 25%; alder, 20%; and lime, 50%.

RESULTS AND DISCUSSION

Let us analyze the results of the simulation of carbon dynamics in the soil and in the tree stands. As can be seen from Fig. 1, the carbon pool of the soil is more stable. The maximum accumulation of carbon in the soil takes place in the case scenario of natural development (22 t/ha per 200 years). In the case scenario of selective cutting, the accumulation of organic carbon in the soil reaches 7.4 t/ha per 200 years; in the case scenario of the existing management practice, it decreases to 1.3 t/ha per 200 years. Finally, in the case of the scenario of illegal practices, the soil carbon pool decreases by about 8.2 t/ha per 200 years. The presence of undecomposed forest litter is predicted only in the case of the scenario of natural development. The pool of stable humic substances varies insignificantly and does not depend on the scenario of forest management. The scenario of natural development is accompanied by a considerable accumulation of carbon in the deadwood (up to 30–40 t/ha). In the other scenarios, the carbon pool in the deadwood is two to three times lower.

The patterns of carbon dynamics in the tree stands are more diverse, which is explained by the fact that the stands are subjected to the most significant anthropogenic impacts (Fig. 2). For a period of 200 years, the net primary production (NPP) constitutes 1273.3 t C/ha in the case scenario of natural development, 1107.2 t C/ha in the case scenario of selective cuttings, 950.3 t C/ha

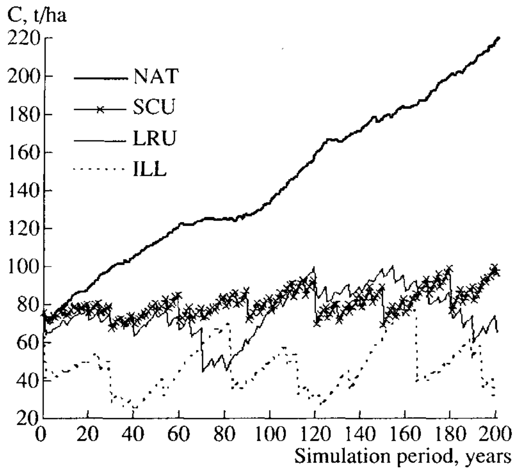

Fig. 2. Carbon dynamics in the tree stands from different scenarios of forest management (NAT, natural development; SCU, selective cuttings; EFM, existing practice of forest management; and ILL, illegal practice of forest management).

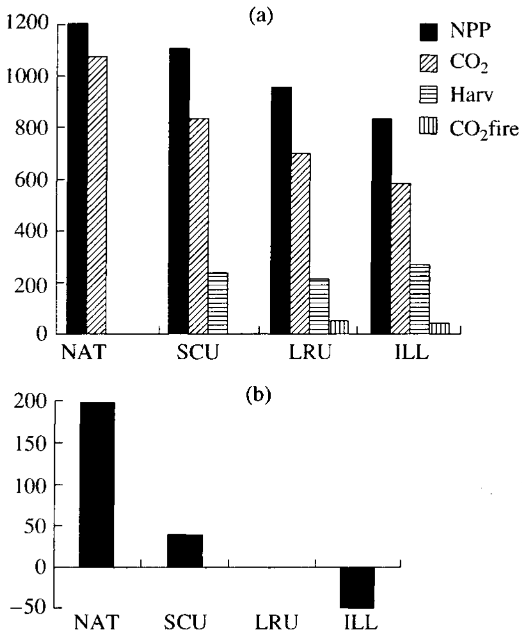

Fig. 3. Carbon budget in the tree stand–soil system from different scenarios of forest management (NAT, natural development; SCU, selective cuttings; EFM, existing practice of forest management; and ILL, illegal practice of forest management) for the entire period of simulation (200 years): (a) major carbon fluxes (NPP, net primary production; CO_2, CO_2 emission; Harv, wood harvest; and CO_2 fire, burning of felling debris) and (b) carbon accumulation in the system.

in the case scenario of the existing practice, and 830.2 t C/ha in the case scenario of illegal practice. The emission of CO_2 from the soil is generally proportional to the NPP (Fig. 3a). The maximum extraction of carbon (with felled trees) from the ecosystem is observed in the case scenario of illegal practice (265.5 t C/ha); the scenario of selective cuttings yields 235.3 t C/ha of carbon, whereas the scenario of the existing practice yields 208.6 t C/ha. The burning of felling debris results in the additional removal of 46.9 and 35.3 t C/ha from the ecosystem under the scenarios of the existing and illegal practices, respectively.

The predicted values of the carbon budget in the entire ecosystem for a period of 200 years are displayed in Fig. 3b. As can be seen from this figure, the illegal practice leads to a net loss of carbon from the ecosystem (about 49.7 t C/ha). The net accumulation of carbon in the ecosystem (about 38 t C/ha) during the simulated period takes place in the case scenario of selective cuttings. In the case scenario of natural development, the net accumulation of carbon in the ecosystem might reach 200 t C/ha. The existing practice of forest management does not lead to considerable changes in the carbon pool of the forest ecosystem: the predicted loss of carbon should be about 0.5 t C/ha.

CONCLUSIONS

The results obtained in this study allow one to judge the merits and demerits of the particular scenarios of forest management with respect to the carbon budget in the ecosystem. This is important for finding the optimum strategy of forest management. As follows from the model, the scenario of selective cuttings ensures the maximum accumulation of carbon in the forest ecosystem and yields a considerable amount of wood. In practice, the optimum strategy of forest management may include different practices (except for illegal cuttings) adjusted to the local conditions of the relief, the soil quality, the availability of roads for wood transportation, etc.

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