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Aggregated Estimation of Basic Parameters of Biological Production and Carbon Budget of Russian Terrestrial Ecosystems: 3. Biogeochemical Carbon Fluxes

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Abstract—The biogeochemical cycle of organic carbon in Russian terrestrial ecosystems in 1990 is considered. Its components have been estimated as follows: net primary production, 4354 million metric tons of carbon (Mt C); annual amount of plant detritus, 3223 Mt C; heterotrophic soil respiration, 3214 Mt C; biomass utilization, 680 Mt C; damage to vegetation caused by fire and pests, 140 Mt C; and removal by surface and ground waters, 79 Mt C. Anthropogenically regulated fluxes of organic carbon (820 Mt C) are comparable to its amount involved in the natural cycle.

Key words: biogeochemistry of terrestrial ecosystems, balance of biogeochemical carbon fluxes, greenhouse gases.

This work is a part of the forest research project "Full Carbon Account for Russian Terrestrial Ecosystems" implemented by the International Institute for Applied Systems Analysis and some Russian research agencies (Nilsson *et al.*, 2000). Attention is focused on the hypergene transformation of organic carbon and its redistribution (in the gaseous, liquid, and solid phases) in the geosphere, i.e., on its biogeochemical fluxes (BGCFs). A theoretical basis for their analysis has been created by specialists in biogeochemistry (Vernadsky, 1965; Glazovskaya, 1996). Numerous publications are devoted to specific aspects of BGCFs. Among them, attention should be paid to general studies on the biological cycle of organic carbon (Bazilevich, 1978, 1993; Bazilevich *et al.*, 1986; Kobak, 1988), humus formation (Orlov, 1990), emission of carbon dioxide (Stolbovoi, 2003) and methane (Zelenev, 1996), primary ecosystem production (Mokronosov, 1999; Shvidenko *et al.*, 2000, 2001), and carbon migration in the aqueous phase (D'yakonova, 1972; Ponomareva and Plotnikova, 1972; Belousova, 1983; Romankevich and Vetrov, 1997; Vinogradov *et al.*, 1998).

To date, the importance of the carbon cycle problem has gone far beyond the context of purely scientific knowledge. The Kyoto protocol to the United Nations Framework Convention on Climate Change (*UNFCCC...*, 1998) is aimed at reducing anthropogenic carbon fluxes to the atmosphere. In our opinion, a partial assessment of the carbon cycle is insufficient for its comprehensive characterization and, hence, cannot be used as a basis for making decisions concerning its control. For example, measures taken to change hydrologic conditions and improve productivity in order to enhance carbon assimilation may cause drainage of peat deposits and uncompensated carbon emission resulting from their mineralization. However, comprehensive assessment is impossible without a detailed knowledge of the specific regional features of carbon turnover, their spatiotemporal variation, the processes accounting for carbon fluxes, their interactions, and the methods of their control. These problems have priority in the new Global Carbon Project.

The purpose of this study was to create a systemically integrated computer model of the main BGCFs to assess the full carbon budget of Russian terrestrial ecosystems. The results of this work represent an integrated spatiotemporal profile for the year 1990, which was obtained and analyzed by means of GIS technologies on the basis of numerous sources of relevant information.

MATERIAL AND METHODS

The method of geosystems analysis used in this study is based on georeferenced digital databases for geochemically coupled fluxes of organic carbon. The main sets of data (agricultural statistics and the data of land and forest inventories) concern the period of 1988–1993 and are accessible to a wide circle of specialists (Stolbovoi and McCallum, 2002). The type of data arrangement in a computer allows the analysis of both individual data sets and their combinations based on unity in terms of geographic location (coordinates), which is the essence of GIS technologies (Burrough, 1986; Magure *et al.*, 1992). Details concerning GIS analysis of organic carbon pools are considered using an example of Russian tundras (Stolbovoi, 1998).

When the assessment of biogeochemical fluxes is made for large areas, it is important to estimate the reliability (significance) of its results. Although the amount of relevant data is vast, they are structurally heterogeneous and have been obtained and verified by different methods. Therefore, their statistical and geographical representativeness and, hence, reliability cannot be correctly estimated by the classic methods of statistical analysis. Taking into account that the problem at issue belongs to the category of fuzzy problems, we have used an approach allowing us to estimate uncertainties in fuzzy systems (Shvidenko and Nilsson, 2003). Confidence intervals indicated below are partly based on subjective (personalistic) probabilities and correspond to a confidence probability of 0.9.

The biological productivity of Russian terrestrial ecosystems was characterized in our previous work (Shvidenko *et al.*, 2001). The vegetation map of the Soviet Union (*Rastitel'nost' SSSR…*, 1990) provided a geometric background for constructing an electronic database. The corresponding segment of the map included 100 plant associations and approximately 4500 polygons (contours). The database provided detailed information about the stocks of phytomass and its fractions, as well as the annual net primary production of ecosystems. This information, derived from numerous publications and archive data by N.I. Bazilevich and many other specialists, was supplemented by characteristics of arable lands (calculated from statistical data on crop yields) and data of the State Forest Inventory (Shvidenko *et al.*, 2000, 2001). In addition, the database included information about the calculated turnover of root necromass and the rate of plant debris humification (Grishina, 1986).

Arable lands were delimited using the land-use (soil) database created on the basis of the map of land quality classes (*Karta…,* 1989). Organic carbon transformation was calculated for individual soil polygons (contours) (Stolbovoi and McCallum, 2002). The legend to this database included approximately 160 items associated with 1300 polygons.

Soil respiration and CO_2 emission were among the attributes of the soil database. The corresponding data were derived mainly from the review by Kudeyarov *et al.* (1995) and some other publications (Makarov, 1988; Fedorov-Davydov and Gilichinskii, 1993) and supplemented by the results of more recent investigations. A detailed analysis of this database was made in the previous paper (Stolbovoi, 2003).

The values of specific CH_4 emission taken from the study performed by Zelenev (1996) were linked with the aforementioned polygons of the soil database. Note that Zelenev's calculations were based on the international soil database of the FAO (1974–1981), which was not very accurate in reflecting the present-day knowledge of Russian soils (Stolbovoi and Sheremet, 1997).

The fluxes of organic carbon migrating with surface and ground waters were estimated using the database on its hydrochemical sink. As the initial data, we used the results of studies by Vinogradov *et al.* (1998), Romankevich and Vetrov (2001), and some other authors. The geometric component of the database was represented by the drainage areas of rivers of different orders, which were delimited on the basis of a global three-dimensional topographic model (Stolbovoi and McCallum, 2002). The magnitudes of groundwater carbon fluxes correlating with the concentrations of dissolved organic matter in lysimetric solutions were taken from available publications (Ponomareva and Plotnikova, 1972; D'yakonova, 1972; Belousova, 1983).

Anthropogenic fluxes of organic carbon are related to the production and utilization of agricultural and forest products. We calculated carbon emission resulting from the use of organic fertilizers and soil liming (in addition to soil respiration), as well as fluxes accounted for by the vital functions of livestock. The data pertaining to agriculture were taken from statistical reports (*Sel'skoe khozyaistvo…*, 1995). Calculations were made by the methods approved by the Intergovernmental Group of Experts on the Problem of Climate Change (*IPCC…*, 1997).

The data on carbon fluxes resulting from various kinds of damage to the plant cover (see below) were considered with regard to the full carbon budget (Nilsson *et al.*, 2000).

RESULTS AND DISCUSSION

The net primary production of ecosystems in 1990 amounted to 4354 million metric tons of carbon (Mt C) (table). This value is slightly above the average level of photosynthetic activity in the long-term developmental cycle of Russian terrestrial ecosystems. The factors enhancing their productivity include climate warming, an increased duration of the growing season, and intensification of vegetation recovery after damage sustained in previous years (Hulme, 1995; Myneni *et al.*, 2001; Shvidenko and Nilsson, 2003; Stolbovoi, 2003).

The total amount of plant detritus (necromass) reached 3223 Mt C, or about 74% of the net photosynthetic production. The amount of above-ground necromass (59%) was slightly greater than that of underground necromass because of the large proportion of forests in the plant cover of Russia.

The above-ground necromass is almost fully utilized by the soil microbiota and fauna. The consumption of its greater part (96–97%) by soil organisms is accompanied by CO_2 emission (Grishina, 1986; Glazovskaya, 1996). Decomposed organic matter (88–92%) is released into the atmosphere mainly in the form of CO_2. A small amount of organic carbon is removed

Biogeochemical fluxes of organic carbon in the Russian territory in 1990

Flux	Magnitude, Mt C per year	Comments
Net primary production	4354 ± 118	For all terrestrial ecosystems of Russia
Detritus:		Including detritus formed in natural ecosystems and the results of economic activities (afterharvest crop residues, wastewood in felling areas, etc.)
above-ground	1907 ± 71	
underground	1316 ± 60	
Total	3223 ± 93	
Anthropogenic fluxes:		The first two fluxes were calculated from statistical data by internationally accepted methods (IPCC..., 1997). The third item refers to additional biomass consumption (not taken into account above) for manufacturing food products, as well as utilization of forest and other plant products, with regard to export–import fluxes (calculated using the results of expert evaluation)
agriculture	290 ± 20	
stored products of the timber industry	81 ± 15	
others	311 ± 33	
Total	682 ± 43	
Damage to the plant cover:		Direct emission in the year of damage
forest fires	89 ± 10	
insect pest outbreaks	49 ± 6	
Total	138 ± 11	
Organic matter transformation		
heterotrophic respiration	3214 ± 124	Total emission of CO_2 (3194 Mt C) and CH_4 (20 Mt C)
humus balance (Hum)	22 ± 4	Calculated taking into account the increments of biomass and concentration of dissolved organic matter
Transport by waters:		Surface runoff carries suspended organic particles coming from above-ground necromass; subsurface drainage carries dissolved organic matter leached from the litter and deeper soil horizons
surface runoff	9 ± 3	
subsurface drainage	50 ± 13	
deep drainage	20 ± 13	
Total	79 ± 13	
Net biome production (NBP)	–340 ± 176	Calculated value

by surface runoff. According to our estimation, it does not exceed 0.5% of the total amount of detritus. The remaining part is converted into the water-soluble form and migrates with soil solutions down the soil profile and laterally.

Decomposition of underground necromass is accompanied by heterotrophic soil respiration, the outflow of water-soluble products, and humification (Grishina, 1986; Orlov, 1990). The rate of humification depends on a number of factors, including the amount and quality of necromass, soil type, climate, and other geographic conditions. We used the averaged coefficients of humification of underground necromass (dead roots) for the soil–vegetation zones of Russia (Grishina, 1986; Orlov, 1990). The total amount of newly formed humus was estimated at approximately 122 Mt C. Assuming that most of the natural ecosystems and soils in Russia are in a state of quasi-equilibrium, it could be concluded that the humification of organic carbon coming with necromass is counterbalanced by its mineralization. In the course of the analysis, we allowed for a trend toward an increase in humus content due to the increment of phytomass and the consequent proportional increase in the amount of necromass and the rate of organic carbon mineralization in the litter.

Heterotrophic soil respiration accounts for the sum of gaseous products of organic carbon transformation (including mineralization of the remains of soil fauna and decomposition of coarse woody debris) and, hence, is the main mechanism of CO_2 return to the atmosphere. In 1990, approximately 3194 Mt C were released with CO_2 by heterotrophic soil respiration, which agreed with the previous estimation (3120 Mt) made by Kudeyarov *et al.* (1995). Note, however, that the validity of approaches to determining heterotrophic soil respiration, the duration of the biologically active period, and other parameters used in our calculations has been considered questionable (Stolbovoi, 2003). In this study, CO_2 emission at above-zero temperatures was taken into account.

According to the most recent data, the global CO_2 flow resulting from soil respiration amounts to 60000 Mt C. Taking autotrophic respiration as one-third of the total, we estimate heterotrophic soil respiration on the global scale at 40000 Mt C. Thus, the contribution of Russia to global soil respiration is about 8%, which is almost one-third smaller than the part of the world's total land area occupied by Russia (12%). This disproportion is explained by a relatively low rate of biological turnover in a country with a cold climate, which agreed with the data on a relatively low specific productivity of Russian ecosystems (Shvidenko *et al.*, 2001).

Compared to CO_2 emission, CH_4 emission from Russian soils is much lower, approximately 20 Mt C. Zelenev (1996) estimated this parameter at a similar value (18 Mt C). The greatest contributions to CH_4 emission belong to three categories of natural soils: gley, peat, and alluvial soils. As the area of irrigated and swamped soils is limited, CO_4 emission from them has not been considered. Global CH_4 emission from natural overmoistened soils is about 35 Mt C (Fung *et al.*, 1991). Thus, Russian overmoistened soils produce more than half of the global CH_4, which corresponds to the great proportion of wetlands (more than 30%) in the soil cover of our country.

Carbon transport by waters is accounted for by surface and subsurface flows carrying mineral and organic carbon in the forms of solutions and suspensions. According to our calculations, the outflow of organic carbon with the waters of Russian rivers, including its transport in the continental Caspian and Aral Seas, reaches 59 Mt, with 85% of this amount being water-soluble organic carbon carried by river flow in the low-water period. This estimation agrees with published data (Vinogradov *et al.*, 1998; Romankevich and Vetrov, 2001). Organic suspensions are transported mainly during floods. Thus, according to Vinogradov *et al.* (1998), the Lena River transports approximately 5300×10^3 t of organic carbon during a flood, compared to 3000×10^3 t in the low-water period.

In the regions with a humid boreal climate, the concentration of water-soluble organic carbon in soil solutions is fairly high. According to the results of lysimetric studies (Ponomareva and Plotnikova, 1972; Belousova, 1983), it varies from 30 to 100 mg/l, on average, depending on soil texture. Concentrations indicated in other review articles are similar: 80–100 mg/l (Glazovskaya, 1996) or 30–10 mg/l (Thurman, 1985). However, the concentrations of organic carbon dissolved in river waters in the low-water period are markedly lower, varying from 15 to 25 mg/l (Vinogradov *et al.*, 1998; Romankevich and Vetrov, 1997). This is evidence that a large part of the organic carbon migrating out of the soil profile is mineralized or absorbed by rocks in the aeration zone. A high rate of organic carbon accumulation in deep soil horizons is confirmed by its high content at a depth of 2 m (approximately 20% of the total stock) (Stolbovoi, 2002) and in most types of loose deposits (0.1–1.5%) (Kramer, 1994). Thus, only part of the water-soluble organic carbon leached from the soil enters the streams and migrates to the terminal basins.

At the global level, the amount of organic carbon transferred by surface runoff has been estimated at 400 Mt. Therefore, the corresponding flux from the Russian territory reaches almost 20% of the global flux, which is more than 1.5 times greater than the share of Russia in the world's total area of drainage basins. To a large extent, this is explained by the accumulation of plant debris on the soil surface and the formation of deep organogenic soil horizons. According to our estimations, approximately 60% of the total organic matter in Russian soils concentrates in their organogenic horizons, which is 20% greater than the average degree of organic carbon accumulation in the upper soil horizons in other parts of the world (Batjes, 1996; Stolbovoi, 2002).

Anthropogenic fluxes of organic carbon have been estimated at 820 Mt. Biomass consumption for feeding and the production of energy and raw materials accounts for 80% of this amount; the rest is accounted for by direct emission resulting from damage to the plant cover (mainly by fire and pests). It is noteworthy that the magnitude of anthropogenic fluxes markedly exceeds the magnitude of total organic carbon flow to the lithosphere and hydrosphere, which confirms the concept of a massive geochemical impact of human activities, formulated by Vernadsky (1965). Moreover, this concept implies the possibility of controlling the carbon cycle in order to regulate the chemical composition of the atmosphere. However, this problem should be approached comprehensively, based on the integrated assessment of all carbon fluxes, which has not yet been achieved.

Net primary production is the main income article in the organic carbon budget of terrestrial ecosystems (table). Reverse fluxes to the atmosphere resulting from heterotrophic respiration, consumption of plant products, and damage to the plant cover are the main expenditures of organic carbon. In addition, some organic carbon is lost due to its transport to the coastal and inland water areas. The balance of organic carbon income and expenditure is the net biome production. It reaches approximately 340 Mt C, which corresponds to the amount of atmospheric carbon sequestered by Russian terrestrial ecosystems in 1990, the reference year for the Kyoto protocol (*UNFCCC…*, 1998).

Our estimation of the net biome production is in agreement with the general trend in the dynamics of organic carbon exchange in the Russian territory over the past few decades. This is the trend toward organic carbon accumulation promoted by climate change and the ensuing increase in the duration of the growing season and the activity of photosynthesis (Hulme, 1995; Myneni *et al.*, 2001; Lucht *et al.*, 2002). According to our data (Stolbovoi *et al.*, 2001), organic carbon accumulation in individual ecosystems and elements of their landscape mosaics is geographically nonuniform. At high latitudes, climate warming stimulates peat accumulation in the dominant peaty gley soils. In peat deposits, conversely, intensification of peat mineralization is observed. There is evidence for a recent increase in the specific biomass density in open tree stands of the forest–tundra zone (Kharuk *et al.*, 1999). In the forest–steppe and steppe landscapes, carbon emission from the soil increases due to more active substitution of forest vegetation by herbaceous associations at the southern boundary of these landscapes. The results of detailed studies on boreal forests (Shvidenko and Nilsson, 2003) and tundra ecosystems (Zamolodchikov and Karelin, 1998) confirm these conclusions.

CONCLUSIONS

(1) Components of the biogeochemical cycle of organic carbon in Russian terrestrial ecosystems in 1990, the reference year for the Kyoto protocol, were as follows (annual data): net primary production of plant ecosystems, 4354 Mt C; annual formation of plant detritus, 3223 Mt C; heterotrophic respiration, 3214 Mt C; carbon transport to coastal sea areas and deep layers of the lithosphere, 79 Mt C; biomass utilization, 680 Mt C; and damage to the plant cover inflicted by fire and pests, 140 Mt C. The net biome production, i.e., the amount of carbon sequestered by Russian ecosystems in 1990, reached approximately 340 Mt.

(2) The magnitude of anthropogenic carbon fluxes (820 Mt C per year) is comparable with that accounted for by natural processes. This fact confirms Vernadsky's concept of a massive geochemical impact of human activities and provides evidence for the possibility of controlling the biogeochemical carbon cycle in the Russian territory.

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