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CARBON AND NITROGEN CYCLES AND THE COMPOSITION OF GREENHOUSE GASES

Carbon Budget and Emission of Greenhouse Gases in Bog Ecosystems of Western Siberia

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Abstract—Generalized data on carbon dioxide and methane emission that were obtained from a study of different bog ecosystems in the northern, middle, and southern taiga subzones using a uniform procedure are presented. The average estimates of the CO_2 and CH_4 contents in the surface atmosphere layer and bog water are given. The main carbon-cycle constituents of the bog ecosystems are scrutinized both for different subzones and for the entire territory of the forest–bog zone. The tendency to sequestering carbon by the West Siberian bogs along the latitudinal–zonal climatic gradient is discussed. The reassimilation of CO_2 inside the peat massif is proved experimentally. A new conceptual model of the carbon cycle in surface ecosystems is developed on this basis.

INTRODUCTION

The accumulation of greenhouse gases in the atmosphere is a current global environmental problem. Taking account of sources and runoffs, the assessment of their power and dynamics, as well as study of their functioning mechanisms are necessary for understanding the essence of changes occurring in the environment. Bog ecosystems stand out in this respect due to their wide variety and geographical spreading. The role of bogs in the planetary carbon cycle, as well as in manifestation of the greenhouse effect, still remains unknown.

Peat mires and wetlands occupy about 40–60% of the West Siberian territory, i.e., about one million km^2. Their considerable extent in the longitudinal direction and leveled relief result in a markedly zonal distribution of heat and moisture, which controls the distribution of the main types of bog ecosystems as well as the facial and provincial structure of the landscapes. The carbon cycle parameters have not been investigated much in this region, which is unique in terms of extensive bogging. Studies on carbon dioxide and methane emission started in 1992 [25, 26] were restricted to only the bog massif in the southern taiga subzone. In bog ecosystems of the middle and northern taiga subzones, emission of greenhouse gases has remained unstudied until recently. The absence of data on the sources and discharge of carbon dioxide and methane for most of the area has prevented researchers from making an adequate assessment of its contribution to global processes. This report presents data on CH_4 and CO_2 fluxes measured by the author in different subzones in West Siberia according to a standard field procedure in the period from 1999 to 2001. The peculiarities of the carbon cycle in bog ecosystems are discussed.

This research was aimed at obtaining quantitative estimates on carbon dioxide and methane emission in different bog ecosystems operating under close climatic conditions as well as in bogs of one type located in different bioclimatic zones. This approach was believed to provide more ample evidence on gas exchange between mires and the atmosphere permitting extrapolation of the results obtained in the field to the bulk of the West-Siberian Plain.

OBJECTS AND METHODS

The zonal distribution of mires suggested the method of key sites to be the principal investigation procedure. The fluxes of CH_4 and CO_2 were measured at the surface of different bog ecosystems for each key site, which characterized the most widespread type of bog landscape in the northern, middle, and southern taiga. The observation key sites were situated in the vicinity of the following settlements: Noyabr'sk (63°10′ N, 75°30′ E), Nizhnevartovsk (60°56′ N, 76°50′ E), and Plotnikovo (56°50′ N, 82°50′ E). The vegetation, the peculiarities of bog development, and the climatic and other conditions at the key sites have been described in detail in publications [3, 20]. The measurements were carried out in summer at the following places: (1) an ombrotrophic bog surrounded by a ridge–swamp–lake complex with pine–shrub–sphagnum (PSS) and sedge–sphagnum (SS) communities; an ombrotrophic flat-hummocky swamp on the permafrost (FHP); and a meso-oligotrophic and minerotrophic sedge–sphagnum mire (SSM) in the valley of the small Yanga–Yakha River (northern taiga, 1999); (2) an ombrotrophic mire massif with a ridge–swamp–lake complex in its central part and swamp complexes in its periphery and at the boundary with mineral islands with

Table 1. Grouped average estimates of carbon fluxes at the key sites (mg C/m^2/hour), average ± standard deviation (sample volume)

Key site, ecosystem (area, %)	Respiration, R_d	Net-assimilation, P_n	Methane emission, E_m
Northern taiga	22.2 ± 6.7 (196)	25.1[1]	0.47 ± 0.21 (209)
SSM (3.3)	41.1 ± 1.0 (60)	Not det.	0.80 ± 0.12 (60)
PSS (30.0)	30.8 ± 13.6 (19)	Not det.	0.00 ± 0.01 18()
SS (24.6)	15.4 ± 3.1 (27)	Not det.	1.05 ± 0.56 (26)
FHP (15.9)	12.6 ± 0.3 (90)	Not det.	0.39 ± 0.09 (105)
Middle taiga	10.4 ± 1.4 (152)	22.2 ± 11.7 (150)	0.32 ± 0.08 (130)
SSSM (2.1)	16.5 ± 2.5 (12)	19..4 ± 33.1 (12)	0.24 ± 0.19 (12)
PSS (35.0)	12.6 ± 1.7 (62)	29.1 ± 12.0 (60)	0.01 ± 0.03 (52)
SS (40.5)	6.7 ± 0.9 (72)	13.5 ± 9.7 (72)	0.60 ± 0.12 (60)
SSM (2.2)	36.3 ± 4.9 (6)	77.0 ± 25.0 (12)	0.30 ± 0.12 (6)
Southern taiga	34.7	44.5	0.81
PSS (33.4)	33.2[2]	Not det.	0.35[3]
SS (51.5)	35.8 ± 2.2 (63)	46.4 ± 22.0 (69)	1.10 ± 0.10 (63)
SSS (7.3)	33.8 ± 2.5 (42)	37.9 ± 15.2 (46)	0.88 ± 0.09 (42)

[1] Value is calculated from the budget equation $P_n = G \times (P_g/G)_{av}$, where G is the green phytomass reserve, $(P_g/G)_{av}$ is the average intensity of gross-photosynthesis (per 1 g of green phytomass) according to the observations at the middle and southern taiga mires; phytomass reserves are borrowed from [9].

[2] According to [22].

[3] According to [22, 23].

* Not det. designates that the fluxes were not measured.

pine–shrub–sphagnum (PSS), sedge–sphagnum swamp (SS), and sedge–sphagnum mire (SSM) communities, the minerotrophic bog massif near the southern slope of the Aganskaya elevation in a shrub–sedge–sphagnum mire association (SSSM) in the middle taiga; and (3) at the periphery of an ombrotrophic bog with a ridge–swamp complex in shrub–sedge–sphagnum (SSS) and sedge–sphagnum (SS) communities (southern taiga, 2000).

Carbon dioxide emission was measured using the chamber static method during daylight in a 3- to 3.5-hour interval. In some periods, the field measurements of emission fluxes were carried out for a 24-hour cycle. The total volume of the exposure chamber was equal to 2 l with a base area of 100 cm^2. For measuring the total respiration, the chambers were covered by a dense cover with the reflecting surface made out of aluminum foil. In the course of exposure, three samples were taken with a syringe in a 10-minute interval. After the cover had been removed, the fourth sample was taken in the same interval. To gain a high reliability of results, carbon dioxide and methane fluxes were calculated according to the stochastic diffusion model [27] and the routine linear regression equation. The net-assimilation rate was estimated from the variation of carbon dioxide concentrations inside the exposure cambers at daylight after the removal of the protective cover. Gas samples were analyzed with a "Kristall 5000" chromatographer with a flame-ionization detector and methanator (SKB "Khromatek", Russia). The measuring block was equipped with an M-3m × 2mm packed column with Porapak N 80/100 using argon as a carrier gas at 60°C.

Bog water was sampled at different depths with a brass tube. The composition of dissolved gases was chromatographically analyzed according to the above-described procedure after their displacement by a saturated salt solution or the establishment of gas equilibrium with argon. The reference data on the physical properties of gases were used in calculations.

RESULTS AND DISCUSSION

Calculations were based on the seasonal-average values of carbon dioxide and methane fluxes in various bog ecosystems. The indices for a subzone were calculated using the average weighed method taking into account the areas occupied by bog ecosystems at the key sites (Table 1). A general trend toward an increase in carbon dioxide and methane emission as well as carbon net-assimilation in the southward direction is revealed. The difference in carbon cycles between the middle and northern taiga must be related to the more complex pattern of the northern key site and the greater variability of fluxes under these conditions. We suppose also that a certain relative increase in the budget parameters may be caused by the varying metabolism of plants and microbes requiring supplementary energy for growth and sustaining vital functions under the conditions of the permafrost. Within one subzone, bog ecosystems with a richer mineral nutrition are also characterized by higher average values of the carbon fluxes. A low methane emission from the bog surface in the northern and middle taiga should be noted. This is related to the fact that about 30–35% of bog massifs is occupied by pine–shrub–sphagnum bogs that operated as weak sources of methane only in the beginning of the warm season and consumed methane from the atmosphere for most of the time.

The content of greenhouse gases in the surface air layer should also be regarded as the main factor controlling the gas exchange between mires and the atmosphere, because the steady-state concentration gradients influence the rate of gas diffusion out of soil and carbon dioxide ingress to the green plant leaves. The experimental tests revealed a close linear correlation between the net-assimilation rate and the CO_2 concentration inside the exposure chambers. This seems to prove that the bog plant photosynthesis is restricted by CO_2 within the range of 0.03–0.1 of its volume % in daylight. The key sites differed significantly in the CO_2 and methane concentrations in the surface atmosphere layer (near the sphagnum surface). In the northern, middle, and southern taiga, the calculated average concentrations of gases (ppm) constituted 463.30 ± 4.06, $n = 212$; 416.73 ± 3.95, $n = 150$; 555.43 ± 9.69, $n = 130$ for CO_2; and 0.95 ± 0.21, $n = 206$; 2.27 ± 0.16, $n = 149$; 1.01 ± 0.08, $n = 130$ for CH_4, respectively. The content of carbon dioxide in the surface atmospheric layer in this row fits the variation in the rate of total respiration and net-assimilation in the same direction.

The methane content in the atmosphere over the northern bog in the vicinity of Noyabr'sk settlement shows an irregular impulse distribution for a relatively low average concentration. The widespread permafrost may supposedly suppress methane formation and the dynamics of atmospheric gas composition. In the southern and middle taiga, the CH_4 content in the surface atmosphere layer is mainly controlled by local sources and discharges. The impact of local conditions on methane dynamics in a high-moor bog and adjacent landscapes was also noted by Vomperskii [4]. The average background concentration of CH_4 was equal to 1.7 ppm [1]. According to our estimates, the average concentration of methane was equal to 2.21–2.27 ppm in the surface atmosphere layer to a height of 2 m over the mires in the vicinity of Nizhnevartovsk in summer. For a relatively low emission from natural sources (Table 1), this value must be caused by a significant contribution of fossil CH_4 passing to the atmosphere upon the intense development of oil and gas deposits. The results of the isotope analysis of atmospheric methane in the regions of intense development of gas deposits in the Western Siberia also point to the considerable contribution of an anthropogenic component [5, 24].

Three methods of gas transfer in bog soils are usually considered, i.e., molecular diffusion in gas and liquid phases, bubble transportation, and flow through the aerenchyma of vascular plants. Plant transportation obviously appears to be a passive diffusive transfer. To assess the roles of diffusion and bubble components, we used the data on gas distribution from the profile. The fluxes of dissolved methane and carbon dioxide were calculated according to the diffusion equation. We believed that the contribution of bubble transfer to the atmosphere is equal to the difference between the methane emission measured by the chamber method and the calculated diffusive flow. The passive transportation through plants was discounted for the total and aeration porosity equal to 0.95 and 0.04, respectively. According to the calculations, the methane and carbon dioxide emission measured by the chamber method exceeds substantially the diffusive flows of these gases in the liquid phase. For example, the share of dissolved methane ranged from 6.2 to 13.2% of its emission to the atmosphere in the oligotrophic sedge–sphagnum bog in the middle taiga. This index appeared to be the highest for mires of ground-water and mixed alimentation (14.0 and 32.5%, respectively). For the same objects, the share of dissolved CO_2 flow ranged within wider limits, i.e., 1.8–19.8% and 0.6–1.6% (for SS and SSM–SSSM, respectively) of its emission into the atmosphere. Direct analysis of the gaseous phase composition revealed either equilibrium or close to the equilibrium state between the dissolved and bubble gases. For instance, at a depth of 150–180 cm, the gaseous phase in the oligotrophic sedge–sphagnum swamp contained at different times 6.7–8.4% CO_2, 45.3–65.7% CH_4, 25.6–45.1% (N_2 + Ar), and 0.5–1.2% O_2, the latter apparently having penetrated into samples upon their collection and preparation for analysis. The bubble CO_2 obviously cannot contribute significantly to the total flow. Thus, the bubble transportation of methane to the atmosphere prevails at the studied objects. Its role may be even greater taking into account the high methane-oxidizing activity of sphagnum. As compared to diffusion and respiration of the surface plant parts, the bubble transportation of CO_2 contributes insignificantly to the total flux.

The budget calculations were based on the seasonal-average values of carbon fluxes obtained for the key sites from the following equation: $Y_{\text{balance}} = [P_n\tau - R_d(24 - \tau) - 24E_m]\Delta t - L$, where τ is the duration of daylight, Δt is the duration of a season with the air temperature above 0°C, P_n is assimilation, R_d is respiration, E_m is methane emission, and L is carbon discharge with bog water outside the ecosystem (Table 2). The carbon loss L was calculated proceeding from the water budget for each subzone [14] and the dissolved carbon content in bog water in the form of organic compounds, carbon dioxide, and methane.

The obtained values of carbon accumulation in the West Siberian mires seem to be somewhat overestimated, since they do not take into account carbon fluxes

Table 2. Carbon accumulation in West Siberian mires of oligotrophic and mesotrophic alimentation based on carbon dioxide and methane fluxes measured in the field

Subzone	Bog area, 10^3 km^2	Fluxes, g C/m^2/year					Y_{budget}, T g C year^{-1}
		P_n	R_d	E_m	L	Y_{budget}	
Northern taiga	183	65.5	19.3	1.6	11.0–14.9	29.7–33.6	5.4–6.1
Middle taiga	186	66.0	12.7	1.3	22.5–29.0	23.0–29.5	4.3–5.5
Southern taiga	170	146.0	56.9	4.0	13.6–21.4	63.7–71.5	10.8–12.2
Total	539						20.5–23.8

Note: Bog areas are given according to the data of Yefremov and Yefremova, 2001.

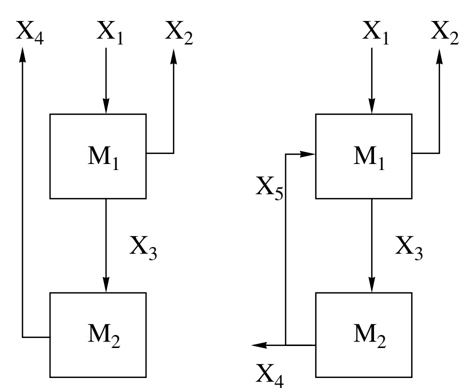
into the atmosphere in winter. Another error is related to the selected procedure specifics, i.e., the limited size of exposure chambers that do not permit us to measure the gas exchange of the aboveground parts of trees and large shrubs. In our opinion, the opposite sign of these summands mitigates the risk of obtaining inadequate final budget parameters. We think, however, that it is too early to extrapolate the data obtained over the entire forest–bog zone of Western Siberia, because eutrophic swamps may contribute rather significantly, in particular, in the southern part.

The rates of carbon sequestering listed in Table 2 agree with the data on peat accumulation obtained from radiocarbon dating [8, 11, 20]. The methane emission to the atmosphere (1.22 Tg C year^{-1}) is much lower than the previously published value [19, 25] and appears to be more realistic.

Specifics of the carbon cycle in bog ecosystems. The organic-substance accumulation in the form of thick peat deposits represents one of the carbon-cycle specifics in bog ecosystems. CO_2 is assimilated from the environment in the course of photosynthesis of primary producers, and the unique species assemblage of phytocenosis controls the spatial distribution of the input flow to the ecosystem. The main events related to the transformation of organic substances in the carbon cycle occur below the daylight surface, for which the moss surface is taken. These processes encompass the entire peat layer. However, stating the importance of carbon cycle studies, we have to admit that our knowledge of the structure and functioning of the subsurface (swamp ecosystems, in particular) is insufficient for assessing the status and dynamics of the most significant natural objects undergoing global environmental changes [21].

It is believed that carbon entry into the ecosystem is mainly controlled by pure primary phytocenosis production also referred to as visible photosynthesis or net-assimilation; whereas carbon return to the atmosphere in the form of CO_2 occurs due to the mineralization of organic remnants (heterotrophic respiration) [7, 13, 15]. A similar general scheme is applied to the carbon cycle in bog ecosystems [4]. In this case, methane is added to the output flux. However, direct comparison of gas emission with the pure initial product values [29] shows that a considerable amount of carbon can participate once again in re-assimilation processes inside the ecosystem. A thick moss cover effectively captures carbon dioxide emitted upon decay. The assimilation of CO_2 by bacteria in the dark should also be considered [5]. Methane ascending to the aeration zone from deep peat layers is oxidized to CO_2 by methanotrophic microflora and is also added to the soil carbon cycle. The experiments with tracer carbon performed with *Sphagnum fuscum* [28] testified to the consumption of the extracted soil CO_2 by the moss cover upon photosynthesis. Therefore, it appears to be reasonable to include the inner transformation cycle to the general scheme of the carbon cycle enclosed in the atmosphere (Fig. 1b).

Mathematical ecology presents the balance relationships between biogeocenosis components (ecosystems) in the form of vertical structure or trophic chain models [17]. Two kinds of trophic chains are usually considered, i.e., open (flowing) and closed (cyclic) chains. Formally, the new stress put on the biological carbon cycle interpretation in surface ecosystems implies a transition from the adopted "flowing" scheme to the



The scheme of two-level vertical structure of carbon fluxes in surface ecosystems. (A) flowing and (B) cyclic systems. M_1 is the carbon reserve in the above-ground phytomass, M_2 is the soil pool of carbon; X_1 is photosynthesis, X_2 is respiration; X_3 is litter, translocation; X_4 is the emission and outflow with runoff; and X_5 is re-assimilation.

"cyclic" scheme (Fig. 1). Previous publications give a general analysis of mathematical models of trophic chains and the conditions of their existence and equilibrium stability [16, 17]. Therefore, proceeding from the problems set, we restricted our investigations to the comparative consideration of the "lowing" and "cyclic" models with two trophic levels.

Note that the systems discussed are specified by the so-called paradoxical structure of trophic chains with higher reserves at the lower level as compared to the upper level. The balance equations for the schemes shown in Fig. 1 appear as follows:

$$\frac{dM_1}{dt} = X_1 - X_2 - X_3 \quad \frac{dM_2}{dt} = X_3 - X_4$$

(a) the flowing system

$$X_1 = k_1C, \quad X_2 = k_2M_1, \quad X_3 = k_3M_1, \quad X_4 = k_4M_2$$

(b) the cyclic system

$$\frac{dM_1}{dt} = X_1 + X_5 - X_2 - X_3 \quad \frac{dM_2}{dt} = X_3 - X_4$$

$$X_1 = k_1C, \quad X_2 = k_2M_1, \quad X_3 = k_3M_1, \quad X_4 = k_4M_2, \quad X_5 = \alpha k_4M_2.$$

Symbol **C** designates the carbon dioxide concentration in the atmosphere. Parameter α determines the degree of completeness of the inner carbon cycle. Because the inflow to the ecosystem is limited by carbon dioxide (photosynthesis), the regime lacking nutrition (with "strained" trophic bonds) is established there. This permits us to write the following equations for carbon fluxes in the chain: $X_i = k_iM_i$ ($i = 1, \ldots, 5$), where $\mathbf{k_i}$ is the constant of the appropriate process rate. Substituting the expressions for the flux rates to balance equations, we come up with two systems of differential equations describing the carbon dynamics in surface ecosystems:

$$\frac{dM_1}{dt} = k_1C - k_2M_1 - k_3M_1 \qquad \begin{cases} M_1^* = \dfrac{k_1C}{(k_2 + k_3)} \\ M_2^* = \dfrac{k_1k_3C}{(k_2 + k_3)k_4} \end{cases}$$

$$\frac{dM_2}{dt} = k_3M_1 - k_4M_2$$

(a) the flowing system

$$\frac{dM_1}{dt} = k_1C + \alpha k_4M_2 - k_2M_1 - k_3M_1$$

$$\frac{dM_2}{dt} = k_3M_1 - k_4M_2$$

$$\begin{cases} M_1^* = \dfrac{k_1C}{(k_2 + k_3\alpha k_3)} \\ M_2^* = \dfrac{k_1k_3C}{(k_2 + k_3 - \alpha k_3)k_4} \end{cases}$$

(b) the cyclic system.

Setting the right sides of the equations equal to zero, we find the conditions of stationary solutions. The formulas provided attest to a single stationary state for both systems, specified by M_1^* and M_2^* carbon reserves at trophic levels. We may show that the roots of characteristic equations are negative numbers. In this case, the special (stationary) point represents a stable center, around which the forces operate returning the system to equilibrium.

$$M_1(t) = C_1e^{\omega_1t} + M_1^*$$

$$M_2(t) = C_1ke^{\omega_1t} + C_2e^{\omega_2t} + M_2^*$$

$$k = k_3/(k_2 + k_3 - k_4) \quad \omega_1 = -(k_2 + k_3) \quad \omega_2 = -k_4.$$

For the model discussed, the general solution may be written as follows:

(1) for the flowing system:

(2) for the cyclic system:

$$M_1(t) = C_1(\omega_1 + k_4)e^{\omega_1t} + C_2(\omega_2 + k_4)e^{\omega_2t} + M_1^*$$

$$M_2(t) = C_1k_3e^{\omega_1t} + C_2k_3e^{\omega_2t} + M_2^*$$

$$\omega_{1,2} = \frac{1}{2}[-(k_2 + k_3 + k_4) \pm \sqrt{(k_2 + k_3 + k_4)^2 - 4}k_4(k_2 + k_3 - \alpha k_3)].$$

Here, ω_1 and ω_2 are the roots of characteristic equations, and $\mathbf{C}_1$ and $\mathbf{C}_2$ are the constants depending on the carbon reserves at trophic levels at the time instant $t_0 = 0$ and the coefficients in model equations. The obtained solutions show the asymptotic time dynamics of carbon reserves M_1 and M_2, which complies with the results of direct investigations of the peat profile [6].

As proceeds from analysis of the solutions of the mathematical models discussed, the carbon reserve reaches a value close to the stationary state rather quickly at the first trophic level. For the sedge–sphagnum bog with atmospheric alimentation, the following values of model parameters were obtained: $X_1 = 68.3$ gC/m^2/year, $k_2 = 0.11$ year^{-1}, and $k_3 = 0.57$ year^{-1}. At present, the average carbon reserve in peat is equal to about 200 kg/m^2 [11]. If a carbon reserve of 200 g/m^2 in the surface phytomass is assumed to correspond approximately the stationary state, it is easy to calculate the α parameter of soil cycle closeness, which turns out to be equal to 0.6. Thus, 60% of carbon was reutilized inside the peat deposit. About 90% of the stationary carbon reserve is concentrated in peat now [6], which corresponds to 5.2×10^{-4} year^{-1} for k_4. Substituting the appropriate parameter values into the $M_2(t)$ equation (the cyclic model), we can find in what time period M_2 will differ from the stationary value by less than 1%. According to our calculations, this time period τ constitutes 17690 years, which fits our prediction assessment of mire dynamics in Western Siberia given in [6]. The open system model suggests a τ value of about 8850 years. However, there is evidence on persisting peat accumulation in the bogs that has already reached this “critical” age.

The inner carbon cycle model may be used for describing the organic substance dynamics in ecosystems with mineral soils. A closed regime is evidently realized in forest ecosystems with a specific vertical structure of aboveground layer r and in dense agricultural crops. These peculiarities should be also taken into account upon assessing the regional budget values. The difference between the CO_2 total emission from the soil-cover surface (3.12 G t C) and the photosynthesis product value (4.4 G t C) for the territory of Russia [12] may result from the conceptual discrepancy rather than methodological errors. This is also the reason for the fact that the global budget models of the open (flowing) type [2, 10, 18, etc.] cannot predict reliably the biosphere process dynamics. The bulk of carbon circulates inside the ecosystem (pedosphere) exerting no substantial effect on the gas composition of the atmosphere. The adoption of the new conceptual model fitting the close (cyclic) model will provide the possibility for a more adequate description of processes operating in the biosphere.

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