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SPATIAL VARIABILITY OF SOIL CO_2 EFFLUX IN THE FOREST-TUNDRA ZONE OF WEST SIBERIA (NOVY URENGOI): ABIOTIC CONTROLS

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Studies at site CALM R50 in Novy Urengoi, northern West Siberia, reveal high spatial variability in the patterns of soil CO_2 efflux, active layer thickness, and landscape parameters (elevations, volumetric soil moisture, and soil surface temperature). The distribution of carbon dioxide emission from soil over the area correlates with active layer thickness, soil temperature and moisture contents, as well as with elevation. Active layer thickness is the major control of soil moisture and temperature distribution.

Permafrost, permafrost-affected soils, peat, soil moisture, CO_2 efflux

INTRODUCTION

The spatial pattern of soil CO_2 efflux, a large respiratory flux from terrestrial ecosystems, is an integrated proxy of soil biological activity and a critical component of the global carbon (C) cycle [*Wang et al., 2002; Jones et al., 2005; Li et al., 2008*]. Lateral variations in CO_2 emission from soil are commonly estimated using soil maps and few databases [*Chestnykh et al., 2004; Hugelius et al., 2013*]. Quantitative evaluation of carbon stocks in permafrost soils and CO_2 emission rates is a focus of special attention in the context of climate change. The common approach to this quantification is to multiply carbon stocks in reference soil profiles by the surface areas of each soil type zone (contour). However, this approach neglects variability of soil carbon contents and its emission within soil zones. There are few publications on spatial variations in emission of greenhouse gases and in soil carbon for Arctic and Subarctic systems [*Rodionov et al., 2007; Bobrik et al., 2016*], and special investigation is required to bridge the gap.

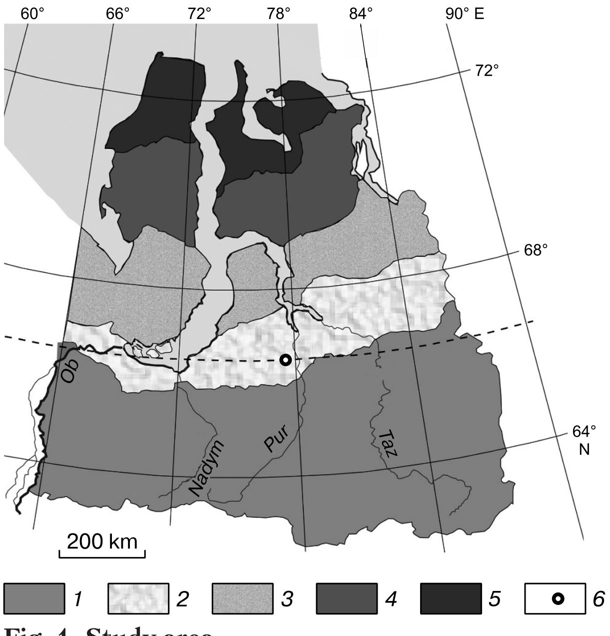

Fig. 1. Study area.

1 – boreal taiga, *2* – forest tundra, *3* – southern tundra, *4* – typical tundra, *5* – Arctic tundra, *6* – Novy Urengoi station.

Monitoring at CALM sites (Circumpolar Active Layer Monitoring) is the best way to study spatial variations of soil carbon and CO_2 emission. 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. The reported data are from site CALM R50 run since 2008 in southern forest tundra 30 km north of Novyi Urengoi city (Fig. 1).

We investigate correlations among values and spatial variations of soil CO_2 emission, active layer thickness, and landscape parameters. The specific objectives of the study are to estimate spatial variations of biotic (vegetation) and abiotic (active layer thickness, volumetric soil moisture contents, and soil surface temperatures) factors within the study area, and to compare variations in soil CO_2 efflux with those of active layer thickness and landscape parameters.

OBJECT OF STUDIES

We studied soils and landscapes at the CALM R50 site located in the forest tundra of West Siberia. It is a swampy land where paludal ecosystems occupy 50 % of the area in forest tundra and adjacent northern taiga in the West Siberian plain and 70 % in the Nadym–Pur interfluve [*Romanova, 1985*]. The monitoring site is a flat and gently dipping hummocky surface of a typical peatland grading into larch groves and yernik shrubs near the creek valley [*Ukraintseva et al., 2011*].

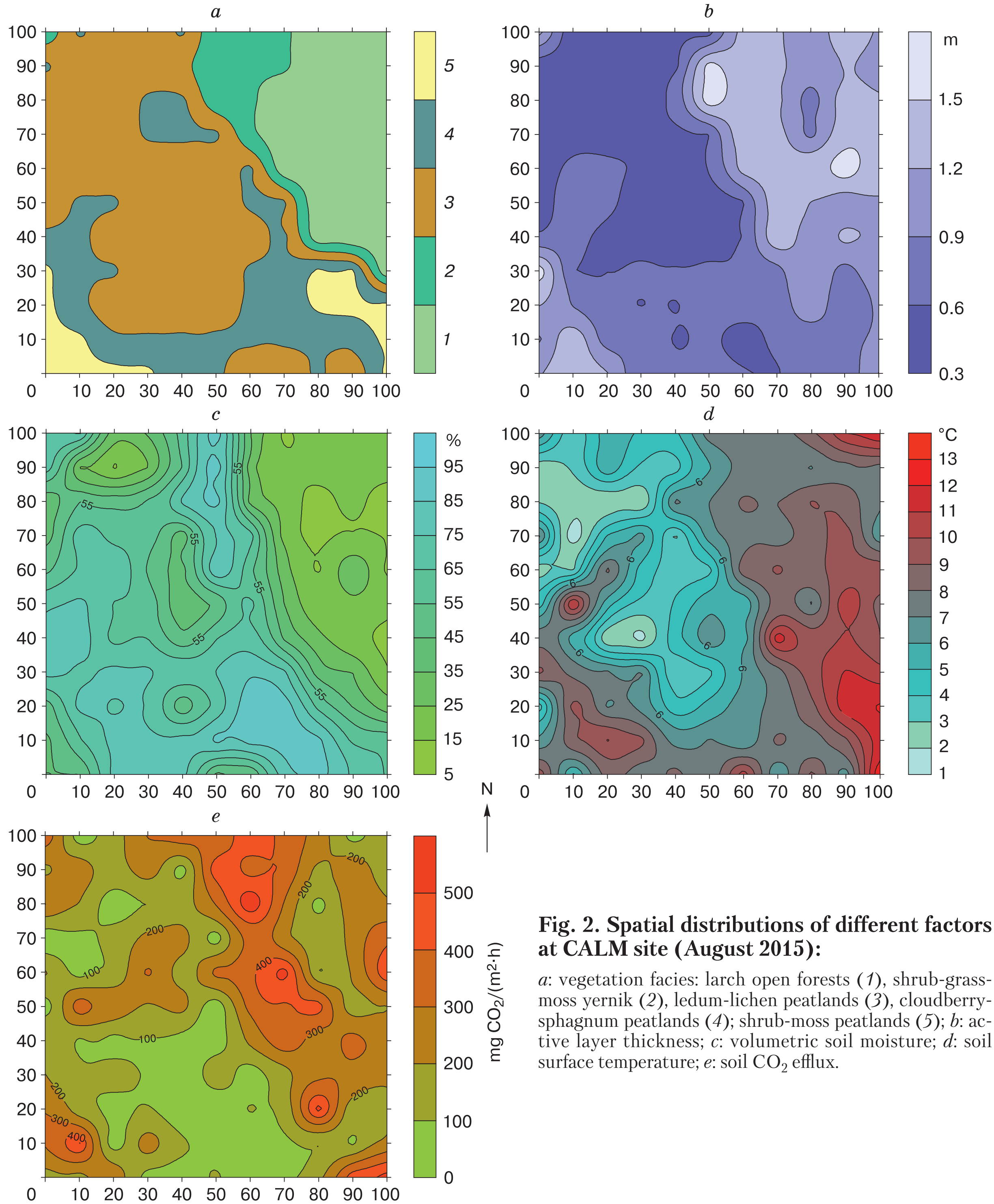

Fig. 2. Spatial distributions of different factors at CALM site (August 2015):

a: vegetation facies: larch open forests (*1*), shrub-grass-moss yernik (*2*), ledum-lichen peatlands (*3*), cloudberry-sphagnum peatlands (*4*); shrub-moss peatlands (*5*); *b*: active layer thickness; *c*: volumetric soil moisture; *d*: soil surface temperature; *e*: soil CO_2 efflux.

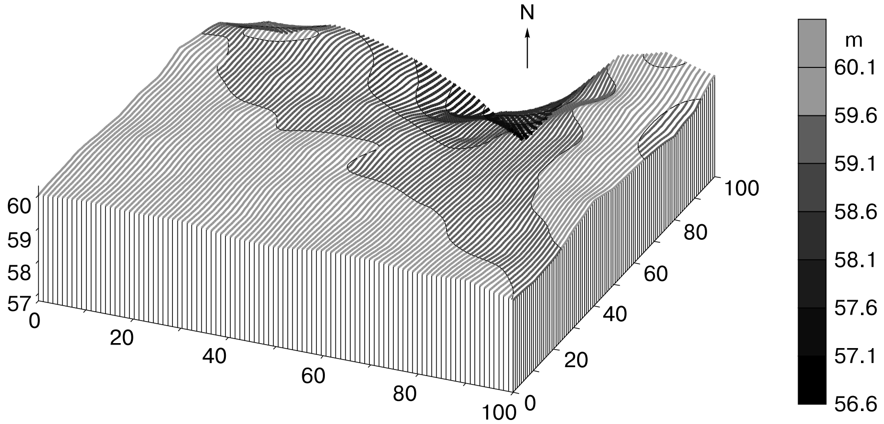

Fig. 3. Digital elevation model of R50 CALM site (August 2015).

Table 1. **Average values of parameters**

Facies	*n*	Elevations, m	Active layer thickness, m	Volumetric soil moisture, %	Soil surface temperature, °*C*	Soil CO_2 efflux, mg $CO_2/(m^2 \cdot h)$	Peat thickness, cm
Larch open forests	25	59.61 ± 0.29	1.20 ± 0.23	*18.4 ± 6.0*	8.8 ± 1.4	246 ± 100	*3.9 ± 3.2*
Shrub-grass-moss yernik	10	*58.25 ± 0.63*	1.29 ± 0.32	63.5 ± 28.0	7.3 ± 0.6	*417 ± 61*	29.7 ± 10.9
Ledum-lichen peatlands	37	59.63 ± 0.29	*0.52 ± 0.11*	56.3 ± 18.0	*4.4 ± 1.6*	140 ± 90	39.5 ± 3.5
Cloudberry-sphagnum peatlands	34	59.56 ± 0.39	*0.71 ± 0.19*	72.1 ± 15.0	7.6 ± 1.7	161 ± 90	40.3 ± 4.4
Shrub-moss peatlands	15	59.77 ± 0.27	1.17 ± 0.25	54.3 ± 16.3	9.8 ± 2.1	277 ± 75	37.6 ± 10.6

Note. Parameter values are quoted as mean values ± rms erros. Values that show statistically significant difference from others are in italic. *n* is number of replica measurements.

The soil cover is highly heterogeneous and consists of organic (peat), Al–Fe-humus, cryoturbated and gley layers. Peat soils predominate, and soil profiles consist of two or three ~30 cm thick layers of weakly- or moderately decayed peat lying over mineral layers, except for areas of lichen open forests with sandy (podzol or Al–Fe-humus) soils instead of <10 cm peaty soil profiles.

The R50 site comprises five landscape facies distinguished according to lithology, terrain, microclimate, soil profiles, and biocenoses, with reference to [*Ukraintseva et al., 2011*] (Fig. 2, *a*). They are, namely (1) larch open forests with lichen growing upon knob-and-kettle terrain: thin forests with dispersed trees (no canopy), on gley podzol and peat-podsolized Fe-rich brown soils with illuvial horizons; (2) dense thickets of 1.0–1.5 m high shrub birch (yernik) with a grass-moss understorey and depressions with mounds and grass-shrub-moss vegetation mainly on slimy peat-gley permafrost soils; (3) ledum-lichen peatlands (high and low mounds) with typical peat and oligotrophic peat permafrost soils; (4) cloudberry-sphagnum peatlands with typical peat and slimy peat permafrost soils; (5) shrub-moss peatlands (low mounds) with typical peat-gley and cryoturbated gley soils [*Shisov et al., 2004*].

Leveling surveys at the site show a difference of 3.56 m between the maximum and minimum elevations (Fig. 3) and average elevations of 59.51 ± 0.52 m asl. Four out of five landscape facies have similar elevations (Table 1). The yernik facies has the lowest statistically significant elevation (58.25 ± 0.63 m asl).

The vegetation consists of lichens (*Cladonia* sp.) and mosses (*Sphagnum* sp., *Pleurozium* sp., *Politrichum* sp.); bilberry (*Vaccínium myrtíllus*), bog bilberry (*Vaccínium uliginósum*), red bilberry (*Vaccínium vítis-idaéa*), wild rosemary (*Ledum palustre*), various sedge species (*Carex* sp.), cloudberry (*Rubus chamaemorus*), cotton grass (*Eriophorum* sp.), and andromeda (*Andromeda* sp.); shrub and dwarf birch (*Betula fruticosa* and *Betula nana*); and larch trees (*Lárix* sp.).

METHODS

In August 2015, the patterns of vegetation, soil, and microtopography were documented at all points of the site, with relative elevations measured by leveling surveys in a 100 × 100 m plot on a regular 10 m grid, at 121 measuring points. Peat 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 [*Bobrik et al., 2015*].

Soil CO_2 efflux was measured once during the field season in early August (on 11.08.2015), in the daytime (from 12.00 to 15.00), simultaneously at all 121 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.

Volumetric soil moisture was measured in triplicate at each point in the upper 10 cm of soil by a *Spectrum TDR-100* soil moisture meter. Active layer thickness (thaw depth) was estimated in late August and early September [*Melnikov et al., 2005; State Standard, 2015*] by inserting a 2 m long graduated steel rod, 10-mm in diameter, into the soil to the point of refusal.

The collected data were processed by correlation and regression 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 normal distribution, the Spearman rank correlation was applied with a coefficient of $r > 0.18$ assumed to be significant for a sample size of $n > 119$ ($p < 0.05$ significance). The statistical sample for the CALM R50 site was 121 for each monitored parameter.

The spatial variations of measured parameters were imaged in maps using *Golden Software Surfer 8* modeling.

RESULTS

Active layer thickness. Active layer thickness at the site varied from 0.31 to 1.71 m, 0.85 ± 0.37 m on average, in August 2015 (Fig. 2, *b*). Thaw depth was the lowest in ledum-lichen peatlands and the highest in larch-lichen open forests. It showed high spatial variability (44 % variance) and an asymmetric distribution, with the median shifted to low values. The thaw depths in the facies of open forest (1), yernik (2), and low-mound peatland (5) are within average values (1.22 ± 0.30 m mean over three facies) and differ to statistical significance from those in the ledum-lichen (3) and cloudberry-sphagnum (4) peatlands. The peatland areas of facies 3 and 4, with thick peat, have a thinner active layer (a mean of 0.62 ± 0.15 m over two facies). The reason is that peat has low thermal conductivity and thus provides heat insulation for permafrost [*Zimov et al., 1998; Mazhitova et al., 2004; Goncharova et al., 2015*].

Soil moisture. The amount of moisture (water content) in soil depends on the type of substrate and is informative of its biological acitivity. The meausred volumetric soil moisture varied strongly over the area, with 48 % variance: from 7.0 to 91.0 vol.%, 52.5 ± 25.1 vol.% on average, exceeding 60 vol.% at about 48 % of points (Fig. 2, *c*). Four out of five facies showed similar rather high values, with a mean of 61.3 ± 19.4 vol.% over four facies (Table 1). Soil in facies 1 (open forest) turned out to be much drier than in other facies and differed both in water contents (18.4 ± 6.0 vol.%) and in their variance. Low moisture was measured in facies 1, with the mineral component predominant in the upper layer, and high values were obtained for facies 2 (yernik) located in topographic lows and for cloudberry-sphagnum wet peatland (facies 4).

Soil surface temperature. Soil temperatures measured at the depth 10 cm in the daytime were quite variable over the area (38 % variance) and showed a quasi-log-normal distribution. The temperature values ranged from 1.2 to 13.0 °C, 7.4 ± 1.8 °C on average (Fig. 2, *d*). They were the coldest in cloudberry-sphagnum peatlands (significantly different from other facies, Table 1) due to small active layer thickness.

Soil CO_2 efflux. Soil CO_2 efflux at the site varied in a large range from 10 to 590 mg $CO_2/(m^2 \cdot h)$ being 202 ± 142 mg $CO_2/(m^2 \cdot h)$ on average (Fig. 2, *e*). Spatial variations are especially high in this parameter, the variance reaching 73 %. The emission rates show asymmetric distribution, with the median shifted to low values. They are the highest from yernik facies soil (417 ± 61 mg $CO_2/(m^2 \cdot h)$) and differ significantly from the respective average rates for the other facies, both in measured values and in their variability. The reason is that this facies area differs in relatively large thaw depths (1.29 ± 0.32 m) and, hence, has hydrothermal conditions favorable for microbial activity. Furthermore, active root respiration in the shrub thickets makes a large contribution to soil carbon dioxide emission.

DISCUSSION

Correlation among environmental factors. Active layer thickness is an important characteristic of permafrost soils. Permafrost, as an aquiclude on one hand and a low-temperature layer on the other hand, influences the evolution of ecosystems and soils, especially via control of the moisture and temperature regimes [*Makeev, 1999*].

According to regression analysis, the active layer thickness measured in August 2015 at the CALM site R50 shows statistically significant correlation with volumetric soil moisture (1) and soil surface temperature (2), as well as with soil CO_2 efflux (4):

(1) Soil moisture [vol.%] = 73.3 [%] – 24.5 [%/m] × × Active layer thickness [m], $r = -0.28$, p-level < 0.05;

(2) Soil temperature [°C] = 3.5 [°C] + 4.1 [°C/m] × × Active layer thickness [m], $r = 0.65$, p-level < 0.05.

The surface temperature of soil also correlates with its volumetric moisture (3):

(3) Soil temperature [°C] = 8.1 [°C] – 0.02 [°C/%] × × Soil moisture [vol.%], $r = -0.21$, p-level < 0.05.

As we have found out, thaw depth variations are responsible for 43 % of soil temperature variance while the effect of soil moisture is limited to 4.5 %. On the other hand, only 8 % of variance in soil moisture is due to thaw depth, and the variance controls are mutually independent to 72 %.

The active layer thickness variations do not show statistically significant correlation with elevations, except for the facies of cloudberry-sphagnum peatlands ($r = 0.65$, p-level < 0.05, $n = 34$).

Soil respiration. CO_2 efflux is an integrated indicator of soil biological activity and depends on several factors: soil moisture and temperature patterns; physical properties of the substrate; phytomass growth of above-ground vegetation and roots; and transformations of organic matter [*Kobak, 1988*].

According to the obtained CO_2 efflux data, the sampled soils of southern forest tundra show lower biological activity than their counterparts from other zones [*Naumov, 2009; Goncharova et al., 2014, 2016; Bobrik et al., 2016*].

Regression analysis reveals statistically significant correlation of soil CO_2 efflux (August 2015) with active layer thickness (4), volumetric soil moisture (5), soil surface temperature (6) and elevations above sea level (7):

(4) Efflux rates [mg CO_2/(m^2·h)] = 9 [mg CO_2/(m^2·h)] + + 255.5 [mg CO_2/(m^2·h)] × Active layer thickness [m], $r = 0.50$, p-level < 0.05;

(5) Efflux rates [mg CO_2/(m^2·h)] = = 291 [mg CO_2/(m^2·h)] – 1.3 [mg CO_2/(m^2·h)/%] × × Soil moisture [vol.%], $r = -0.27$, p-level < 0.05;

(6) Efflux rates [mg CO_2/(m^2·h)] = = 119 [mg CO_2/(m^2·h)] + 15.2 [mg CO_2/(m^2·h)/°C] × × Soil temperature [°C], $r = 0.23$, p-level < 0.05;

(7) Efflux rates [mg CO_2/(m^2·h)] = = 8767 [mg CO_2/(m^2·h)] – 143 [mg CO_2/(m^2·h)/m] × × Elevation [m asl], $r = -0.42$, p-level < 0.05.

We estimate that 25 % of CO_2 efflux variance is due to variations in active layer thickness, 18 % of variance is associated with elevations, while soil moisture and temperature are responsible for 7.5 % and 5.5 % of variance, respectively; 44 % of variance is independent of these factors.

The reported statistically significant correlation of carbon dioxide emission rates with soil moisture contents and temperatures is consistent with the key role of abiotic factors in production, migration, and emission of soil greenhouse gases inferred previously [*Kobak, 1988; Smagin, 2005; Liu et al., 2006; Naumov, 2009*]. The observed inverse correlation of CO_2 efflux with elevations may be due to facies specificity and soil properties. Namely, yernik areas are hypsometrically lower than the others and show the highest emission rates of soil CO_2 (Table 1).

Of special interest is the significant correlation between active layer thickness and biological activity of soil. Soils in zones of thickest active layer correspond to those of highest CO_2 efflux. This may be due to high biological activity of upper soil in favorable hydrothermal conditions (retreating freezing front and low moisture). Therefore, biological activity of soil increases with thaw depth.

The observed correlation between soil CO_2 efflux and active layer thickness implies the necessity for estimation of the spatial variability of thaw depth as an important control of regional CO_2 emission. Therefore, neglect of spatial heterogeneity in geocryological conditions of permafrost areas can lead to distortions in total carbon flux estimates.

CONCLUSIONS

1. All abiotic factors (active layer thickness, soil moisture and temperature) at the CALM R50 site show high spatial variability, with variance from 38 to 48 %. Active layer thickness is responsible for most of variance in soil moisture and temperature and is thus the principal control.

2. Soil CO_2 efflux rates at the site, measured at the vegetation season peak, are generally low and highly variable (202 ± 142 mg CO_2/(m^2·h), variance 73 %), but are greater in the yernik facies area (417 ± 61 mg CO_2/(m^2·h)) than in the other facies.

3. The spatial distribution of soil CO_2 efflux in August 2015 (at the peak of vegetation) depends on thaw depths ($r = 0.50$, p-level < 0.05), soil temperatures ($r = 0.23$, p-level < 0.05) and volumetric moisture ($r = -0.27$, p-level < 0.05), as well as on elevations asl ($r = -0.42$, p-level < 0.05). The reason is in higher microbiological activity in the upper soil layer at large thaw depths due to the favorable thermal and moisture regime (retreating freezing front and low moisture contents).

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