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SPATIAL DISTRIBUTION OF SOIL CARBON CYCLE COMPONENTS AND ENVIRONMENTAL FACTORS IN SOUTHERN TUNDRA ECOSYSTEMS OF THE TAZ PENINSULA

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The spatial patterns of soil CO_2 efflux measured at the Novyi Urengoy station in southern tundra (Taz Peninsula) correlate with soil volumetric moisture and water-extractable organic carbon and with elevations above sealevel. The contents of soil water-extractable and microbial biomass carbon are highly variable over the territory. The distribution of soil microbial biomass partly depends on organic layer thickness and soil moisture, which are responsible for 19 % and 8 % of its variance, respectively. The environmental factors of active layer thickness, soil volumetric moisture, and soil surface temperature are relatively stable as the soil and vegetation covers are homogeneous while the soil organic layer is thin.

Permafrost-affected soils, CO_2 *efflux, soil labile carbon, microbial biomass carbon, soil moisture, soil surface temperature*

INTRODUCTION

The behavior of thermal, moisture, and biotic parameters of permafrost-affected soils in response to the ongoing climate change has been a focus of recent attention in Russia and worldwide [*Davidson and Janssens, 2006; Turetsky et al., 2007; Karelin and Zamolodchikov, 2008; Schuur et al., 2008, 2009; Natali et al., 2011; Golovatskaya and Dyukarev, 2012; Fouche et al., 2014; Goncharova et al., 2014; Jensen et al., 2014; Ping et al., 2015*]. Most of research in this line consists in predicting the consequences of global change and estimating the sensitivity of models to various parameters, such as soil properties, thermal, moisture, biological, and other factors. Therefore, it is important to estimate quantitatively the components of the global carbon (C) cycle in permafrost soils, including CO_2 efflux, which is a large respiratory flux from terrestrial ecosystems. Lateral variations in CO_2 emission rates are commonly inferred from soil maps and few databases [*Chestnykh et al., 2004; Hugelius et al., 2013*]. There are only few publications that concern spatial variations in emission of greenhouse gases and stocks of organic carbon in Arctic and Subarctic systems required for estimating carbon fluxes [*Rodionov et al., 2007; Kelsey et al., 2012; Zamolodchikov et al., 2014*].

The rate of greenhouse gas emission from the surface into the atmosphere is an integrated proxy of soil biological activity. The CO_2 efflux of soil depends on its moisture and temperature, level of groundwaters, wind speed, growth rates of plant components above and below the ground, alteration of organic matter, etc. [*Smagin, 2005*]. It may correlate or not with other parameters because soil responses show up in different ways depending on specific conditions [*Smagin, 2005*]. Emission of soil greenhouse gases and its correlations with various environmental factors in areas of continuous and discontinuous permafrost in the northern taiga and tundra of West Siberia remains poorly investigated.

We study the spatial patterns of CO_2 efflux and soil labile (water-extractable) and microbial biomass carbon, three components of the soil carbon cycle, in typical southern tundra ecosystems of West Siberia. The specific objectives are to investigate (i) different environmental factors (vegetation, elevations, active layer thickness, soil volumetric moisture, and soil surface temperature) and the carbon cycle components in southern tundra ecosystems; (ii) their spatial variations and correlations; (iii) the relationship of CO_2 efflux with soil moisture and temperature, active layer thickness, and with contents of soil labile and microbial biomass carbon in soil.

The reported data are from a site of Circumpolar Active Layer Monitoring (CALM R50B) run since

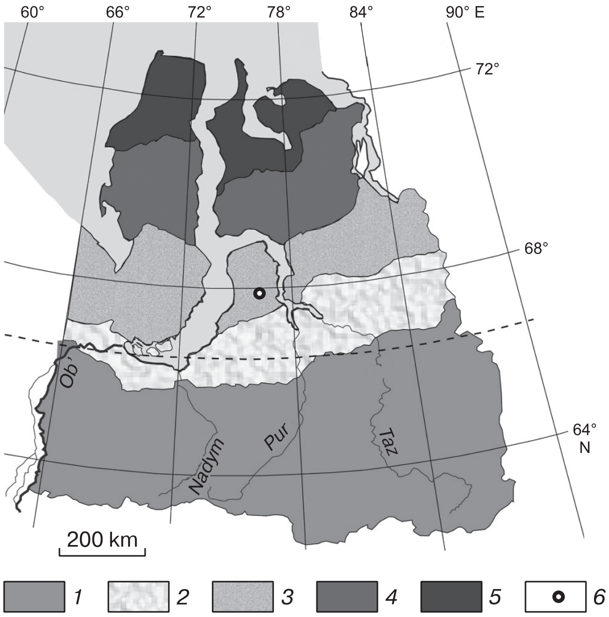

Fig. 1. Location map of study area.

1–5 – landscape zones and subzones: *1* = boreal taiga, *2* = forest tundra, *3* = southern tundra, *4* = typical tundra; *5* = Arctic tundra; *6* = Novyi Urengoi station (CALM R50B site).

2008 in southern tundra 100 km north of Novyi Urengoi city (Fig. 1). Monitoring at CALM sites is the best way to study spatial variations of soil carbon components and CO_2 efflux. The CALM international program aims at monitoring the behavior of active layer thickness as permafrost response to climate change in the long-term perspective (www.gwu.edu/~calm/data/north.html). Thirteen out of sixty four CALM sites in the territory of Russia are located in West Siberia.

This work continues a series of studies on the distribution of carbon cycle components in soils of typical ecosystems in West Siberia along a bioclimatic and geocryological transect from southern taiga to southern tundra [*Bobrik et al., 2015, 2016, 2017*].

OBJECT OF STUDIES

The CALM R50B site (67°48′ N; 76°69′ E) is located in southern tundra, on marine terrace III, on the left side of the Khadutte River, northern West Siberia (Fig. 1). It is a hummocky plain cut by a branching network of gullies, with elevations of 30–40 m above sea level. The soils are derived mainly from Upper Quaternary silt and clay silt containing sand layers and lenses. It is an area of continuous ice-rich permafrost (total moisture contents reach 60 % in clay silt and 21–28 % in sand) [*Drozdov et al., 2010; Ukraintseva et al., 2011*]. The CALM site is set up on a gently dipping hilltop with poorly pronounced (vegetated) small landforms. Predominant grass-shrub-moss-lichen vegetation is punctuated with bare mineral patches. Gullies are grown with low willow thickets and shrub birch (yernik) and contain pieces of grass-moss bogs. Low frost heaves appear on the floor of large gullies [*Ukraintseva et al., 2011*].

METHODS

In August 2016, the patterns of vegetation, soil, and surface topography were documented at all points of the site, with relative elevations measured by leveling surveys (using an automatic *SAL24ND CST/Berger* level) within a 70 × 100 m plot on a regular 10 m grid, at 77 measuring points. Peat (organic layer) thickness was estimated using an *Eijkelkamp* gouge auger designed for sampling wet clay and peat with minimal disturbance of soft cohesive soils. Similar methods were used in previous studies at CALM R1 and R50A [*Bobrik et al., 2015, 2016, 2017*].

Soil CO_2 efflux was measured once during the field season on 7 August 2016, in the daytime (from 11.00 to 14.00), simultaneously at all points of the site, using the technique of discrete surface chambers for soil respiration, with vegetation clipping [*Smagin, 2005*; *Riveros-Iregui et al., 2008*]. CO_2 in samples was determined with a portable *RMT DX6210* infrared gas analyzer.

Air temperature was taken at the same time, using a *Thermochron iButton™* programmable temperature logger [*Smagin, 2005*]. Volumetric moisture was measured in the upper 20 cm of soil by a *Spectrum TDR-100* soil moisture meter, with its operation principle based on the fact that water has a much greater dielectric constant than soil. Soil surface temperature was measured by a *TP3001* electronic thermometer (resolution 0.1 °C, precision ±1 °C), in triplicate at each point, within upper 10 cm of soil, according to the standard recommendations. Active layer thickness (thaw depth) was estimated by inserting a 2 m long graduated steel rod, 10-mm in diameter, into the soil to the point of refusal [*State Standard, 2015*].

Soil samples were collected and stored fresh at natural air humidity and 4 °C air temperature for microbiological studies.

The contents of soil labile organic carbon were determined in a 0.05 M K_2SO_4 solution on a *Shimadzu TOC-*V_{CPN} automatic analyzer, in five replicated portions of samples [*Chantigny, 2003*]. Carbon can be considered water-extractable in this case [*Makarov et al., 2013*] because the diluted K_2SO_4 solution used for analysis is a coagulation agent of soil colloids rather than an extraction agent. Weight soil moisture was measured with an *OHAUS MB-35* moisture analyzer.

Soil microbial biomass carbon was determined by fumigation-extraction, likewise in five replicated portions of samples [*Vance et al., 1987*]. The components of microbial cells that died as soil was exposed to $CHCl_3$ vapor were extracted with 0.05 M K_2SO_4

[*Makarov et al., 2013*] from fumigated and non-fumigated (control) specimens. Fresh soil samples were fumigated at a natural humidity, using amylene-stabilized $CHCl_3$ vapor, without ethanol, for 24 hours. The content of carbon extracted by K_2SO_4 solution was determined on a *Shimadzu TOC-V$_{CPN}$* automatic analyzer. Microbial biomass carbon was calculated as $C_{micr} = F_C/k_C$, where F_C is the difference of carbon contents in fumigated and non-fumigated specimens; k_C is the correction that allows for the share of extracted soil carbon [*Joergensen et al., 2011*], which is $k_C = 0.45$ for organic soils (with 10 % TOC: litter, peat layers) and $k_C = 0.33$ for mineral soils [*Vance et al., 1987; Martens, 1995; Joergensen et al., 2011*].

The collected data were processed by correlation and regression statistical methods using *Excel* and *Statistica 7.0* software. Distribution types were identified by checking deviation from the lognormal distribution. The results were presented as mean values ± standard deviation. The means were compared according to the parametric Student criterion (paired *t*-test), at $p < 0.05$ significance, and the non-parametric Wilcoxon signed-rank test, at $\alpha = 0.05$ significance. In the case of deviation from the lognormal distribution, the Spearman rank correlation was applied with a coefficient of $r > 0.24$ assumed to be significant for a sample size of $n > 77$ ($p < 0.05$ significance) [*Dmitriev, 1995*]. The statistical sample for the CALM R50B site was 77 for each monitored parameter.

The spatial variations of the measured parameters were mapped using *Golden Software Surfer 8*.

RESULTS

According to the *leveling* surveys at the CALM site, the difference between the maximum and minimum elevations is 2.48 m, while the average elevation is 31.95 ± 0.76 m asl. The elevations are almost invariable over the site (within 2 % variance) and have a lognormal distribution. The site surface slopes generally to the north.

Vegetation has a uniform facies structure, with various lichen (*Cladonia* spp.) and moss (*Sphagnum* spp., *Pleurozium* spp., *Politrichum* spp.) species in the understorey. The moss-lichen storey covers 85 % of the projected area, with 36 % variance, and has an asymmetrical distribution, with a median shifted to high values. Moss and lichen cover 90 to 100 % of the projected area at 73 % of sampling points.

The grass-shrub storey consists of *Vaccínium myrtíllus*, *Vaccínium uliginósum*, *Vaccínium vítis-idaéa*, *Ledum palustre*, as well as *Carex* spp., *Rubus chamaemorus*, *Eriophorum* spp., and *Andromeda* spp. This storey covers 37 % of the projected area on average, with 54 % variance. It has an asymmetrical distribution, with a median shifted to low values. Grass and shrubs cover 20 to 60 % of the projected area at 74 % of sampling points.

The *soil cover* is slightly inhomogeneous and consists of cryometamorphic and cryoturbated soils associated with different terrain elements. Although clay silt is the predominant lithology at the site, the soils are not gleyic, with prominent cryoturbation signatures and thin organic profiles composed of one or two more or less strongly degraded peat layers. The mineral soil profile consists of two or three layers with poorly pronounced processes of humus and gley formation and with prominent signatures of cryogenic structure formation and cryoturbation. Soils that form on bare mineral patches (about 5 % of the site area) are remarkable by the absence of organic profiles. Most of soils with organic and coarse-humus cryometamorphic profiles develop on negative and positive landforms, respectively. Typical coarse-humus cryozem and cryoturbated gleyic soils are restricted to the bare patches.

Active layer thickness at the site varied from 0.59 to 1.34 m, 0.95 ± 0.13 m on average at the time of measurements (Fig. 2, *a*). It showed moderate spatial variability (14 % variance) and a lognormal distribution. The active layer is 0.9 to 1.0 m thick at 50 % of points.

Volumetric soil moisture measured in the upper 20 cm varied moderately over the area, with 13 % variance and a lognormal distribution. The variation range was from 20.5 to 48.3 vol.%, 37.8 ± 5.1 vol.% on average; 35 to 45 vol.% at 70 % of points (Fig. 2, *b*).

Soil surface temperatures measured at the 10 cm depth in the daytime showed a variance of 29 % and a lognormal distribution. The temperatures ranged from 1.0 to 6.3 °C, 4.2 ± 1.2 °C on average (Fig. 2, *c*) and exceeded 4 °C at 60 % of points. The daytime air temperature was 22 °C.

Organic layer thickness was in a range of 0 to 6 cm, 2.2 ± 1.4 cm on average (Fig. 2, *d*), and varied strongly over the area (61 % variance), with an asymmetrical distribution and a median shifted to low values.

Soil CO_2 *efflux* (emission rates) was from 60 to 470 mg $CO_2/(m^2 \cdot h)$ at the time of measurements, 198 ± 75 mg $CO_2/(m^2 \cdot h)$ on average (Fig. 2, *e*). The spatial variability was quite moderate (36 % variance) and the distribution was lognormal. The values were below 100 mg $CO_2/(m^2 \cdot h)$ at 10 % of sampling points and exceeded 300 mg $CO_2/(m^2 \cdot h)$ at 12 % of points.

Soil labile organic carbon in the upper 15 cm of soil at the site varied in a large range from 2 to 486 mg C/kg soil, 91 ± 71 mg C/mg soil on average (Fig. 2, *f*). The parameter showed high spatial variability (77 % variance) and an asymmetrical distribution with a median shifted to low values. The contents of labile carbon were less than 100 mg C/kg at 70 % of points.

Microbial biomass carbon in the upper 15 cm of soil varied from 98 to as high as 2990 mg C/kg soil,

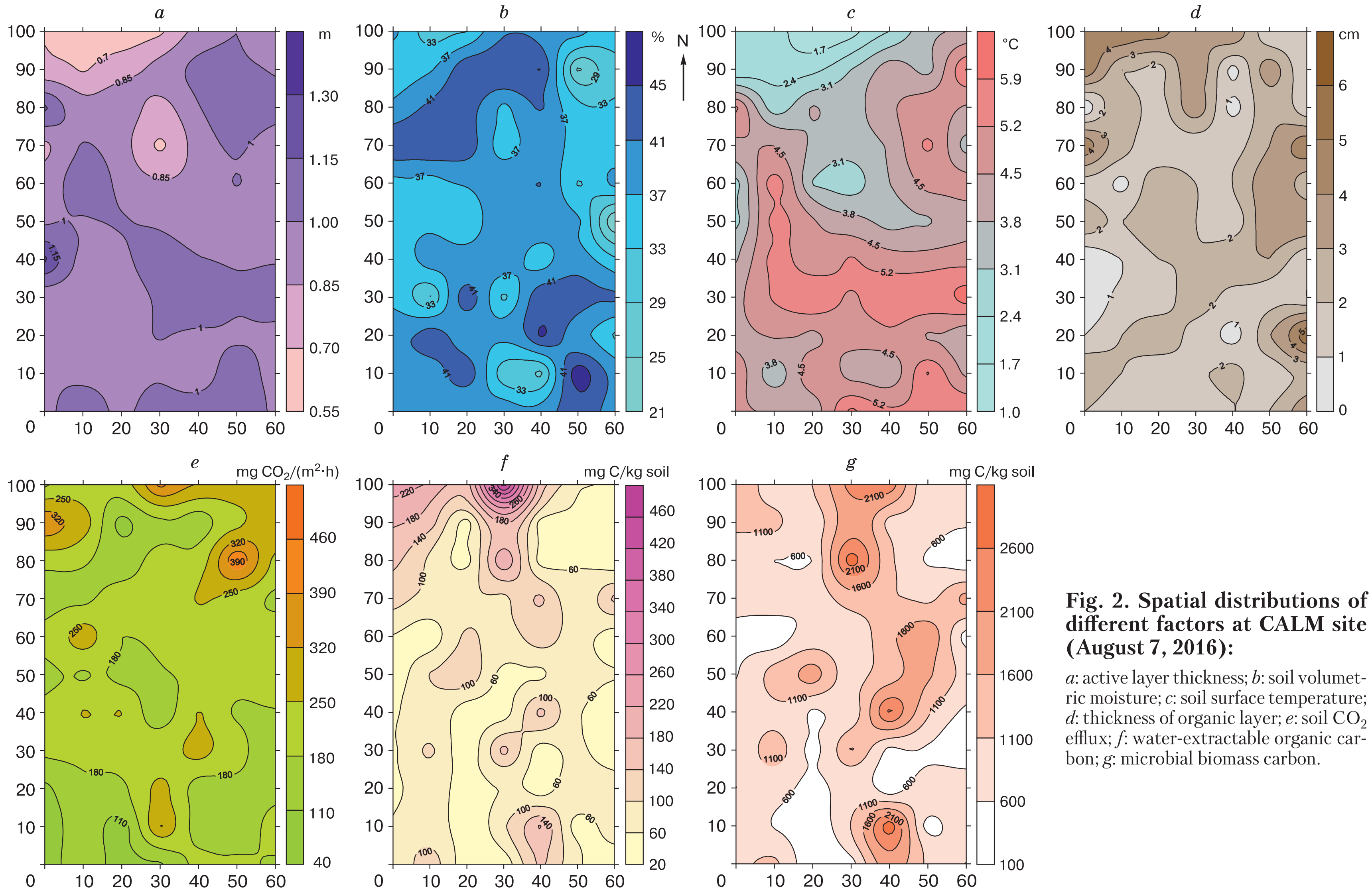

Fig. 2. Spatial distributions of different factors at CALM site (August 7, 2016):

a: active layer thickness; *b*: soil volumetric moisture; *c*: soil surface temperature; *d*: thickness of organic layer; *e*: soil CO_2 efflux; *f*: water-extractable organic carbon; *g*: microbial biomass carbon.

1005 ± 647 mg C/kg soil on average (Fig. 2, *g*). It varied strongly over the area (65 % variance) and showed an asymmetrical distribution, with a median shifted to low values. The contents of this carbon component exceed 1500 mg C/kg soil at 20 % of sampling points.

DISCUSSION

Correlation among environmental factors

According to regression analysis, soil surface temperature measured at the daytime on 7 August 2016 at the CALM R50B site shows statistically significant correlation with the thicknesses of active layer (1) and organic layer (2):

$$\text{soil temperature [°C]} = -1.8\text{ [°C]} + 6.3\text{ [°C/m]} \times \times \text{ active layer thickness [m]};\ r = 0.69,\ p\text{-level} < 0.05,\ n = 77; \quad (1)$$

$$\text{soil temperature [°C]} = 5.1\text{ [°C]} - 0.37\text{ [°C/cm]} \times \times \text{ organic layer thickness [cm]};\ r = -0.42,\ p\text{-level} < 0.05,\ n = 77. \quad (2)$$

The active layer thickness variations are responsible for 48 % of variance in soil temperature while the effect of organic layer thickness is limited to 18 %; the parameters are mutually independent to 34 %.

Active layer and organic layer thicknesses, in their turn, correlate to a statistically significant level (3):

$$\text{active layer thickness [m]} = 1.1\text{ [m]} - 0.04\text{ [m/cm]} \times \times \text{ organic layer thickness [cm]},\ r = -0.45,\ p\text{-level} < 0.05,\ n = 77. \quad (3)$$

The effects of organic layer thickness and soil surface temperature are responsible for 20 % and 48 % of active layer thickness variance, respectively; 32 % of these effects are mutually independent. These results are consistent with evidence that the presence of peat and moss cover can reduce considerably the thaw depth reported from northern West Siberia [*Tyrtikov, 1980*], because unfrozen peat, with its low thermal conductivity, provides thermal insulation of permafrost [*Zimov et al., 1993; Mazhitova et al., 2004; Goncharova et al., 2015*].

Organic layer thickness shows statistically significant correlation with soil volumetric moisture (4):

$$\text{soil moisture [\%]} = 40.6\text{ [\%]} - 1.3\text{ [\%/cm]} \times \times \text{ organic layer thickness [cm]},\ r = -0.34,\ p\text{-level} < 0.05,\ n = 77. \quad (4)$$

However, the organic layer thickness variations are responsible for only 12 % of soil moisture variance, and the two parameters vary independently in most cases (88 %).

As we have demonstrated, organic layer thickness correlates weakly, but to a statistically significant level, with all environmental factors we monitored. Thus, soil and vegetation cause marked influence on active layer thickness which has to be taken into account in the respective estimation.

Soil respiration

According to the obtained data, the sampled soils of southern tundra, as well as northern taiga and forest tundra, show quite low CO_2 emission rates of 198 ± 75, 142 ± 21 and 202 ± 142 mg $CO_2/(m^2 \cdot h)$, respectively [*Bobrik et al., 2016, 2017*]. Thus, these soils are less biologically active than their counterparts from other zones [*Naumov, 2009; Kurganova, 2010; Semenyuk et al., 2013*]. Average soil CO_2 efflux values for these zones are statistically similar because the parameter varies strongly over the area (85 and 73 % variance in northern taiga and forest tundra, respectively).

Regression analysis reveals statistically significant correlation of soil CO_2 efflux (07.08.2016) with soil volumetric moisture (5), soil water-extractable carbon (6), and elevations above sea level (7). Specifically, the correlation with soil moisture is (5):

$$\text{efflux rate [mg } CO_2/(m^2\cdot h)] = 357\text{ [mg } CO_2/(m^2\cdot h)] - -4.2\text{ [mg } CO_2/(m^2\cdot h)/\%] \times \text{soil moisture [vol.\%]},\ r = -0.27,\ p\text{-level} < 0.05,\ n = 77. \quad (5)$$

The determination coefficient of the model is as low as 0.08, possibly, because only soil moisture data collected in August were used, but it would be higher with integrated data over the warm season.

The correlation relationships with water-extractable carbon (6) and elevations (7) are:

$$\text{efflux rate [mg } CO_2/(m^2\cdot h)] = 164\text{ [mg } CO_2/(m^2\cdot h)] + + 0.38\text{ [mg } CO_2/(m^2\cdot h)/\text{mg C/kg soil]} \times \times C_{lab}\text{ [mg C/kg soil]},\ r = 0.36,\ p\text{-level} < 0.05,\ n = 77; \quad (6)$$

$$\text{efflux rate [mg } CO_2/(m^2\cdot h)] = 1227\text{ [mg } CO_2/(m^2\cdot h)] - - 32\text{ [mg } CO_2/(m^2\cdot h)/m] \times \text{elevation [m asl]},\ r = -0.33,\ p\text{-level} < 0.05,\ n = 55. \quad (7)$$

We estimate that only 8 % of CO_2 efflux variance is due to variations in soil moisture, while water-extractable carbon contents and elevations are responsible for 13 % and 10 % of its variance, respectively; 69 % of variance is independent of these factors.

The observed inverse correlation of CO_2 efflux with elevations may be due to redistribution of soil moisture and temperature according to small-scale landforms.

The statistically significant correlation of CO_2 emission rates with soil moisture is consistent with the key role of this and other abiotic factors (temperature, groundwater level, etc.) in production, migration, and emission of soil greenhouse gases [*Kobak, 1988; Smagin, 2005; Liu et al., 2006; Naumov, 2009*]. The lack of such significant correlation with other parameters of soils and ecosystems (active layer thickness, soil temperature, organic layer thickness, and microbial mass carbon) may result from neglect of plant root respiration.

Contents of labile and microbial biomass carbon

The CO_2 efflux rates largely depend on organic matter composition, specifically, on the presence or absence of labile substrate prone to salination which controls microbial activity [*Golovatskaya and Dyukarev, 2012*].

The contents of labile (water-extractable) carbon correlate, to a statistically significant level, with soil organic layer thickness (8) and elevations above sea level (9):

$$C_{lab}\ [\text{mg C/kg soil}] = 40\ [\text{mg C/kg soil}] + 23\ [\text{mg C/kg soil/cm}] \times \text{organic layer thickness [cm]},\quad r = 0.44,\ p\text{-level} < 0.05,\ n = 77; \tag{8}$$

$$C_{lab}\ [\text{mg C/kg soil}] = 1476\ [\text{mg C/kg soil}] - 43\ [\text{mg C/kg soil/m}] \times \text{elevation [m asl]},\quad r = -0.42,\ p\text{-level} < 0.05,\ n = 55. \tag{9}$$

The variations in organic layer thickness and elevation are responsible for 20 % and 18 % of C_{lab} variance, and 69 % of its variance is independent of the two factors.

The correlation of water-extractable carbon contents in soil with elevations may be implicit and may result from accumulation of this carbon in depressed landforms.

The carbon of microbial biomass correlates with two parameters: organic layer thickness (10) and soil volumetric moisture (11):

$$C_{micr}\ [\text{mg C/kg soil}] = 543\ [\text{mg C/kg soil}] + 206\ [\text{mg C/kg soil/cm}] \times \text{organic layer thickness [cm]},\quad r = 0.44,\ p\text{-level} < 0.05,\ n = 77; \tag{10}$$

$$C_{micr}\ [\text{mg C/kg soil}] = 2374\ [\text{mg C/kg soil}] - 36\ [\text{mg C/kg soil/\%}] \times \text{soil moisture [vol. \%]},\quad r = -0.28,\ p\text{-level} < 0.05,\ n = 77. \tag{11}$$

The spatial variations of C_{micr} depend only moderately on organic layer thickness (19 % of variance) and still less on soil moisture (8 % of variance), while 73 % of variance are independent of these parameters.

Our data on microbial biomass carbon in soils agree with published evidence for northern taiga and tundra ecosystems [*Cheng and Virginia, 1993; Cheng et al., 1998; Fisk et al., 2003; Potila and Sarjala, 2004*].

CONCLUSIONS

The environmental factors of active layer thickness and soil volumetric moisture and temperature studied at the CALM R50B site in northern West Siberia (Taz Peninsula) show moderate spatial variability as the soil and vegetation covers are homogeneous while organic soil profiles are thin. This is the principal reason of weak but statistically significant correlation among the parameters.

Active layer thickness is low and quite uniform over the area (0.95 ± 0.13 m, 14 % variance) at the peak of the vegetation season (August 2016) in southern tundra ecosystems. Its spatial distribution shows positive correlation with soil surface temperature ($r = 0.69$, p-level < 0.05) and negative correlation with organic layer thickness ($r = -0.45$, p-level < 0.05).

According to the reported statistical analysis, soil organic layer thickness correlates with all other factors (active layer thickness, $r = -0.45$, p-level < 0.05; soil surface temperature, $r = -0.42$, p-level < 0.05; soil volumetric moisture, $r = -0.34$, p-level < 0.05), as well as with the carbon cycle components (C_{lab}, $r = 0.44$, p-level < 0.05; C_{micr}, $r = 0.44$, p-level < 0.05), except for CO_2 efflux. However, the organic layer (peat) causes implicit influence on CO_2 emission rates via soil moisture and temperature, as well as via the processes of organic matter alteration.

Soil CO_2 efflux at the monitoring site has low values and moderate spatial variability (198 ± 75 mg CO_2/(m^2·h), 36 % variance). Its spatial distribution correlates with the contents of soil moisture and water-extractable carbon ($r = -0.28$, p-level < 0.05 and $r = 0.36$, p-level < 0.05, respectively), as well as with elevations ($r = -0.33$, p-level < 0.05). The contents of labile and microbial biomass carbon vary significantly over the area (77 and 65 % variance, respectively).

The spatial distribution of the carbon cycle components (CO_2 efflux and water-extractable and microbial biomass carbon) in the soils of typical ecosystems in the West Siberian southern tundra has been studied for the first time. The obtained data and the revealed relationships among various relevant parameters can be used to estimate and compare CO_2 efflux from the soils of West Siberian ecosystems along the bioclimatic and geocryological transect from southern taiga to southern tundra.

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References

Bobrik, A.A., Goncharova, O.Yu., Matyshak, G.V. Ryzhova, I.M., Moskalenko, N.G., Ponomareva, O.E., Ogneva, O.A.,

2015. Correlation of active layer thickness and landscape parameters of peatland in northern West Siberia (Nadym station). Earth's Cryosphere (Kriosfera Zemli) XIX (4), 29–35.

Bobrik, A.A., Goncharova, O.Yu., Matyshak, G.V., Ryzhova, I.M., Makarov, M.I., 2016. State of permafrost and soil properties as controls of soil CO_2 efflux from peatlands in areas of sporadic permafrost of West Siberia. Pochvovedeniye, No. 12, 1445–1456.

Bobrik, A.A., Goncharova, O.Yu., Matyshak, G.V. Drozdov, D.S., Ponomareva, O.E., 2017. Spatial variability of soil CO_2 efflux in the forest-tundra zone of West Siberia (Novyi Urengoi): abiotic controls. Earth's Cryosphere (Kriosfera Zemli) XXI (2), 46–51.

Chantigny, M.H., 2003. Dissolved and water-extractable organic matter in soils: a review on the influence of land use and management practices. Geoderma 113, 357–380.

Cheng, W., Virginia, R.A., 1993. Measurement of microbial biomass in Arctic tundra soils using fumigation-extraction and substrate-induced respiration procedures. Soil Biol. Biochem. 25 (1), 135–141.

Cheng, W., Virginia, R.A., Oberbauer, S.F., Gillespie, C.T., Reynolds, J.F., Tenhunen, J. D., 1998. Soil nitrogen, microbial biomass and respiration along an Arctic toposequence. Soil Sci. Soc. America J. 62, 654–662.

Chestnykh, O.V., Zamolodchikov, D.G., Utkin, A.I., 2004. Total resources of biogenic carbon and nitrogen in forest soils of Russia. Lesovedeniye, No. 4, 30–42.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173.

Dmitriev, E.A., 1995. Mathematical Statistics in Soil Science. Moscow University Press, Moscow, 320 pp. (in Russian)

Drozdov, D.S., Ukraintseva, N.G., Tsarev, A.M., Chekrygina, S.N., 2010. Changes of permafrost temperature field and geosystem state on the Urengoy oil-gas-field territory during the last 35 years (1974–2008). Kriosfera Zemli XIV (1), 22–31.

Fisk, M.C., Ruether, K.F., Yavitt, J.B., 2003. Microbial activity and functional composition among northern peatland ecosystems. Soil Biol. Biochem. 35 (4), 591–602.

Fouche, J., Keller, C., Allard, M., Ambrosi, J.P., 2014. Increased CO_2 fluxes under warming tests and soil solution chemistry in Histic and Turbic Cryosols, Salluit, Nunavik, Canada. Soil Biol. Biochem. 68, 185–199.

Golovatskaya, E.A., Dyukarev, E.A., 2012. Environmental effects on CO_2 efflux from oligotrophic peaty soils in West Siberia. Pochvovedenie, No. 6, 658–667.

Goncharova, O.Yu., Matyshak, G.V., Bobrik, A.A., Moskalenko, N.G., 2014. Carbon dioxide production by northern taiga soils of West Siberia (Nadym site). Earth's Cryosphere (Kriosfera Zemli) XVIII (2), 58–63.

Goncharova, O.Yu., Matyshak, G.V., Bobrik, A.A., 2015. Thermal regime of northern taiga soils in areas of discontinuous permafrost in West Siberia. Pochvovedenie, No. 12, 1462–1473.

Hugelius, G., Tarnocai, C., Broll, G., Canadell, J.G., Kuhry, P., Swanson, D.K., 2013. The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions. Earth Syst. Sci. Data 5, 3–13.

Jensen, A.E., Lohse, K.A., Crosby, B.T., Mora, C.I., 2014. Variations in soil carbon dioxide efflux across a thaw slump chronosequence in northwest Alaska. Environ. Res. Lett. 9, 1–11.

Joergensen, R.G., Wu, J., Brookes, P.C., 2011. Measuring soil microbial biomass using an automated procedure. Soil Biol. Biochem. 43 (5), 873–876.

Karelin, D.V., Zamolodchikov, D.G., 2008. Carbon Exchange in Permafrost Ecosystems. Nauka, Moscow, 344 pp. (in Russian)

Kelsey, K.C., Wickland, K.P., Striegl, R.G., Neff, J.C., 2012. Variation in soil carbon dioxide efflux at two spatial scales in a topographically complex boreal forest. Arctic, Antarctic and Alpine Res. 44 (4), 457–468.

Kobak, K.I., 1988. Biotic Components of the Carbon Cycle. Gidrometeoizdat, Moscow, 248 pp. (in Russian)

Kurganova, I.N., 2010. Soil Carbon Dioxide Efflux and Budget in Terrestrial Ecosystems of Russia. Author's Abstract, Doctor Thesis (Biology). Pushchino, 50 pp. (in Russian)

Liu, Q., Edwards, N.T., Post, W.M., Gu, L., Ledford, J., Lenhart, S., 2006. Temperature-independent diel variation in soil respiration observed from a temperate deciduous forest. Glob. Change Biol. 12 (11), 2136–2145.

Makarov, M.I., Shuleva, M.S., Malysheva, T.I., Menyailo, O.V., 2013. Solubility of water-extractable carbon and soil nitrogen in K_2SO_4 of different concentrations. Pochvovedenie, No. 4, 408–413.

Martens, R., 1995. Current methods for measuring microbial biomass C in soil: Potentials and limitations. Biol. Fertil. Soils 19, 87–99.

Mazhitova, G., Malkova, G., Chestnykh, O., Zamolodchikov, D., 2004. Active-layer spatial and temporal variability at European Russian Circumpolar-Active-Layer-Monitiring (CALM) sites. Permafrost and Periglacial Processes 15 (2), 123–139.

Natali, S.M., Schuur, E.A.G., Trucco, C., Pries, C.E.H, Crummer, K.G., Lopez, A.F.B., 2011. Effects of experimental warming of air, soil and permafrost on carbon balance in Alaskan tundra. Global Change Biol. 17, 1394–1407.

Naumov, A.V., 2009. Soil Respiration: Components, Environmental Functions, and Geographic Patterns. Izd. SO RAN, Novosibirsk, 208 pp. (in Russian)

Ping, C.L., Jastrow, J.D., Jorgenson, M.T., Michaelson, G.J., Shur, Y.L., 2015. Permafrost soils and carbon cycling. Soil 1, 147–171.

Potila, H., Sarjala, T., 2004. Seasonal fluctuation in microbial biomass and activity along a natural nitrogen gradient in a drained peatland. Soil Biol. Biochem. 36, 1047–1055.

Riveros-Iregui, D.A., McGlynn, B.L., Epstein, H.E., Welsch, D.L., 2008. Interpretation and evaluation of combined measurement techniques for soil CO_2 efflux: Discrete surface chambers and continuous soil CO_2 concentration probes. J. Geophys. Res. 113, 1–11.

Rodionov, A., Flessa, H., Grabe, M., Kazansky, O.A., Shibistova, O., Guggenberger, G., 2007. Organic carbon and total nitrogen variability in permafrost-affected soils in a forest tundra ecotone. Europ. J. Soil Sci. 58, 1260–1272.

Schuur, E.A.G., Bockheim, J., Canadell, J.G., Euskirchen, E., Field, C.B., Goryachkin, S.V., Hagemann, S., Kuhryet, P., Lafleur, P.M., Lee, H., Mazhitova, G., Nelson, F.E., Rinke, A., Romanovsky, V.E., Shiklomanov, N., Tarnocai, C., Venevsky, S., Vogel, J.G., Zimov, S.A., 2008. Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. Bioscience 58, 701–714.

Schuur, E.A.G., Vogel, J.G., Crummer, K.G., Lee, Hanna, Sickman, J.O., Osterkamp, T.E., 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature 459, 556–559.

Semenyuk, O.V., Iliyashenko, M.A., Bobrik, A.A., 2013. Estimating environmental functions of park soils based on biological activity. Problemy Agrokhimii i Ecologii, No. 3, 35–39.

Smagin, A.V., 2005. Soil Gas Phase. Moscow University, Moscow, 301 pp. (in Russian)

State Standard, 2015. Working Document GOST 26262-2014. Methods of Field Thaw Depth Measurements. Standartinform, Moscow, 11 pp. (in Russian)

Turetsky, M.R., Wieder, R.K., Vitt, D.H., Evans, R.J., Scott, K.D., 2007. The disappearance of relict permafrost in boreal north America: Effects on peatland carbon storage and fluxes. Global Change Biol. 13, 1922–1934.

Tyrtikov, A.P., 1980. Effect of Vegetation on Soil Temperature in Northern West Siberia, in: Natural Conditions of West Siberia. Moscow University Press, Moscow, 112 pp. (in Russian)

Ukraintseva, N.G., Drozdov, D.S., Popov, K.A., Gravis, A.G., Matyshak, G.V., 2011. Landscape indication of local permafrost variability (West Siberia, Urengoy territory). Earth's Cryosphere (Kriosfera Zemli) XV (4), 32–35.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703–707.

Zamolodchikov, D.G., Grabovskiy, V.I., Kurtz, V.A., 2014. Management of carbon budget in Russian forests: past, present, and future. Ustoichivoe Lesopolzovanie, No. 2, 23–31.

Zimov, S.A., Zimova, G.M., Daviodov, S.P., Daviodova, Y.V., Voropaev, Y.P., Semiletov, I.P., 1993. Winter biotic activity and production of CO_2 in Siberian soils: a factor in the greenhouse effect. J. Geophys. Res. 98, 5017–5023.

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