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PALEOCRYOGENESIS AND SOIL FORMATION

CARBON DIOXIDE PRODUCTION BY NORTHERN TAIGA SOILS OF WESTERN SIBERIA (NADYM SITE)

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Two-year field research has revealed that soils of northwestern Siberia are characterized by low values of carbon dioxide production, indicating their low biological activity. The value of CO_2 emission in the peak of a vegetative season varies from (40 ± 21) mg/(m²·hr) on the old and (108 ± 41) mg/(m²·hr) on the young frozen peatland to (210 ± 68) mg/(m²·hr) in the forest. The lowest values of carbon dioxide emissions and the concentration inside the profile are observed for soils with shallow permafrost and as a result, low temperature.

Western Siberia, CO_2 *emission, peatland, cryogenesis, greenhouse gases*

INTRODUCTION

Over the recent years, the interest for permafrost soils of the earth has considerably grown, which is related to recognition of the global biospheric functions of the soil cover. Together with the traditional issues of soil and soil cover pollution and destruction in the North, serious attention is being paid to the problem of the carbon balance of northern ecosystems due to the threat of the global climate change and possible permafrost degradation [*Billings, 1983; Christensen, 1992; Fedorov-Davydov and Gilichinsky, 1993; Davidson et al., 2002; Kurganova and Tipe, 2003; Zamolodchikov et al., 2003; Masyagina et al., 2005; Reth et al., 2005; Heimann and Reichstein, 2008; Shmelev et al., 2013*]. As these ecosystems function under conditions of severe heat shortage, they are most vulnerable to temperature changes.

The main trend of the global climate change consists in modeling its scenarios, with evaluation of the sensitivity of these models to such parameters as soil characteristics, like hydrothermal, biological characteristics, etc. [*Billings, 1983; Heimann and Reichstein, 2008*]. Insufficiently investigated is the issue of the impact of cryogenesis on the processes related to carbon dioxide production in soil and its behavior in the soil profile.

In considering the issues of carbon dioxide flows, it is necessary to differentiate certain concepts: CO_2 emission is a process characterizing efflux of CO_2 from the soil surface into the atmosphere, and CO_2 production, which is formation of this gas as a result of biogenic and abiogenic processes in soil. Often a concept of "soil respiration" is used, denoting the process of CO_2 evolution and of oxygen consumption by soil. The value of CO_2 emission varies in soils within the range of n (10–1000) mg/(m²·hr). CO_2 production in soil includes several components: microbial root exudations, root respiration, and microbial decomposition of organic matter [*Davidson et al., 2002*], and is an important integral characteristic of the biological activity of soils. Among the components participating in the soil respiration, microbes have the major importance, while roots account for about one-third of the total CO_2 production [*Kobak, 1988; Soil Respiration..., 1993*]. The respiration intensity and the content of CO_2 in the soil air depend on the hydrothermic characteristics, the level of ground waters, the physical properties of the substrate, the growth of the aboveground and root mass of plants and on the specific features of organic matter transformation. Some researchers [*Smagin et al., 2010*] have demonstrated that it is not correct to identify gas emission from three-phase ecosystems with their biological activity and to interpret the regularities of the response of the respiration process to temperature and moisture changes from a purely biological standpoint. Soil respiration, on the one hand, characterizes the total metabolism of the soil animals, microorganisms and underground plant organs and, on the other hand, it reflects the specific features of the physical and physic-chemical processes in the organo-mineral substrate mass [*Naumov, 2009*]. For example, in some estimates, the total CO_2 production in wetland soils may exceed its surface emission by a factor of 1.2–1.5 due to accumulation, redistribution, lateral and vertical gas transport and its interaction with the aqueous and solid soil phases [*Smagin, 2005*]. Modern literature actually has no data on the impact of permafrost on the intensity of CO_2 production and its subsequent life in cryogenic soils.

The objectives of the present study are as follows: 1) to evaluate the regularities of carbon dioxide production by the soils of geocryologically differing ecosystems of western Siberia; 2) to reveal the causes of variability of this characteristic; 3) to evaluate the impact of geocryological conditions on the gas function of soils.

OBJECTS OF STUDY

The investigations were carried out in the north of western Siberia (Nadym district, Tyumen region) in the interfluve area of Rivers Heygiyakha and Levaya Heta. The important characteristics of the region under study are its location on the northern border of northern taiga, a large number of water bodies and the presence of sporadic permafrost located under peatland, which accounts for the unique features of the terrain in terms of combination and the degree of expression of the cryogenic processes of different scale and attributed to different times. The specific features of the territory allow researchers to choose objects significanty differing by their geocryological conditions and located in a relatively small territory.

The territorial landscapes are sharply contrasting and are divided into two main types, differing by the degree of hydromorphism and the presence of permafrost. These are forest landscapes, where permafrost is now absent, and wetlands, represented by oligotrophic marshes as such and by specific permafrost terrains – young and old frozen peatland, with permafrost located 1–2 m deep [*Moskalenko, 2012*].

Three sites were selected as the key monitoring sites, being specific both from the botanical, edaphic and geocryological viewpoints: pine forest (65°18′52,8″ northern latitude, 72°52′54,2″ eastern longitude), young frozen peatland (65°18′54,4″ northern latitude, 72°52′10,0″ eastern longitude), and old frozen peatland (65°18′55,1″ northern latitude, 72°52′33,9″ eastern longitude).

The forest site is represented by lichen pine forest. The vegetation mostly consists of *Pinus sibirica*, *Larix sibirica*, *Betula* sp. in the overstorey; representatives of the Ericaceae family, namely *Vaccinium uliginosum*, *Vaccinium myrtillus*, *Vaccinium vitisidaea*, *Ledum* sp. – in the middle storey; *Polytrichum strictum*, *Cladonia rangiferina*, *Sphagnum* sp. – in the lower storey. Soil formed under conditions of deep permafrost was classified as Folic Podzol [*IUSS…World reference base for soil resources…, 2006*]. The podzol profile consists of peated substrate about 10 cm thick, sporadically expressed lighted sandy-eluvial horizon (от 0 до 5 cm), sandy loam horizon up to 30 cm thick, gradually changing into sandy rock of non-homogeneous colouring – from grey to yellowing-brown. The pH of the soil changes from strongly acidic (3.4) in the organogenic horizon to acidic (4.5) in the lower horizons. In the organogenic horizon, the content of organic carbon reaches 45 %, while in the mineral rock is it about 1 %.

The vegetation of the young frozen peatland is represented in the ground cover by different lichens and mosses (*Cladonia rangiferina*, *Cladonia stellaris*, *Cladonia sylvatica*, *Sphagnum* sp.), in the subshrub layer – by *Betula nana*, *Rubus chamaemorus*, *Ledum* sp., *Vaccinium uliginosum*, *Vaccinium myrtillus*; for the grass layer, the most typical plants are the representatives of the Cyperaceae family – *Eriophorum* sp., *Carex* sp. Permafrost was uncovered on average at the depth of 60 cm in the sand layer. Soil was classified as Turbic Cryosol. The profile consists of reindeer lichen tirr (peat containing a substantial fraction of live non-vascular vegetation), peat horizon, poorly decomposed in the upper part and medium-decomposed in the lower part. In the lower part of the peat horizon, whitish sandy interlayers are found. The total thickness of the peat layer is about 40 cm. Peat is of the oligotrophic type. About 50 % decomposition degree and the prevalence of the remains of *Sphagnum* sp. and of the subshrub roots of the Ericaceae family can be seen. The mineral part is represented by strongly mixed sabulous horizons of non-homogeneous colouring – grey, whitish, and brownish. The soil is acidic, with pH slightly varied in the horizons from 4.2 in the organic part to 5.0 in the mineral part. The content of organic carbon in peat horizons is about 40 %, while that in the mineral horizons does not exceed 0.3–1.5 %. The ash content of the peat is on average 9 %.

Old frozen peatland is an undulating surface of a series of hillocks elevated over the bog. This area is characterized by the locally bare peat spots, sparse vegetation, and permafrost from 40 cm in the peat layer. Vegetation on the overgrown areas is represented by *Ledum* sp., *Betula nana*, and in depressions by *Cladonia* sp. Soil was classified as Cryic Histosol. The profile consists of a series of peat horizons of different composition: from the horizon with the prevailing remains of *Betula nana* L. and of subshrub roots of the Ericaceae family in the upper part of the profile, which allows it to be referred to the oligotrophic birch type, to the horizon having remains of *Equisetum palustre* L., *Comarum palustre* L., *Betula pubescens* Ehrh., *Carex* sp. (including *Carex lasiocarpa* Ehrh.) in the lower part of the profile, which determines the peat type as eutrophic. The degree of peat decomposition changes down the profile from 60 to 45 %. The soil is acidic throughout the profile, and pH varies from 4.0 to 4.5. The peat has low ash content and a large portion of organic carbon (about 50 % throughout the profile). In addition, increased amount of total nitrogen is found in the peat of old frozen peatland. The radiocarbon dating data testify that the peat age in this type of terrain is essentially higher that the age of the peat of old frozen peatland (5,000 and 1,500 years, respectively) [*Matyshak, 2009*]. All these data indicate the relict character of the peatland. Currently it is likely to be degrading.

THE STUDY METHOD

Temperature profiles were taken on the sites, including measuring the temperature of air, soil surface and horizons at the depths of 10, 20, 40, and 60 cm with a 3 hr interval. Loggers Thermochron iButton™ were used for these measurements. Carbon dioxide emission from the soil surface was measured by the closed chamber technique [*Orlov et al., 1987; Reth et al., 2005*] in a fivefold series, several times a day in August – September, 2010–2011 (the total number of probes exceeding 100 for each site). To measure carbon dioxide concentrations at different depths, sealed tubes were placed in the soil, 1 cm in diameter and perforated on the bottom part. Sampling was conducted with a rubber stopper several times a day. CO_2 concentrations were measured with a portable GAZ ANALYZER DX6210 gas analyzer. Statistical processing of the data was carried out using the Statistica 6.0 software program.

CARBON DIOXIDE PRODUCTION

It was found during the study that emission of carbon dioxide by the soils of the ecosystems is low to amount on average for all the sites to (119 ± 84) mg/(m^2·hr).The values of CO_2 obtained significantly differ at the sites investigated (Fig. 1): from (40 ± 21) mg/(m^2·hr) on old frozen peatland to (210 ± 68) mg/(m^2·hr) on the forest site. Young frozen peatland occupies an intermediate position, where CO_2 emission is (108 ± 41) mg/(m^2·hr). The high values of standard deviation are accounted for, on the hand, by high variability of the parameter by sites and years, and, on the other hand, by the fact that the measurements were taken considering daily temperature fluctuations. It is to be noted that, by the results of statistical processing, the sites reliably differ for the carbon dioxide emission, and the confidence intervals practically coincide for the two years of measurements (Fig. 1). The data obtained suggest low biological activity of soils in the region, although, as mentioned previously, the studies were conducted in the peak of the vegetation season.

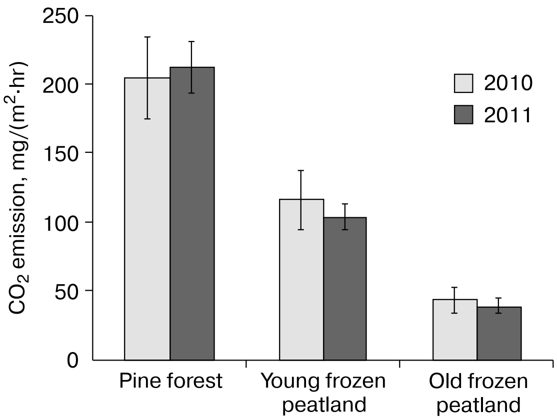

Fig. 1. Carbon dioxide emission from soil surface (August–September).

The vertical line denotes the confidence interval.

CARBON DIOXIDE CONCENTRATION IN SOIL

The emission value does not fully reflect biological activity in the soil, as it is the function of not only the biological processes going on in the soil, primarily physical processes. The processes of gas diffusion are related to soil humidity, temperature, climatic characteristics of the near-surface air, etc. Evaluation of the gas function only by the amount of emission may be underrated, as part of the gas gets accumulated and redistributed in the soil [*Smagin, 2005*].

To ensure more detailed evaluation of carbon dioxide production and to compare the sites based on this characteristic, we measured the gas concentration values immediately in the soil at different depths, using the method described above. Simultaneously with measurements of CO_2 concentrations, soil temperatures were measured at the same depths.

The general trend for all the soils investigated is gradual increase in the concentration of carbon dioxide from 0.1 to 0.2–0.5 %, related to its movement down the profile. This type of a curve (belt-like) describing changes in carbon dioxide concentration is characteristic of most soils.

Podzol of forest ecosystems is characterized by the maximum averaged values of CO_2 concentrations (0.18–0.50 % – in 2011), despite the low organogenic horizon thickness, where gas is mostly generated. Concentrations of carbon dioxide in permafrost soils are similar: from 0.1 % in the upper horizons to 0.2–0.3 % directly beside permafrost. To take an example, at the depth of 20 cm, the differences in the CO_2 concentrations are less than 0.1 %, while at the depth of 60 cm they reach 0.3 % (Fig. 2).

Peatland soils are characterized by much smaller increases in CO_2 concentrations as the depth increases, compared to forest soils. The authors assume that this is related to dissolution of carbon dioxide in cold solution formed when the seasonally frozen layer of the soil gets frozen. At the level of top permafrost, activity of aerobic microbes may be inhibited due to low temperatures approaching 0 °C and increased humi-

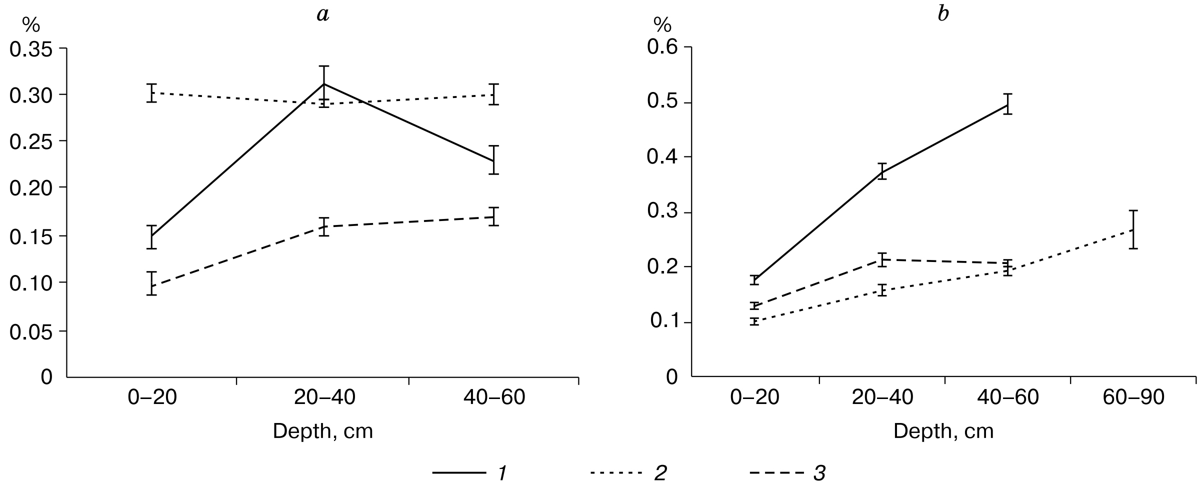

Fig. 2. Carbon dioxide concentration in soil air.

a – 2010; *b* – 2011; *1* – pine forest; *2* – young frozen peatland; *3* – old frozen peatland. The vertical line denotes the confidence interval.

dity, despite availability of substrate required for microbe viability: in the soil of old frozen peatland, this is peat, while in the soil of young frozen peatland, it is organic matter accumulated directly above the permafrost.

Thus, the general trend for the changes in the carbon dioxide concentration in soil profiles of the sites investigated remains, just like in the case of carbon dioxide emissions. It is to be emphasized that the differences in carbon dioxide emissions from the surface of forest soil and of the soils of peatlands are much more essential and reliable than the differences in the concentrations of this gas in the soil air (Fig. 1, 2). This seems to be related to the major role of the thermal factor inside the soil profile and the leading role of permafrost. The presence and proximity of permafrost rocks determine both the values of carbon dioxide production in soils and the processes of its diffusion and fixation in the soil profile.

SOIL TEMPERATURES

In order to evaluate the impact of the permafrost depth on the production of carbon dioxide, analysis of temperature data obtained in August 2010 and 2011 was made. Analysis of the average temperature curves reveals essential differences only in the lower parts of the soil profiles of the sites investigated (Fig. 3). In the author's opinion, representation of the data as sums of temperatures measured at different depths for the period under study, as well as minimum and maximum temperature values, are most representative. It follows from the characteristics shown in Table 1 that the maximum differences among the sites under study are observed for the sites with different geocriological conditions. Forest soils are the "warmest" soils.

The causes of it are both the absence of permafrost and the microclimatic characteristics of the forest communities – there is more heat coming to the surface of forest soils (the sum of average daily temperatures on the surface). Evaluating the temperatures at the depth of 20 cm, the Turbic Cryosol of the young frozen peatland may be named the coldest soils for this season. The low temperatures at the depth of 20 cm are accounted for by the mineral character of the soil mass, which has high heat conductivity and increased humidity compared to the other soils. The organogenic (peat) character of the soil profile of Cryic Histosol accounts for higher temperatures at the depth of 20 cm and for lower temperatures at the depth of 40 cm (which is close to permafrost temperatures).

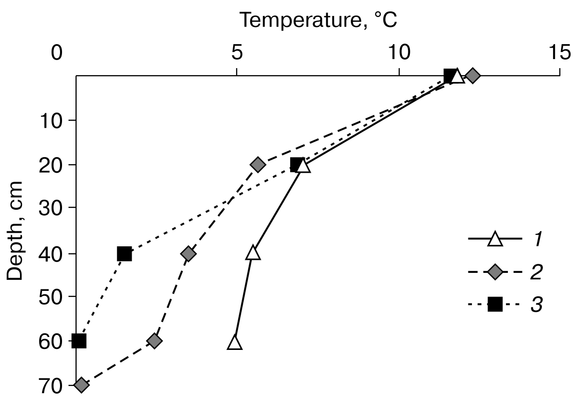

Fig. 3. Average temperatures for soil profiles in the observation period (2011).

1 – pine forest; *2* – young frozen peatland; *3* – old frozen peatland.

Table 1. **Soil temperatures at observation sites**

Site	Sum of average daily air temperatures		Temperature at the depth of 20 cm in the observation period, °C		Sum of average daily soil temperatures, °C		
					Depth, cm		
	>0 °C	>10 °C	max	min	0	20	40
Pine forest	65.1/34.4	65.1/0.0	7.5/6.1	6.5/5.5	59.2/37.1	34.6/28.8	27.6/26.2
Young frozen peatland	65.1/34.4	65.1/0.0	6.0/1.6	4.5/1.5	62.7/31.0	27.3/7.6	18.0/5.0
Old frozen peatland	65.1/34.4	65.1/0.0	7.5/3.6	5.5/2.9	56.5/31.0	33.0/16.3	7.7/2.3

Note. The periods of observations were August 2011 (numerator), August 2010 (denominator). The sums of average daily values were calculated based on the data of 5 days' observations in the indicated observation periods.

It can be concluded that the temperature patterns of soil are likely to produce a significant and direct effect on the amount of carbon dioxide produced. It is also to be mentioned that no direct connection between carbon dioxide concentration in the soil profile and the soil temperature at the same depth has been found, suggesting the defining role of physical processes in the gas transfer.

It is interesting that the soil of old frozen peatland, characterized by the lowest values of CO_2 production and the high position of permafrost, is well warmed at the depth of 20 cm. It is evident that in this case other factors, in particular, the composition and age of peat, affect the values of carbon dioxide production.

It can be supposed that soils with shallow permafrost (in the area in question the sporadic type of permafrost these are the soils of peatlands) serve as a sink of carbon dioxide, which is fixated in the soil profile not only biologically (as peat deposits) but also physically – in the soil solution in the frozen soil layer.

CONCLUSIONS

1. Emission of carbon dioxide by the northern taiga soils of western Siberia is low, on average it is about 120 mg/(m^2·hr), indicating low biological activity of soils.

2. Reliable differences have been found both among the amounts of carbon dioxide emission and the amounts of its concentrations inside the profile for soils of different ecosystems. The amount of CO_2 emission in the peak vegetative season varies from (40 ± 21) and (108 ± 41) mg/(m^2·hr) on old and young frozen peatland to (210 ± 68) mg/(m^2·hr) on the forest land.

3. The lowest values of carbon dioxide production have been shown to be typical of soils with shallow permafrost and hence having the lowest characteristics of heat capacity.

4. Shallow top of the permafrost not only significantly impedes biological soil activity but also physically reduces the intensity of CO_2 losses from the soil profile.

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