ISSN 1064-2293, Eurasian Soil Science, 2023, Vol. 56, No. 11, pp. 1653–1666. © The Author(s), 2023. This article is an open access publication.
Russian Text © The Author(s), 2023, published in Pochvovedenie, 2023, No. 11, pp. 1385–1339.

SOIL PHYSICS

Analysis of CO_2 Emission from Urban Soils of the Kola Peninsula (European Arctic)

M. V. Korneykova[a, b, *] (ORCID: 0000-0003-1563-8587), V. I. Vasenev[c], N. V. Saltan[d], M. V. Slukovskaya[e], A. S. Soshina[b], M. S. Zavodskikh[d], Yu. L. Sotnikova[a], and A. V. Dolgikh[f]

[a] *Peoples' Friendship University of Russia (RUDN University), Moscow, 117198 Russia*

[b] *Institute of North Industrial Ecology Problems, Kola Science Center of the Russian Academy of Sciences, Apatity, 184209 Russia*

[c] *Soil Geography and Landscape Group, Wageningen University, Wageningen, 6707 Netherlands*

[d] *Polar Alpine Botanical Garden-Institute, Kola Science Center of the Russian Academy of Sciences, Apatity, 184209 Russia*

[e] *Laboratory of Nature-Inspired Technologies and Environmental Safety of the Arctic, Kola Science Center of the Russian Academy of Sciences, Apatity, 184209 Russia*

[f] *Institute of Geography, Russian Academy of Sciences, Moscow, 119017 Russia*

**e-mail: korneykova.maria@mail.ru*

Received May 26, 2023; revised June 20, 2023; accepted June 21, 2023

Abstract—Dynamics of soil CO_2 emission, temperature, and moisture were studied during the vegetation season (from May to October) in 2021 and 2022 in the residential areas of Murmansk and Apatity cities (Murmansk oblast) in comparison with natural areas. The mean emissions from urban soils were 5–7 g C/(m^2 day) in summer and 1–2 g C/(m^2 day) in spring and fall. Temperature was the main abiogenic factor that determined the seasonal dynamics of soil respiration (R^2 from 0.4 to 0.7, $p < 0.05$; Q_{10} temperature coefficient up to 2.5), while excess moisture had a limiting effect, especially in the natural areas. The heterogeneity of hydrothermal conditions and the content of biophilic elements determined the differences in the mean CO_2 emission between natural and urban soils. For the natural soils, the mean temperature was lower and the moisture content was higher than for urban areas, which determined the lowest emission values. Among urban sites, higher CO_2 emissions were found for tree and shrub vegetation sites.

Keywords: urbanization, Arctic, green infrastructure, ecological functions of soils, seasonal dynamics, soil respiration, Albic Podzols, Urbic Technosols

DOI: 10.1134/S1064229323601749

INTRODUCTION

Arctic ecosystems play an important role in the global carbon cycle. Occupying about 15% of the total area, cryogenic soils contain, according to various estimates, from 30 to 50% of the world stocks of soil organic carbon [15, 54, 67, 84, 89]. For centuries, low temperatures and high moisture content have limited the rate of decomposition of organic matter below the rate of primary production, ensuring the accumulation and conservation of organic carbon in arctic soils [20, 34, 37, 66]. Climate changes influence this ratio; as a result, Arctic ecosystems can turn from a net sink into a powerful source of greenhouse gas emissions [37, 45, 78]. The high vulnerability of the accumulated stocks of organic matter in northern soils to climate change and topics of associated climate risks are regularly reflected in global reports [62] and regional studies [59, 64, 92]. At the same time, special attention is paid to the role of the anthropogenic factor in changing the carbon balance of fragile Arctic ecosystems [51, 58, 75].

Anthropogenic activities have a complex and diverse impact on the carbon balance of Arctic ecosystems, suppressing or enhancing greenhouse gas emissions. For example, drainage and exploitation of tundra areas leads to an increase in soil CO_2 emission (E_{CO_2}), but reduces CH_4 emission [68]. For soils of technogenic territories (industrial wastelands, abandoned mines, impact zones of enterprises), E_{CO_2} can be both higher [39] and lower [13, 14, 81] than for soils of natural sites, depending on the type of anthropogenic impact and the degree of soil degradation. Among various types of anthropogenic changes that affect greenhouse gas emissions from northern soils, the impact of urbanization remains perhaps the least understood and most interesting.

The cities of the Arctic are unique ecosystems, where harsh climatic conditions are combined with continuous anthropogenic impact. Urban soils are highly heterogeneous, as they are formed and function under the influence of various, and often multidirectional factors. Thus, soil pollution from industrial and transport facilities is combined with soil construction for landscaping and landscaping [8, 34, 87]. The main factors that have a potential impact on the E_{CO_2} from soils of Arctic cities include changes in the temperature and hydrological regime [10, 21], changes in the species composition of vegetation and its projective cover [16, 17, 79], and application of organic material for landscaping [4, 33, 56]. Despite the fact that significant data have been collected on greenhouse gas emissions from natural and anthropogenic soils of the Arctic [16, 38, 42, 51, 65], the understanding of E_{CO_2} from urban soils is mainly based on irregular measurements in settlements and cities differing in their size, climate, and soil and landscape conditions in (Vorkuta, Yakutsk, Syktyvkar, Barentsburg). The accumulated data make it possible to identify the main patterns of anthropogenic impact on the soil E_{CO_2} but do not characterize the factors of spatial and temporal variability of E_{CO_2} from soils of urban areas under the conditions of the Arctic region and cryogenic ecosystems.

The study aimed to a comparative assessment of E_{CO_2} from soils of the residential areas in the cities of Murmansk and Apatity and the corresponding natural sites, as well as to study the factors that determine the spatial heterogeneity and seasonal dynamics E_{CO_2} from urban and natural soils under the conditions of the Kola Arctic region.

OBJECTS AND METHODS

Urban ecosystems of Murmansk and Apatity. Murmansk (68°58′ N, 33°05′ E) is a regional center in the north of the Kola Peninsula. The climate of studied territory is moderately continental, cold and humid; the winter period is warmer and shorter than in other cities of the region, which is determined by the proximity of the Barents Sea and the influence of the warm North Atlantic Current [53]. The mean long-term January temperature is −10°C; July temperature, +12°C; precipitation is about 500 mm, most of which falls in October [46]. Murmansk is located in the forest-tundra zone; humus-illuvial- and iron-illuvial podzols (Albic Podzols) and podburs (Entic Podzols) predominate in the soil cover on automorphic positions [22, 23]. Building, land improvement, and landscaping have led to significant changes in vegetation and soils of Murmansk. Tree and shrub vegetation, including introduced species, predominates in the city lawns make up about 10% of the total area [43]. The diversity of urban soils includes both weakly disturbed podzols and podburs (Albic and Entic Podzols), their urbostratified subtypes, as well as technogenic surface formations (TSFs)—replantozems and constructozems (Technosols) created using high-moor peat and mixtures based on it [5, 55, 69]. With a population of about 300 thousand people, Murmansk is the largest polar city in the world. Industrial enterprises (a port, a ship repair, metalworking, marine geology), transport and heat and power complex are the main sources of anthropogenic load on the soils of Murmansk.

The city of Apatity (67°33′ N, 33°24′ E) is located 160 km south of Murmansk; it is three times smaller in area and five times smaller in population. Compared to Murmansk, Apatity is characterized by a higher temperature amplitude (mean temperature of January is −13.5°C, in July, +13.5°C) and a greater precipitation (up to 850 mm), a significant proportion of which is snow [46, 47, 53]. A stable snow cover forms in late October—early November and lasts until early May. The duration of the winter period is more than 210 days (in Murmansk, about 200 days). Apatity is located in the northern taiga subzone; zonal soils of automorphic positions are also iron-illuvial and humus-illuvial podzols (Albic Podzols) and podburs (Entic Podzols). Both in Murmansk and its environs and in Apatity, urban and natural soils are seasonally frozen, permafrost is absent. Urban soils are characterized by varying degrees of disturbance, from slightly disturbed Podzols in forest parks to urban stratified soddy podzols in residential areas and replantozems and constructozems (TSFs, Technosols) along roads, near the industrial enterprises and shopping malls [19, 56]. The main sources of anthropogenic load are the mining industry, thermal power engineering, and transport.

Key sites for measuring soil E_{CO_2}. In Murmansk and in Apatity, one site in the residential area and one natural site were selected (Fig. 1).

The natural site for Murmansk with an area of 563 m^2 is located on the territory of Abram-mys settlement (68°59′01″ N, 33°01′06″ E) on a gentle slope of the ridge composed of bouldery sands and loamy sands of the ground moraine. The microrelief is formed on a matrix of large boulders dominated by acid rocks; rises, slopes, and depressions can be distinguished. A typical profile of humus-illuvial podzol of a sandy or loamy sandy texture includes the surface 10-cm-thick peaty litter (O) horizon underlain by a pronounced whitish light-brown podzolic (albic) E horizon (10–23 cm) and an ocherous-dark brown humus-illuvial BH horizon (23–45 cm). The transitional BCf horizon (45–55 cm) is brown with an ocherous tint with mottles of bluish brown sandy—loamy sandy material. The underlying gleyic parent material (Cg, 55–70 cm) is dove-brown with greenish tint, relatively dense silty loamy sand.

Starting from the BH horizon and deeper, a large number of stony inclusions are found, including gravels and boulders. This soil is classified as a gleyic humus-illuvial podzol (Folic Albic Podzol (Arenic)).

The site is located in the forest-tundra zone with two main types of plant communities. The first type is

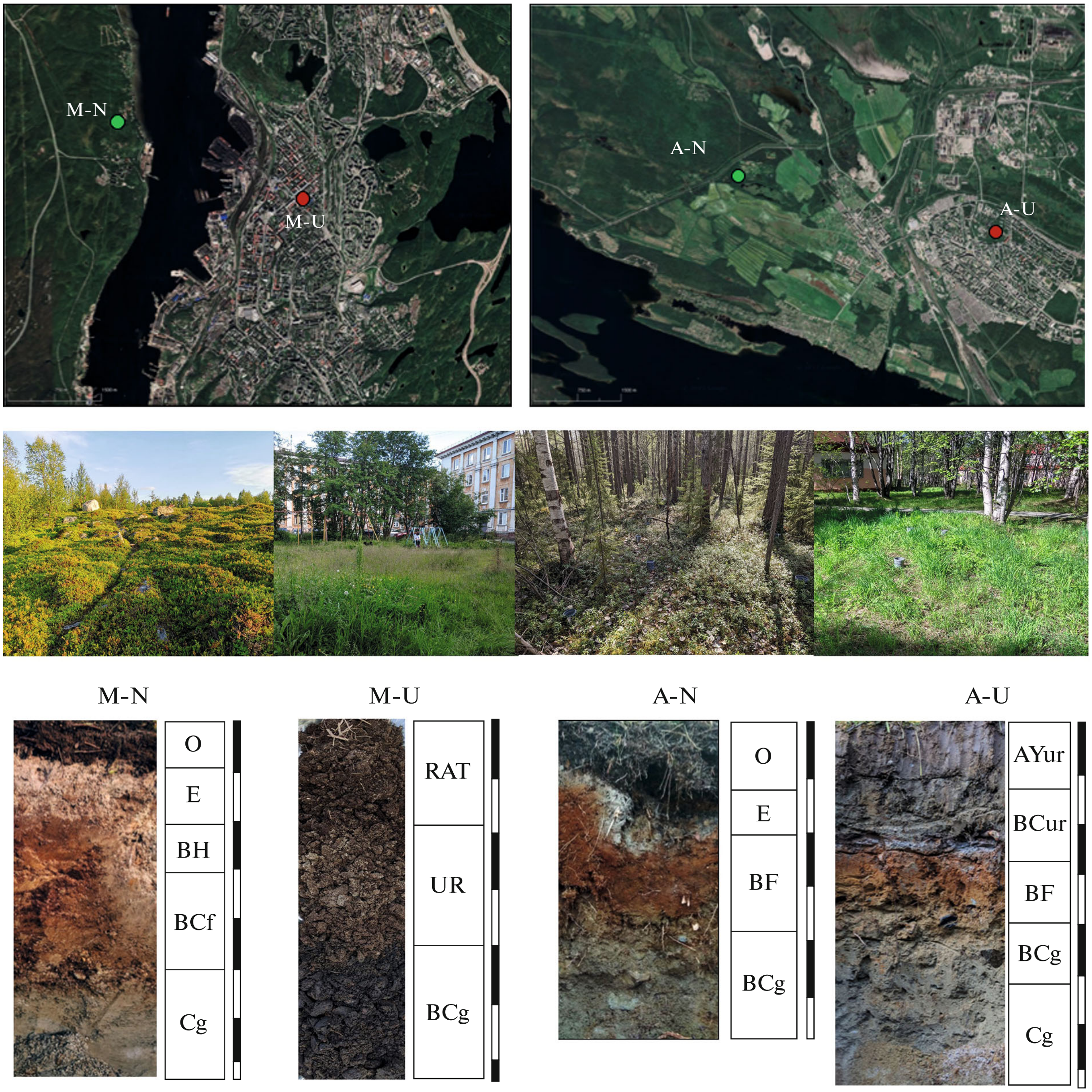

Fig. 1. Location (upper row), appearance (middle row) and soil profiles (lower row) of monitoring sites for soil E_{CO_2} at urban (U) and natural (N) experimental sites in the cities of Murmansk (M) and Apatity (A).

represented by birch crooked forest dominated by *Betula tortuosa* Ledeb. in the tree layer; *Chamaepericlymenum suecicum* (L.) Asch. & Graebn., *Vaccinium vitis-idaea* L., *Chamaenerion angustifolium* (L.) Scop., *Equisetum sylvaticum* L., and *Ledum palustre* L., in the dwarf shrub–herb layer; and *Hylocomium splendens* (Hedw.) Bruch et al. in the moss layer. The second type of communities is characterized by the absence of the tree layer and the predominance of dwarf shrubs (*Empetrum nigrum* L., *V. vitis-idaea*, *Vaccinium myrtillis* L., *L. palustre*).

The urban site in Murmansk with an area of 786 m^2 is located on the adjacent territory (Karl Marksa St., 14; 68°58′23″ N, 33°05′20″ E). The soil profile reflects the anthropogenic genesis, namely the surface organic RAT horizon (presumably, based on high-moor peat) underlain by the urbic UR horizon with a significant amount of anthropogenic inclusions (broken brick, lime, glass). From a depth of 45 cm, the underlying BCg horizon of dark dove color and sandy loamy texture with a large number of stony inclusions is present. The vegetation is represented by a periodically mown grass–forb community with the dominance of *Festuca rubra* L. and the participation of *Taraxacum officinale* L. and *Ranunculus acris* L.; trees (*Sorbus Gorodkovii* Pojark.) grow along the perimeter of this site.

The natural site for the city of Apatity (67°34′43″ N, 33°17′52″ E) with an area of 608 m^2 is located on the border of the forest and is characterized by a gentle relief; the parent rocks are moraine boulder sands and loamy sands. The soil profile is typical for iron-illuvial podzols. Compared to the natural soil for the city of Murmansk, the surface peaty litter–raw-humified horizon Oao is characterized by a smaller thickness (0–7 cm) and a higher degree of decomposition of organic residues. It is underlain by a thin (7–10 cm) bleached E horizon and the ocherous BF horizon (10–35 cm). The transitional BCg horizon with gleyic features is characterized by the maximum amount of rounded and unrounded gravels and boulders. This soil is classified as a raw-humus gleyic iron-illuvial podzol (Folic Leptic Albic Podzol (Arenic)). The vegetation is represented by a typical northern taiga community with a predominance of *Pinus friesiana* Wich. and *Picea obovata* Ledeb. and the presence of *B. pubescens.* The shrub layer is represented by *Juniperus communis* L. The dwarf shrub–herb layer is composed of *E. nigrum*, *V. vitis-idaea*, *V. myrtillis,* and *L. palustre*.

The residential site in the city of Apatity with an area of 833 m^2 is located on the territory of the Akademgorodok district (67°34′11″ N, 33°24′04″ E). In the soil profile, the middle-profile BF and BCg horizons are overlain with anthropogenic horizons formed during the construction and landscaping of the territory, namely the gray-humus AYur horizon and the loamy sandy BCur horizon with a significant amount of anthropogenic inclusions, primarily construction debris. The soil is classified as an urbostratified soddy iron-illuvial podzol (Someriumbric Leptic Entic Podzol (Arenic, Technic)). The site includes two plant communities. The tree–shrub layer of the first community is represented by *Betula pubescens* Ehrh. and *Syringa josikaea* J. Jacq. ex Rchb., the herbaceous layer is dominated by species of the Poaceae family. The second community is formed only by herbaceous vegetation with the dominance of *F. rubra* and the participation of *T. officinale;* the herbs are cut several times during the season.

At each site, 10 points were selected for monitoring E_{CO_2}, temperature, and soil moisture. The points were chosen in such a way as to take into account the factors of the internal heterogeneity of the sites, primarily the predominance of herbaceous or tree–shrub vegetation.

Soil survey and analysis of physicochemical and microbiological properties of soils. At each site, a full-profile soil pit was made (or drilling was carried out to a depth of 100 cm with layer-by-layer reproduction of the profile on a horizontal surface) to classify soils and describe their morphological properties. To analyze the internal heterogeneity, 10 test sites with an area of about 1 m^2 (circles with a diameter of 1 m with a camera in the center) were laid at each site characterizing herbaceous and tree–shrub types of vegetation. At these sites, E_{CO_2}, temperature, and soil moisture were measured, and surface soil sampling was carried out (0–10 cm) to analyze the relationship between E_{CO_2} and the soil physicochemical and microbiological properties. The selected samples were divided into two groups. Samples for physicochemical analyses were dried in air and sieved through a 1-mm mesh, while samples for microbiological analyses were stored in a refrigerator. Before analysis, the soil was sieved through 2-mm mesh, moistened approximately up to 55% of the water-holding capacity and incubated at 25°C for three days.

The following physicochemical properties were analyzed in the samples: bulk density according to Kachinskii, pH_{KCl} (acidity of the salt suspension) with potentiometric method, total carbon (C) and nitrogen (N) contents by dry combustion in a Vario Isotope (USA) CNHS-analyzer. Substrate induced respiration (SIR) was measured by the maximum initial response of microorganisms to the addition of glucose [2, 35]. Soil samples (1 g) were placed in a vial (15 mL) and 0.1 mL of glucose solution (5 mg glucose/g soil) was added dropwise. The vial was then tightly closed and the time was recorded. Soil samples with the addition of glucose were incubated at intervals of 3 to 5 h (22°C); air samples were taken (the time was fixed) and introduced into a gas chromatograph (KristallLyuks 4000 M, Meta-Khrom, Yoshkar-Ola, Russia) equipped with a detector to measure CO_2 concentration. The SIR rate (μL CO_2/(g × h)) was used to estimate the carbon of soil microbial biomass (C_{mic}, μg C/g soil) according to the following formula [35]:

$$C_{mic} = SIR\ 40.04 + 0.37.$$

The incubation time (from 1 to 5 h, every 0.5 h) and glucose concentration (2, 5, and 10 mg/g soil) to achieve the maximum initial respiratory response for the studied soils were based on previous methodological studies [2]. Basal respiration (BR) was measured in soil samples (1 g, 24 h, 22°C, water was added, 0.1 mL/g soil) to assess the rate of decomposition of organic matter [2, 36]. BR was expressed in μg C/(g soil × h).

The ratio of basal respiration and microbial biomass carbon of was used to calculate the microbial metabolic coefficient (qCO_2), the ratio of microbial biomass and organic carbon was used to assess the efficiency of carbon use by microorganisms (C-use efficiency). The resistance of organic matter to biodegradation was evaluated through the biodegradation constant (k), half-life ($T_{0.5}$), and turnover time ($T_{0.95}$). The parameters were calculated as the ratio of BR to the carbon content [82].

Monitoring of soil E_{CO_2}, temperature, and moisture content. The E_{CO_2} measurements were carried out twice a month during the growing season from May to October 2021–2022 by the closed chamber method using AZ-77532 gas analyzer (https://www.az-instrument.com.tw/en/product-616379/CO2-Meter-77532-AZ.html, Taiwan, China) calibrated and verified by high-precision instrument Li-8100A (LiCor, USA) during parallel measurements. The chambers represented opaque PVC 25-cm-long tubes with a base area of 95 cm^2. The measurements were carried out in dry weather (without precipitation) between 10 a.m. and 2 p.m. An analysis of the daily variation of E_{CO_2} in the soils of the natural site of the northern taiga and in the immediate vicinity of soil constructions under lawn phytocenosis (the experiment was carried out in June 2021, data not published) showed that the mean E_{CO_2} values at this time did not significantly differ from the mean daily values. To calculate the total E_{CO_2} for the calendar month, the daily values obtained during the month were averaged and multiplied by the number of days. The total E_{CO_2} for the season was calculated as the sum of monthly emissions.

Two hours before the measurement, the open chambers were deepened into the soil to a depth of 3–4 cm with the preliminary removal of live biomass. Before measurements, the chambers were ventilated and tightly closed with a lid connected by cellulose tubes to the gas analyzer. The lids of the chambers were equipped with fans to mix the air. Soil respiration was assessed by the increase in CO_2 concentration in isolated chambers observed over a 3-min period. After the measurements, the chambers were removed and installed again inside the same test sites 2 h before the next measurement. At the same time, the soil temperature at a depth of 1 and 10 cm was measured with a Checktemp-1 thermometer (Hanna Instruments, USA), and the soil moisture at a depth of 10 cm was measured with an SM-150 moisture meter (Delta-T Devices, UK). Continuous monitoring of soil and air temperatures during the study period was carried out using TR-1G autonomous temperature recorders (Engineering Technologies) with an accuracy of 1°C and a time step of 3 h. The air recorders were placed at a height of 2.0–2.5 m; soil recorders, at the depths of 1, 7, and 20 cm. The temperature dependence of the soil E_{CO_2} was characterized in terms of the temperature Q_{10} coefficient, calculated according to the Vant-Hoff`rule using Eq. (1) [31, 76]:

$$Q_{10} = (R_1/R_2)^{[10/(T1-T2)]}, \quad (1)$$

where R_1 is E_{CO_2} at soil temperature T_1, R_2 is E_{CO_2} at soil temperature T_2.

Statistical processing and data analysis. For primary data processing, traditional methods of descriptive statistics were used (normality check using Levene`s test, estimation of the mean, errors of the mean, and 95%-confidence interval). To compare the significance of differences between the natural and urban objects, a t-test for independent samples was used, and multivariate analysis of variance was used for differences between sites. The correlation between E_{CO_2}, hydrothermal conditions, physicochemical, and microbiological properties of soils was analyzed based on multivariate linear regression, successively removing the factors with the lowest significance (the highest p-level) and controlling the change in the adjusted coefficient of determination (R^2 adj). Data analysis was performed using Statistica 10 and RStudio software.

RESULTS AND DISCUSSION

Physicochemical and microbiological properties of soils. The soils of Murmansk (Urbic Technosols (Arenic) and Apatity (Someriumbric Leptic Entic Podzol (Arenic, Technic)) differed markedly from the natural soils (Folic Leptic Albic Podzol (Arenic)) in morphology, physicochemical and microbiological properties, while the main patterns of anthropogenic transformation in both cities were identical. In contrast to the natural podzols, where the surface peaty litter O horizon was characterized by an acid reaction and a very high carbon content, the soils of urban areas contained the surface gray-humus AYur horizon (Apatity) and the organic horizon RAT (Murmansk) formed as a result of accumulation and transformation of technogenic materials of organic and mineral origin (obvious traces of fresh additions of soils for reclamation tasks were not found) The difference is also noticeable when comparing the mean moisture contents of surface horizons in a saturated state (when analyzing microbiological activity) and reaches 20% for Apatity (62% for the background natural soil and 43% for the city soil) and an order of magnitude (213% for the background natural soil and 29% for the city soil) for Murmansk. The carbon content in the surface horizons of urban soils is 2–3 times lower, and pH_{KCl} is one unit higher than in the natural soils. Urban soils also have a significantly lower C : N ratio and a higher bulk density (Fig. 2).

The revealed characteristics of chemical properties can be either acquired in the course of urban pedogenesis or borrowed from the properties of artificially introduced soils. In Apatity and Murmansk, as in almost all cities, the practice of land improvement and landscaping involves adding organic and organomineral substrates to the soil surface. Regulatory documents [25, 26] do not specify the list of such substrates, as a result of which mixtures of a complex and difficult to predict composition are used in practice, including the upper organic horizon of arable soils, peat, cuttings, and composts. At the same time, the scientific community has accumulated extensive practical experience in creating soil constructions and lawn ecosystems for landscaping tasks [9, 48]. As a rule, when carrying out landscaping works, a mixture of eutrophic or transitional peat and sand (3 : 1, vol %) is used with lime and mineral fertilizers. The successful experience of using apatite–nepheline, serpentine,

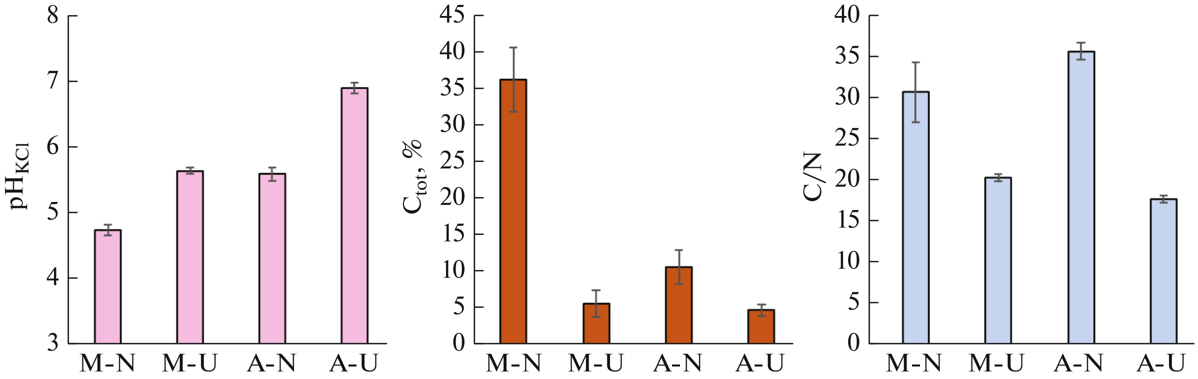

Fig. 2. Chemical properties of urban (U) and natural (N) soils in the cities of Murmansk (M) and Apatity (A).

and carbonatite wastes from the extraction and enrichment of various minerals is known [24, 57, 63, 80].

Higher pH values in urban soils may be due to the addition of carbonatite or lime. At the same time, alkalization of urban soils is a common phenomenon explained by additional sources of calcareous particles with construction dust, inclusions of construction debris (cement, gravel) and other artifacts [27, 60, 72]. A lower carbon content in urban soils compared to natural soils is less characteristic. For example, for the soils of Moscow [86], Berlin [74], and Nanjing [90], the reverse pattern was shown. Probably, the poverty of the natural soils and the limited budget allocated for urban landscaping in the cities of Murmansk oblast determines the lower total volume and frequency of adding soils, as well as the lower weighted mean values of the organic matter content in them. In the profiles of the studied urban soils, no fresh additions were found; for the soil in Apatity, the RAT organic horizon, which is characteristic, in particular, for soil constructions in Moscow [4, 28, 29], was not diagnosed, and the carbon content of 4.5–5.5% did not exceed the mean values for surface soil horizons of northern cities [43, 56, 69]. At the same time, the structural features of the profile of the natural podzols determine the maximum carbon stocks in the surface peat horizons, which were found in both natural soils.

The C_{mic} content in the urban soils of Apatity and Murmansk did not differ significantly and was 1.2 and 6 times lower compared to the corresponding natural background (ANOVA, $p < 0.05$). A similar pattern was shown for BR (Table 1). Taking into account significant differences between the urban and background soils in the content and stocks of organic matter (especially noticeable for sites in Murmansk), the results obtained were standardized by multiplying by soil bulk density (for C_{mic}, this made it possible to obtain a stock for the 0–10 cm layer). As a result, the difference between the natural and urban sites in Murmansk was leveled (2.6 and 3.0 g C/m^2), and the opposite pattern was shown for Apatity: the C_{mic} content in the urban soil was 70% higher than in the natural soil. The maximum density-adjusted BR value was also noted for the urban site in Apatity, while the results for the remaining sites did not differ significantly.

The correlation coefficients for C_{mic} and BR with the carbon content were 0.9 (p <0.05). Accordingly, the decrease in microbiological activity in urban soils compared with the background natural soils is explained by a lower content of organic matter and a higher anthropogenic load, which corresponds to a general trend characteristic of disturbed and natural ecosystems and previously noted for the soils of Moscow [6, 12], Kursk [3], and other cities. At the same time, C_{mic} values in these cities were in the same range of 200–600 μg C/g as the results obtained for Murmansk and Apatity, while C_{mic} for the natural site of Murmansk was almost an order of magnitude higher compared to the natural soddy-podzolic soil in Mos-

Table 1. Microbiological activity (mean ± error of the mean) of urban (U) and natural (N) sites in Murmansk (M) and Apatity (A)

Site	C_{mic}, mg C/g	BR, mg C–CO_2/(g h)	qCO_2, mg CO_2–C/mg C_{mic} /h	$C_{mic} : C_{org}$, %	$T_{0.5}$	$T_{0.95}$
M-U	354 ± 81	0.82 ± 0.15	2.63	0.76	12	52
M-N	2199 ± 353	7.20 ± 1.50	3.04	0.67	16	71
A-U	516 ± 49	0.93 ± 0.05	1.92	1.20	17	72
A-N	630 ± 178	1.52 ± 0.35	2.85	0.62	12	53

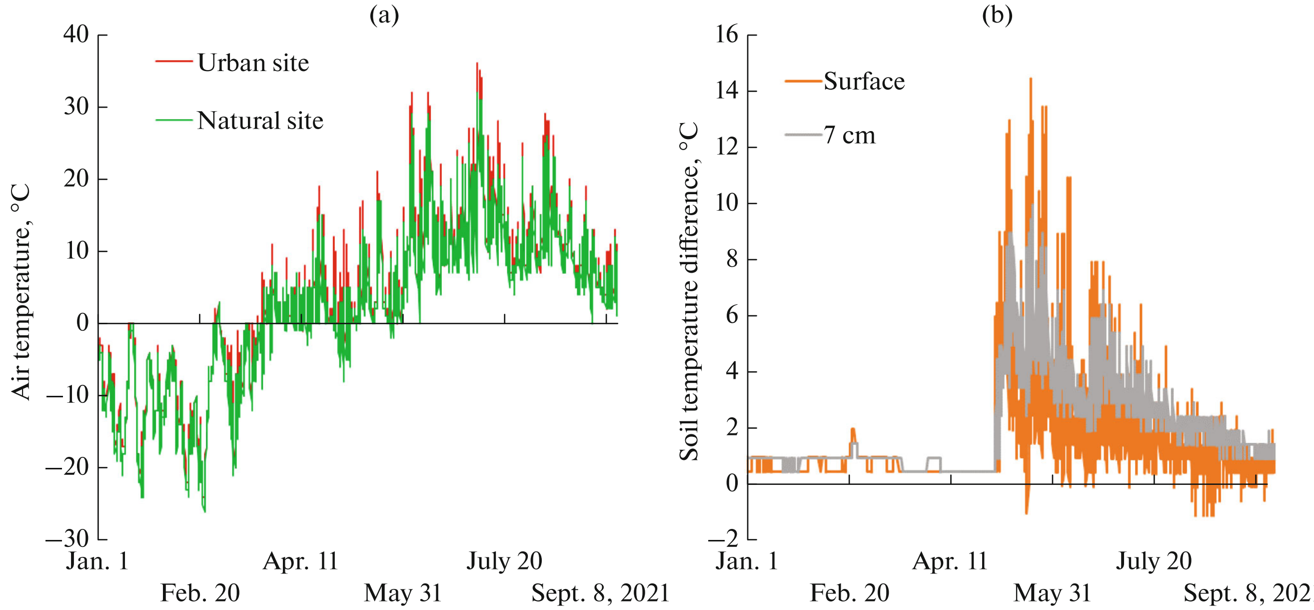

Fig. 3. Dynamics of (a) air temperature (2021) (b) difference of soil temperatures at two depths (2022) in the urban and natural sites in Murmansk (continuous measurement with portable sensors).

cow [83]. At the same time, in contrast to Moscow [49, 50], the microbial availability of carbon, expressed in terms of C_{mic}/C, is higher in the urban soils of Murmansk and, especially, of Apatity than in the corresponding natural soils. The urban soil of Apatity also showed the lowest microbial metabolic qCO_2 coefficient, which is interpreted in the literature as an indicator of a more stable state of the soil microbial community under anthropogenic load [1, 7, 36]. It can be assumed that the green infrastructure facilities of the northern cities form a favorable niche for the development of the soil microbial community, as was previously shown from the analysis of microbial diversity and the structure of the microbial community [55, 56]. This conclusion is also confirmed by a higher biodegradation coefficient, as a result of which the half-life period $T_{0.5}$ in the urban soil of Apatity was 12 years, which is significantly less than in the natural site, although longer than in Moscow [82, 88]. For Murmansk, the reverse pattern was shown, which can be explained by the very high organic matter content in the surface peat horizon, which was 7 times higher than that in the surface horizon of urban soil.

In general, both in terms of chemical and microbiological properties, the studied urban soils were closer to one another than to their natural analogues. Such a homogenization of the properties of urban soils in cities located in different bioclimatic conditions, as a rule, is explained by the similarity of the formation conditions and anthropogenic impact factors. A similar regularity was shown for the soils of cities in the United States [70], Western Europe [61], and European Russia [88], and the concept of convergence of urban soils was proposed for its designation [58].

Microclimatic conditions and E_{CO_2}. Mean air temperatures in Murmansk during the observation period were 1.3°C higher than in Apatity. At the same time, for both Murmansk and Apatity, the air temperature in the urban area was significantly higher than in the natural area (t-test, $p < 0.05$) (Fig. 3a). A similar pattern was shown for soil temperature, and in Apatity the soil surface temperature in the city exceeded the background temperature by almost 3°C on average, and the peak values of the difference exceeded +10°C gradually decreasing with depth. The maximum difference was observed at the end of May—beginning of June, which could be due to an earlier snowmelt in the city (Fig. 3b). The obtained data can be explained by the effect of the urban heat island, shown earlier on the basis of model data for Apatity and other cities of the Russian Arctic [18, 85]. The average moisture contents of soils in both urban areas did not differ much, while soils in the forest-tundra natural area were almost twice as wet as those in the northern taiga. The spring—summer of 2022 in the region was significantly warmer than in 2021, which was more noticeable according to measurements in Murmansk than in Apatity (Table 2).

The mean E_{CO_2} over the observation period for the urban and background areas of Murmansk did not differ significantly (ANOVA, $p < 0.05$), amounting to 4.1 ± 0.2 and 4.2 ±0.2 g C/(m^2 day), respectively. In Apatity, the mean E_{CO_2} for urban soils was 4.8 ± 0.2 g C/(m^2 day) and exceeded the background values by 30%. Among urban soils in both Apatity and Murmansk, the mean emissions for sites with trees and shrubs were 5–15% higher than for lawns. The mean soil E_{CO_2} values in

Table 2. Averaged microclimatic characteristics (*m* is mean value, *s* is error of the mean, CI 95% is 95% confidence interval) of urban (U) and natural (N) sites in Murmansk (M) and Apatity (A) (field measurements during the growing season from May to October)

Object	*T* air, °C			*T* soil at 1 cm, °C			*T* soil at 7 cm, °C			*W* soil at 7 cm, %		
	m	*s*	CI 95%	*m*	*s*	CI 95%	*m*	*s*	CI 95%	*m*	*s*	CI 95%
						2021						
M-U	12.8	6.8	(11.5;14.2)	10.7	5.0	(9.7;11.7)	9.7	4.1	(8.9;10.6)	27	12	(25;30)
M-N	12.4	6.8	(11.0;13.7)	10.1	4.5	(9.2;11.0)	8.8	3.8	(8.1;9.6)	43	29	(37;48)
A-U	13.3	7.8	(11.9;14.8)	12.6	7.0	(11.3;14.0)	10.9	4.9	(10.0;11.8)	23	9	(31;25)
A-N	9.7	6.4	(8.5;10.9)	8.8	4.5	(7.9;9.6)	8.0	4.0	(7.2;8.7)	17	8	(16;19)
						2022						
M-U	15.4	5.3	(14.4;16.5)	13.0	4.4	(12.1;13.9)	11.8	3.5	(11.1;12.5)	27	13	(24;30)
M-N	14.5	4.5	(13.6;15.4)	11.7	3.9	(11.0;12.5)	10.1	3.1	(9.5;10.7)	38	29	(32;44)
A-U	12.6	6.4	(11.5;13.7)	12.4	5.6	(11.4;13.4)	11.1	4.5	(10.3;11.9)	30	7	(29;31)
A-N	10.3	6.9	(9.0;11.5)	8.6	4.9	(7.7;9.5)	7.9	4.3	(7.1;8.6)	17	9	(16;19)

2022 were also significantly higher than in 2021. The greatest difference was shown for the soils of the natural forest-tundra site, where the mean emission increased by more than two times. The most probable reason for such a sharp increase in emissions is the change in hydrothermal conditions in May–June. The surface temperature during this period increased by more than 5°C in 2022 in comparison with 2021, and the moisture content decreased by 10–15%. As a result, conditions for rapid mineralization of the organic matter of the peat horizon were created; its high vulnerability to biodegradation is confirmed by high basal respiration. An increase in E_{CO_2} by tundra soils due to the intensification of microbial degradation of organic matter with an increase in temperature and a decrease in the moisture content has been repeatedly shown earlier in field studies and laboratory experiments [11, 21, 40, 52] and is considered one of the main risks of global warming in the Arctic. In Apatity, on the contrary, more significant increases in emission were shown for urban soils with a maximum difference in July–August (Fig. 4). At all sites, more than half of the emission occurred during the summer period. The share of the spring period at natural sites was lower than at urban sites, which is explained by later snowmelt. The results obtained for Apatity confirm earlier conclusions based on single measurements about the increase in soil E_{CO_2} under the influence of anthropogenic load in the conditions of the Arctic region [16, 21, 51].

Factors of spatiotemporal inhomogeneity of E_{CO_2}. The temporal dynamics of E_{CO_2} from natural and urban soils were mainly determined primarily by temperature and, to a lesser extent, by moisture conditions. The dependence of emission on temperature for all sites was statistically significant, direct, and described by a linear or exponential function. The temperature coefficient varied from 1.5 to 2.5 and was higher for natural soils than for urban soils. No linear dependence of E_{CO_2} intensity on the moisture content was found. Spatial heterogeneity of E_{CO_2} was determined both by the land use (city/natural) and by vegetation within the site. Under trees and shrubs, E_{CO_2} was on average 10–15% higher than under lawn vegetation in the same area in both Murmansk and Apatity. Given that the differences in microclimatic conditions within the sites were insignificant, the higher emission for plots with trees and shrubs can be explained by the input of additional organic matter with leaf litter, which is also confirmed by a higher carbon content in the soil. Multistage regression analysis showed a significant ($p < 0.05$) effect of soil temperature (positive) and C/N ratio (negative) on the E_{CO_2}: together they explained up to 40% of the total variance. The obtained pattern differed from the observations for Moscow, Kursk, and other more southern cities, where, as a rule, E_{CO_2} from lawn soils is higher than that from soils under trees and shrubs [30, 44, 83]. Higher emission values for lawns are explained both by higher surface temperatures and by direct and indirect effects of care activities (irrigation, fertilization, mowing) [73, 77, 91]. In the cities of the Artic region, the intensity of activities for the maintenance and care of green areas, as a rule, is limited both by a short season and a modest budget, which leads to a more "natural" approach—with the exception of certain parterre areas, lawns are not irrigated, the frequency of mowing and fertilization is also less than in Moscow and other

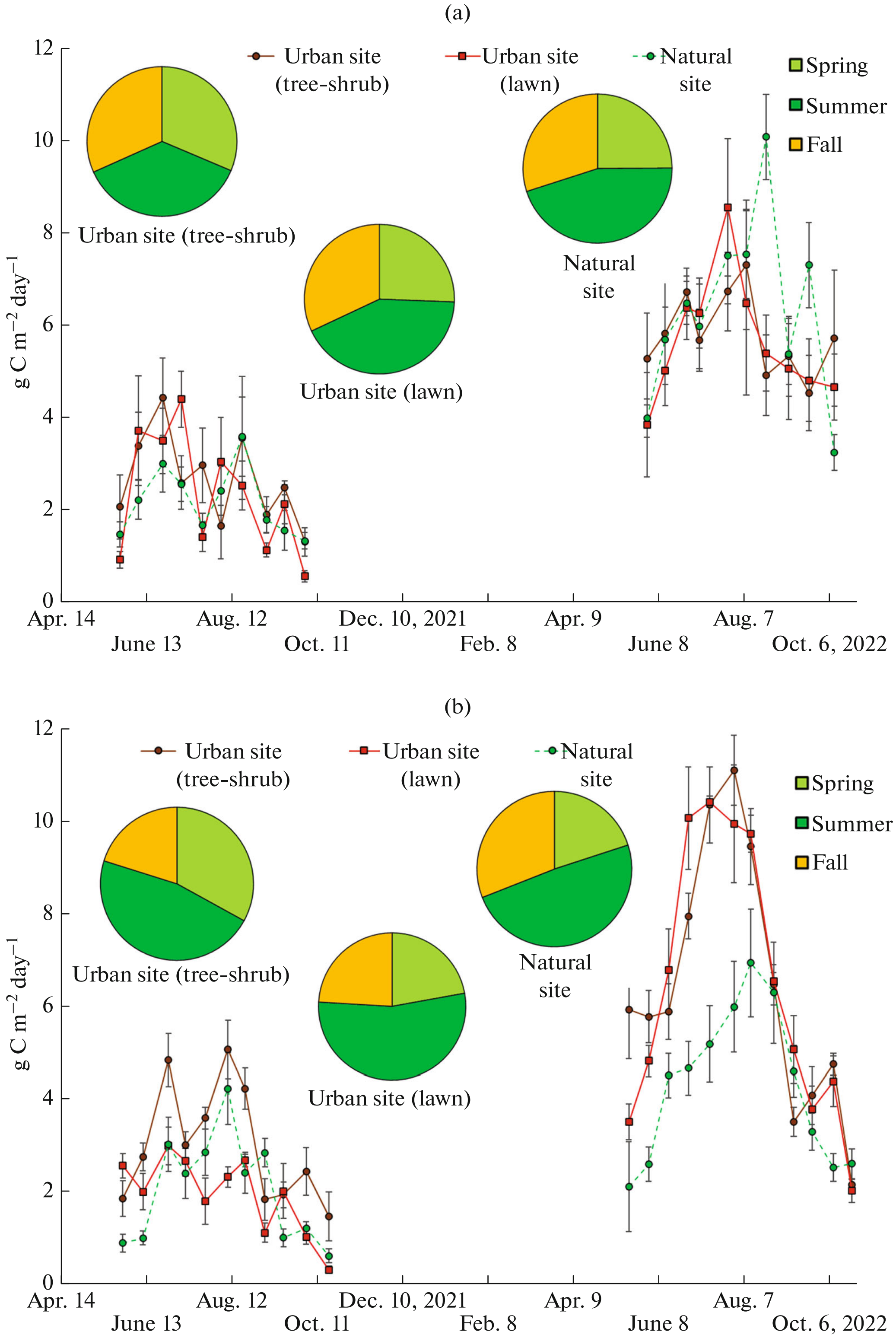

Fig. 4. Dynamics of E_{CO_2} from soils of natural and urban sites with tree–shrub (ts) and lawn (l) vegetation and the contribution (%) of seasons (2022) to the total emission for (a) Murmansk and (b) Apatity.

large cities. Apparently, such a gentle maintenance regime determines the lesser E_{CO_2} from soils of urban lawns, which can be an interesting practice in the context of carbon neutrality and the sustainable development of urban green infrastructure.

CONCLUSIONS

An analysis of the anthropogenic impact on the soil E_{CO_2} and ecosystem carbon balance is especially relevant for the conditions of the Arctic region, where a violation of the fragile balance between primary production and destruction of organic matter against the background of global changes can lead to irreversible environmental consequences. The soils of the cities of the Arctic region are formed and function under conditions of constant and multidirectional anthropogenic impact, which determines the differences of E_{CO_2} between urban and natural soils, their spatial heterogeneity and temporal dynamics. Based on the example of the cities of Murmansk and Apatity in the Kola Arctic region, it is shown that the main factors that determined the spatiotemporal variability of the soil E_{CO_2} were temperature, vegetation type, and C : N ratio. For Murmansk, the mean E_{CO_2} values for urban and natural soils did not differ significantly, and for Apatity, the mean E_{CO_2} for urban soils was 30% higher than the background values. The influence of the urban environment on E_{CO_2} from urban soils is due to a combination of factors, including the additional anthropogenic input of organic matter and its higher availability for biodegradation realized against the background of the influence of the urban heat island. The mean E_{CO_2} values for urban and natural soils were comparable, with a sharp increase of E_{CO_2} in the hot and dry period of May–June 2022. A significant increase in E_{CO_2} in 2022 compared to the cooler 2021 was noted for all sites, but the forest-tundra natural soils were the most vulnerable to climate change. The mean E_{CO_2} from natural soils of the forest-tundra area was 1.5 times higher than that from the northern taiga area, while the values for the urban areas of Murmansk and Apatity were quite close. In both cities, E_{CO_2} from soils under lawns was lower than E_{CO_2} from soils under trees and shrubs, which, given the lower intake of plant residues, can be considered an argument in favor of a more natural approach to the maintenance and care of urban green infrastructure within the carbon neutrality concept and sustainable development of urban ecosystems in the Arctic region.

FUNDING

Expedition works and sampling were carried out within the framework of state assignment, no. 122022400109-7. Monitoring E_{CO_2} and microclimatic parameters were supported by the Russian Foundation for Basic Research (project no. 19-29-05187). The analysis of the carbon and nitrogen stocks of urban and natural soils was carried out with the financial support of the Russian Science Foundation (project no. 23-17-00118). Data analysis and preparation of the paper were carried out within the framework of the RUDN University Scientific Projects Grant System.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

OPEN ACCESS

REFERENCES

1. N. D. Anan'eva, E. V. Blagodatskaya, and T. S. Demkina, "Assessment of resistance of soil microbial complexes to natural and anthropogenic impacts," Pochvovedenie, No. 5, 580–587 (2002).
2. N. D. Ananyeva, L. M. Polyanskaya, E. A. Susyan, I. V. Vasenkina, S. Wirth, and D. G. Zvyagintsev, "Comparative assessment of soil microbial biomass determined by the methods of direct microscopy and substrate-induced respiration," Microbiology (Moscow) **77** (3), 356–364 (2008).
3. N. D. Ananyeva, S. V. Sushko, K. V. Ivashchenko, and V. I. Vasenev, "Soil microbial respiration in subtaiga and forest-steppe ecosystems of European Russia: field and laboratory approaches," Eurasian Soil Sci. **53** (10), 1492–1501 (2020). https://doi.org/10.1134/S106422932010004X
4. I. P. Brianskaia, V. I. Vasenev, R. A. Brykova, V. N. Markelova, N. V. Ushakova, D. D. Gosse, E. V. Gavrilenko, and E. V. Blagodatskaya, "Analysis of volume and properties of imported soils for prediction of carbon stocks in soil constructions in the Moscow metropolis," Eurasian Soil Sci. **53** (12), 1809–1817 (2020). https://doi.org/10.1134/S1064229320120042
5. M. I. Vikhman, E. E. Kislykh, M. M. Moiseeva, and E. S. Nefedova, "Agrochemical assessment of urbanozems in some cities of the Murmansk oblast," Agrokhim. Vestn., No. 4, 17–18 (2008).
6. V. I. Vasenev, N. D. Ananyeva, and O. A. Makarov, "Specific features of the ecological functioning of ur-

ban soils in Moscow and Moscow oblast," Eurasian Soil Sci. **45** (2), 194–205 (2012).

7. V. I. Vasenev, N. D. Anan'eva, and K. V. Ivashchenko, "The effect of pollutants (heavy metals and diesel fuel) on the respiratory activity of constructozems (artificial soils)," Russ. J. Ecol. **44** (6), 475–483 (2013).
8. M. I. Gerasimova, M. N. Stroganova, N. V. Mozharova, and T. V. Prokof'eva, *Anthropogenic Soils: Genesis, Geography, Reclamation* (Oikumena, Smolensk, 2003) [in Russian].
9. O. B. Gontar', V. K. Zhirov, L. A. Kazakov, E. A. Svyatkovskaya, and N. N. Trostenyuk, *Green Building in the Cities of the Murmansk Oblast* (Kol'sk. Nauchn. Tsentr Ross. Akad. Nauk, Apatity, 2010) [in Russian].
10. O. Yu. Goncharova, O. V. Semenyuk, G. V. Matyshak, and L. G. Bogatyrev, "Biological activity of urban soils: spatial variability and control factors," Eurasian Soil Sci. **55** (8), 1082–1094 (2022). https://doi.org/10.1134/S1064229322080038
11. D. G. Zamolodchikov, "CO_2-exchange in tundra ecosystems of Vaygach island in an unusually warm and dry vegetation season," Biol. Bull. Rev. **6** (1), 24–38 (2016)
12. K. V. Ivashchenko, N. D. Ananyeva, V. I. Vasenev, V. N. Kudeyarov, and R. Valentini, "Biomass and respiration activity of soil microorganisms in anthropogenically transformed ecosystems (Moscow region)," Eurasian Soil Sci. **47** (9), 892–903 (2014). https://doi.org/10.1134/S1064229314090051
13. M. S. Kadulin, I. E. Smirnova, and G. N. Koptsyk, "The emission of carbon dioxide from soils of the Pasvik nature reserve in the Kola Subarctic," Eurasian Soil Sci. **50** (9), 1055–1068 (2017). https://doi.org/10.1134/S1064229317090034
14. M. S. Kadulin and G. N. Koptsik, "Changes in the soil carbon dioxide efflux in forest ecosystems caused by technogenic pollution in the Kola Subarctic," Eurasian Soil Sci. **54** (10), 1588–1598 (2021). https://doi.org/10.1134/S1064229321100070
15. D. V. Karelin and D. G. Zamolodchikov, *Carbon Metabolism in Cryogenic Ecosystems* (Nauka, Moscow, 2008) [in Russian].
16. D. V. Karelin, S. V. Goryachkin, D. G. Zamolodchikov, A. V. Dolgikh, E. P. Zazovskaya, V. A. Shishkov, and G. N. Kraev, "Human footprints on greenhouse gas fluxes in cryogenic ecosystems," Dokl. Earth Sci. **477** (2), 1467–1469 (2017). https://doi.org/10.1134/S1028334X17120133
17. D. V. Karelin, E. P. Zazovskaya, V. A. Shishkov, A. V. Dolgikh, A. A. Sirin, G. G. Suvorov, A. I. Azovskii, and N. I. Osokin, "Observations of CO_2 fluxes in the Svalbard archipelago: human use of the territory changes the gas exchange of the Arctic tundra," Izv. Ross. Akad. Nauk. Ser. Geogr., No. 5, 56–66 (2019). https://doi.org/10.31857/S2587-55662019556-66
18. P. I. Konstantinov, M. Yu. Grishchenko, and M. I. Varentsov, "Mapping of the heat islands of the cities of the Arctic using the combined data of field measurements and satellite images on the example of the city of Apatity (Murmansk oblast)," Issled. Zemli Kosmosa, No. 3, 27 (2015).
19. M. V. Korneikova, D. A. Nikitin, A. V. Dolgikh, and A. S. Soshina, "Mycobiota of soils in the city of Apatity (Murmansk oblast)," Mikol. Fitopatol., No. 54, 264–277 (2020). https://doi.org/10.31857/S0026364820040078
20. G. V. Matyshak, M. O. Tarkhov, I. M. Ryzhova, O. Yu. Goncharova, A. R. Sefiliyan, S. V. Chuvanov, and D. G. Petrov, "Temperature sensitivity of CO_2 efflux from the surface of Palsa peatlands in Northwestern Siberia as assessed by transplantation method," Eurasian Soil Sci. **54** (7), 1028–1037 (2021). https://doi.org/10.1134/S1064229321070103
21. D. A. Nikitin, L. V. Lysak, N. S. Mergelov, A. V. Dolgikh, E. P. Zazovskaya, and S. V. Goryachkin, "Microbial biomass, carbon stocks, and CO_2 emission in soils of Franz Josef Land: high-arctic tundra or polar deserts?," Eurasian Soil Sci. **53** (4), 467–484 (2020). https://doi.org/10.1134/S1064229320040110
22. V. N. Pereverzev, "Forest soils of the Kola Peninsula," in *Forestry and Green Building in Western Siberia* (Tomsk. Gos. Univ., Tomsk, 2007), pp. 225-231 [in Russian].
23. V. N. Pereverzev, "Soil formation in the forest zone of the Kola Peninsula," Vestn. Kol'sk. Nauchn. Tsentra Ross. Akad. Nauk, No. 2, 74–82 (2011).
24. A. G. Petrova, M. V. Slukovskaya, M. V. Korneikova, L. A. Ivanova, and I. P. Kremenetskaya, "The use of a pyroxene enrichment product of vermiculite-lizardite waste for the remediation of peat soil in the impact zone of the Kola MMC," Proceedings of Fersman Scientific Session of GI Kol'sk. Nauchn. Tsentra Ross. Akad. Nauk, No. 17, **437–441** (2020). https://doi.org/10.31241/fns.2020.17.084
25. Regulations on the Procedure for Felling (Thinning) Green Spaces in the Territory of the Urban Fistrict of Apatity. Approved by the Decree of the Administration of the City of Apatity Dated October 19, 2018 (Apatity, 2018).
26. Rules for the Improvement and Sanitary Maintenance of the Territory of the Municipality of the City of Apatity with the Jurisdictional Territory of the Murmansk Oblast. Approved by the Decision of the Council of Deputies of the City of Apatity dated October 23, 2017 No. 548 (Apatity, 2017).
27. T. V. Prokofeva and M. I. Gerasimova, "Urban soils: diagnostics and taxonomic position according to materials of scientific excursion in Moscow at the Suitma-9 workshop," Eurasian Soil Sci. **51** (9), 995–1007 (2018). https://doi.org/10.1134/S1064229318090090
28. T. V. Prokof'eva, M. I. Gerasimova, O. S. Bezuglova, K. A. Bakhmatova, A. A. Gol'eva, S. N. Gorbov, E. A. Zharikova, N. N. Matinyan, E. N. Nakvasina, and N. E. Sivtseva, "Inclusion of soils and soil-like bodies of urban territories into the Russian soil classification system," Eurasian Soil Sci. **47** (10), 959–967 (2014). https://doi.org/10.1134/S1064229314100093
29. T. V. Prokofyeva, I. A. Martynenko, and F. A. Ivannikov, "Classification of Moscow soils and parent materials and its possible inclusion in the classification system of Russian soils," Eurasian Soil Sci. **44** (5), 561–571 (2011). https://doi.org/10.1134/S1064229311050127
30. D. A. Sarzhanov, V. I. Vasenev, Yu. L. Sotnikova, A. Tembo, I. I. Vasenev, and R. Valentini, "Short-term dynamics and spatial heterogeneity of CO_2 emission

from the soils of natural and urban ecosystems in the Central Chernozemic Region," Eurasian Soil Sci. **48** (4), 416–424 (2015).
https://doi.org/10.1134/S1064229315040092

31. A. V. Smagin, *Gas Phase of Soils* (Mosk. Gos. Univ., Moscow, 2005) [in Russian].
32. A. V. Smagin, *Theory and Practice of Soil Construction* (Mosk. Gos. Univ., Moscow, 2012) [in Russian].
33. A. V. Smagin, N. A. Azovtseva, M. V. Smagina, A. L. Stepanov, A. D. Myagkova, and A. S. Kurbatova, "Criteria and methods to assess the ecological status of soils in relation to the landscaping of urban territories," Eurasian Soil Sci. **39** (5), 539–551 (2006).
34. V. V. Startsev, A. S. Mazur, and A. A. Dymov, "The content and composition of organic matter in soils of the Subpolar Urals," Eurasian Soil Sci. **53** (12), 1726–1734 (2020).
https://doi.org/10.1134/S106422932012011X
35. J. P. E. Anderson and K. H. Domsch, "A physiological method for the quantitative measurement of microbial biomass in soils," Soil Biol. Biochem. **10**, 215–221 (1978).
36. T. H. Anderson and K. H. Domsch, "Soil microbial biomass: the eco-physiological approach," Soil Biol. Biochem. **42**, 2039–2043 (2010).
37. E. F. Belshe, E. A. G. Schuur, and B. M. Bolker, "Tundra ecosystems observed to be CO_2 sources due to differential amplification of the carbon cycle," Ecol. Lett. **16**, 1307–1315 (2013).
https://doi.org/10.1111/ele.12164
38. Y. Y. Berestovskaya, I. I. Rusanov, L. V. Vasil'eva, and N. V. Pimenov, "The processes of methane production and oxidation in the soils of the Russian Arctic tundra," Microbiology **74**, 221–229 (2005).
https://doi.org/10.1007/s11021-005-0055-2
39. Q. Chen, R. Zhu, Q. Wang, and H. Xu, "Methane and nitrous oxide fluxes from four tundra ecotopes in NyElesund of the High Arctic," J. Environ. Sci. **26**, 1403–1410 (2014).
https://doi.org/10.1016/j.jes.2014.05.005
40. T. R. Crowdhury, E. C. Berns, J. W. Moon, B. Gu, L. Liang, S. D. Wullschleger, and D. E. Graham, "Temporal, spatial, and temperature controls on organic carbon mineralization and methanogenesis in Arctic high-centered polygon soils frontiers," Microbiology **11**, 616518 (2021).
https://doi.org/10.3389/fmicb.2020.616518
41. M. Deeb, P. M. Groffman, M. Blouin, S. P. Egendorf, A. Vergnes, V. Vasenev, D. L. Cao, D. Walsh, T. Morin, and G. Séré, "Using constructed soils for green infrastructure—challenges and limitations," Soil **6**, 413–434 (2020).
https://doi.org/10.5194/soil-6-413-2020
42. A. R. Desyatkin, F. Takakai, P. P. Fedorov, M. C. Nikolaeva, R. V. Desyatkin, and R. Hatano, "CH_4 emission from different stages of thermokarst formation in central Yakutia. East Siberia," Soil Sci. Plant Nutr. **55**, 558–570 (2009).
https://doi.org/10.1111/j.1747-0765.2009.00389.x
43. Y. A. Dvornikov, V. I. Vasenev, O. N. Romzaykina, V. E. Grigorieva, Y. A. Litvinov, S. N. Gorbov, A. V. Dolgikh, M. V. Korneykova, and D. D. Gosse, "Projecting the urbanization effect on soil organic carbon stocks in polar and steppe areas of European Russia by remote sensing," Geoderma **399**, 115039 (2021).
https://doi.org/10.1016/j.geoderma.2021.115039
44. O. Y. Goncharova, G. V. Matyshak, M. M. Udovenko, A. A. Bobrik, and O. V. Semenyuk, "Seasonal and annual variations in soil respiration of the artificial landscapes (Moscow Botanical Garden)," in *Urbanization: Challenge and Opportunity for Soil Functions and Ecosystem Services* (Springer International Publishing, Cham, 2019), pp. 112–122.
https://doi.org/10.1007/978-3-319-89602-1_15
45. M. M. P. D. Heijmans, R. I. Magnusson, M. J. Lara, et al., "Tundra vegetation change and impacts on permafrost," Nat. Rev. Earth Environ. **3**, 68–84 (2022).
https://doi.org/10.1038/s43017-021-00233-0
46. https://ru.climate-data.org/.
47. https://www.weatheronline.co.uk/.
48. L. Ivanova, M. Slukovskaya, I. Kremenetskaya, S. Alekseeva, and A. Neaman, "Ornamental plant cultivation using vermiculite-lizardite mining waste in the industrial zone of the Subarctic," in *Springer Geography* (2020), pp. 199–204.
https://doi.org/10.1007/978-3-030-16091-3_22
49. K. Ivashchenko, N. Ananyeva, V. Vasenev, A. Sushko, A. Selezneva, S. Demina, and V. Kudeyarov, "Microbial C-availability and organic matter decomposition in urban soils of megapolis depend on functional zoning," Soil Environ. **38**, 31–41 (2019).
https://doi.org/10.25252/SE/19/61524
50. K. Ivashchenko, N. Ananyeva, A. Selezneva, A. Sushko, E. Lepore, V. Vasenev, S. Demina, F. Khabibulina, I. Vaseneva, A. Dolgikh, E. Dovletyarova, and S. Marinari, "Assessing soil-like materials for ecosystem services provided by constructed technosols," Land **10**, 1185 (2021).
https://doi.org/10.3390/land10111185
51. D. Karelin, S. Goryachkin, E. Zazovskaya, V. Shishkov, A. Pochikalov, A. Dolgikh, A. Sirin, G. Suvorov, G. Kraev, N. Badmaev, N. Badmaeva, Y. Tsybenov, A. Kulikov, P. Danilov, G. Savinov, A. Desyatkin, and R. Desyatkin, "Greenhouse gas emission from the cold soils of Eurasia in natural setting and under human impact: controls on spatial variability," Geoderma Reg. **22**, e00290 (2020).
https://doi.org/10.1016/j.geodrs.2020.e00290
52. D. Kim, N. Chae, M. Kim, S. Nam, T. K. Kim, K. T. Park, B. Y. Lee, E. Kim, and H. Lee, "Microbial metabolic responses and CO_2 emissions differentiated by soil water content variation in subarctic tundra soils," Microbiology **60**, 1130–1138 (2022).
https://doi.org/10.1007/s12275-022-2378-3
53. M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World Map of the Köppen-Geiger climate classification updated," Meteorol. Z. **15**, 259–265 (2006).
https://doi.org/10.1127/0941-2948/2006/0130
54. M. Köchy, R. Hiederer, and A. Freibauer, "Global distribution of soil organic carbon. Part 1: Masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world," Soil **1**, 351–365 (2015).
https://doi.org/10.5194/soil-1-351-2015

55. M. V. Korneykova, V. I. Vasenev, D. A. Nikitin, A. S. Soshina, A. V. Dolgikh, and Y. L. Sotnikova, "Urbanization affects soil microbiome profile distribution in the Russian Arctic region," Int. J. Environ. Res. Public Health **18** (21), 11665 (2021). https://doi.org/10.3390/ijerph182111665
56. M. V. Korneykova, V. I. Vasenev, D. A. Nikitin, et al., "Soil microbial community of urban green infrastructures in a polar city," Urban Ecosyst. **25**, 1399–1415 (2022). https://doi.org/10.1007/s11252-022-01233-8
57. I. Kremenetskaya, S. Tereshchenko, S. Alekseeva, I. Mosendz, M. Slukovskaya, L. Ivanova, and I. Mikhailova, "Vermiculite-lizardite ameliorants from mining waste," IOP Conf. Ser.: Earth Environ. Sci. **368**, 012027 (2019). https://doi.org/10.1088/1755-1315/368/1/012027
58. R. Lal, "Carbon sequestration," Philos. Trans. R. Soc., B **363** (1492), 815–830 (2008). https://doi.org/10.1098/rstb.2007.2185
59. M. J. Lara, I. Nitze, G. Grosse, P. Martin, and A. D. McGuire, "Reduced arctic tundra productivity linked with landform and climate change interactions," Sci. Rep. **8**, 2345 (2018). https://doi.org/10.1038/s41598-018-20692-8
60. K. Lorenz and R. Lal, "Managing soil carbon stocks to enhance the resilience of urban ecosystems," Carbon Manage. **6**, 35–50 (2015). https://doi.org/10.1080/17583004.2015.1071182
61. L. Madrid, E. Diaz-Barrientos, E. Ruiz-Cortes, R. Reinoso, M. Biasioli, C. M. Davidson, A. C. Duarte, and F. Ajmone-Marsan, "Variability in concentrations of potentially toxic elements in urban parks from six European cities," J. Environ. Monit. **8**, 1158–1165 (2006).
62. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, et al., *Climate Change 2021: The Physical Science Basis; Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, United Kingdom, 2021).
63. I. Mikhaylova, M. Slukovskaya, I. Mosendz, I. Kremenetskaya, E. Karavayeva, and S. Drogobuzhskaya, "Application of silicon-contained mining wastes in urban greening," in *Urbanization: Challenge and Opportunity for Soil Functions and Ecosystem Services* (Springer International Publishing AG, part of Springer Nature, 2019), pp. 145–152. https://doi.org/10.1007/978-3-319-89602-1_18
64. T. Mustonen and B. Van Dam, "Towards a shared understanding of Arctic climate change and urgency in Alaska," Geogr. J. **187**, 269–277 (2021). https://doi.org/10.1111/geoj.12382
65. Z. Namsaraev, A. Bobrik, A. Kozlova, A. Krylova, A. Rudenko, A. Mitina, A. Saburov, M. Patrushev, O. Karnachuk, and S. Toshchakov, "Carbon emission and biodiversity of Arctic soil microbial communities of the Novaya Zemlya and Franz Josef Land archipelagos," Microorganisms **11**, 482 (2023). https://doi.org/10.3390/microorganisms11020482
66. W. C. Oechel and W. D. Billings, "Effects of global change on the carbon balance of arctic plants and ecosystems," in *Arctic Ecosystems in a Changing Climate: An Ecophysiological Perspective* (Elsevier, Amsterdam, 1992), pp. 139–168.
67. C. L. Ping, J. D. Jastrow, M. T. Jorgenson, G. J. Michaelson, and Y. L. Shur, "Permafrost soils and carbon cycling," Soil **1**, 147–171 (2015). https://doi.org/10.5194/soil-1-147-2015
68. A. Petrescu, A. Lohila, J.-P. Tuovinen, et al., "The uncertain climate footprint of wetlands under human pressure," Proc. Natl. Acad. Sci. U. S. A., Early Ed. **112**, 4594–4599 (2015). https://doi.org/10.1073/pnas.1416267112
69. V. Polyakov, A. Petrova, A. Kozlov, and E. Abakumov, "Toxicological state and chemical properties of soils in urbanized ecosystems of Murmansk," Czech Polar Rep. **8**, 230–242 (2018). https://doi.org/10.5817/CPR2018-2-19
70. R. V. Pouyat, I. D. Yesilonis, and D. J. Nowak, "Carbon storage by urban soils in the United States," J. Environ. Qual. **35**, 1566–1575 (2006). https://doi.org/10.2134/jeq2005.0215
71. R. V. Pouyat, I. D. Yesilonis, M. Dombos, K. Szlavecz, H. Setälä, S. Cilliers, E. Hornung, and S. Yarwood, "A global comparison of surface soil characteristics across five cities: A test of the urban ecosystem convergence hypothesis," Soil Sci. **180**, 136–145 (2015). https://doi.org/10.1097/SS.0000000000000125
72. T. V. Prokof'eva, A. V. Kiryushin, V. A. Shishkov, and F. A. Ivannikov, "The importance of dust material in urban soil formation: the experience on study of two young Technosols on dust depositions," J. Soils Sediments **17**, 515–524 (2017). https://doi.org/10.1007/s11368-016-1546-7
73. Y. L. Qian, W. Bandaranayake, W. J. Parton, B. Mecham, M. A. Harivandi, and A. R. Mosier, "Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics: the century model simulation," J. Environ. Qual. **32**, 1694–1700 (2003). https://doi.org/10.2134/jeq2003.1694
74. S. Richter, D. Haase, K. Thestorf, and M. Makki, "Carbon pools of berlin, germany: organic carbon in soils and aboveground in trees," Urban For. Urban Greening **54**, 126777 (2020). https://doi.org/10.1016/j.ufug.2020.126777
75. K. M. Rühland, A. M. Paterson, W. Keller, N. Michelutti, and J. P. Smol, "Global warming triggers the loss of a key Arctic refugium," Proc. Biol. Sci. **280**, 20131887 (2013). https://doi.org/10.1098/rspb.2013.1887
76. C. A. Sierra, "Temperature sensitivity of organic matter decomposition in the Arrhenius equation: some theoretical considerations," Biogeochemistry **108**, 1–3 (2012). https://doi.org/10.1007/s10533-011-9596-9
77. A. S. Shchepeleva, V. I. Vasenev, I. M. Mazirov, I. I. Vasenev, I. S. Prokhorov, and D. D. Gosse, "Changes of soil organic carbon stocks and CO_2 emissions at the early stages of urban turf grasses' development," Urban Ecosyst. **20**, 309–321 (2017). https://doi.org/10.1007 / s11252-016-0594-5
78. E. A. G. Schuur, A. D. McGuire, G. Grosse, J. W. Harden, D. J. Hayes, G. Hugelius, C. D. Koven, and P. Kuhry, "Climate change and the permafrost car-

bon feedback," Nature **520**, 171–179 (2015).
https://doi.org/10.1038/nature14338

79. M. V. Slukovskaya, V. I. Vasenev, K. V. Ivashchenko, D. V. Morev, S. V. Drogobuzhskaya, L. A. Ivanova, and I. P. Kremenetskaya, "Technosols on mining wastes in the subarctic: efficiency of remediation under Cu-Ni atmospheric pollution," Int. Soil Water Conserv. Res. **7**, 297–307 (2019).
https://doi.org/10.1016/j.iswcr.2019.04.002

80. M. V. Slukovskaya, I. P. Kremenetskaya, S. V. Drogobuzhskaya, and A. I. Novikov, "Sequential extraction of potentially toxic metals: alteraion of method for Cu-Ni polluted peat soil of industrial barren," Toxics **8**, 39 (2020).
https://doi.org/10.3390/toxics8020039

81. M. V. Slukovskaya, V. I. Vasenev, K. V. Ivashchenko, et al., "Organic matter accumulation by alkaline-constructed soils in heavily metal-polluted area of Subarctic zone," J. Soils Sediments **21**, 2071–2088 (2021).
https://doi.org/10.1007/s11368-020-02666-4

82. A. V. Smagin, "Biodegradation of some organic materials in soils and soil constructions: experiments, modeling and prevention," Materials (Basel) **11**, 1–22 (2018).

83. S. Sushko, N. Ananyeva, K. Ivashchenko, V. Vasenev, and V. Kudeyarov, "Soil CO_2 emission, microbial biomass, and microbial respiration of woody and grassy areas in Moscow (Russia)," J. Soil. Sediment **19**, 3217–3225 (2019).
https://doi.org/10.1007/s11368-018-2151-8

84. C. Tarnocai, J. G. Canadell, E. A. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov, "Soil organic carbon pools in the northern circumpolar permafrost region," Global Biogeochem. Cycles **23**, GB2023 (2009).
https://doi.org/10.1029/2008GB003327

85. M. Varentsov, P. Konstantinov, A. Baklanov, I. Esau, V. Miles, and R. Davy, "Anthropogenic and natural drivers of a strong winter urban heat island in a typical arctic city," Atmos. Chem. Phys. **18**, 17573–17587 (2018).
https://doi.org/10.5194/acp-18-17573-2018

86. V. I. Vasenev, J. J. Stoorvogel, A. V. Dolgikh, N. D. Ananyeva, K. V. Ivashchenko, and R. Valentini, "Changes in soil organic carbon stocks by urbanization," in *Urban Soils* (CRC Press, Boca Raton, 2017), pp. 61–92.
https://doi.org/10.1201/9781315154251

87. V. I. Vasenev, J. J. Stoorvogel, and I. I. Vasenev, "Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in the Moscow region," Catena **107**, 96–102 (2013).
https://doi.org/10.1016/j.catena.2013.02.009

88. V. I. Vasenev, M. Varentsov, P. Konstantinov, and O. Romzaykina, "Projecting urban heat island effect on the spatial-temporal variation of microbial respiration in urban soils of Moscow megalopolis," Sci. Total Environ. **786**, 147457 (2021).
https://doi.org/10.1016/j.scitotenv.2021.147457

89. D. M. White, D. S. Garland, C. L. Ping, and G. Michaelson, "Characterizing soil organic matter quality in arctic soil by cover type and depth," Cold Reg. Sci. Technol. **38**, 63–73 (2004).

90. J. Yang, F. Yu, Y. Yu, J. Zhang, R. Wang, M. Srinivasulu, and V. I. Vasenev, "Characterization, source apportionment, and risk assessment of polycyclic aromatic hydrocarbons in urban soil of Nanjing, China," J. Soils Sediments **17**, 1116–1125 (2017).
https://doi.org/10.1007/s11368-016-1585-0

91. G. Zirkle, R. Lal, and B. Augustin, "Modeling carbon sequestration in home lawns," HortScience **46**, 808–814 (2011).
https://doi.org/10.21273/hortsci.46.5.808

92. E. M. Zubova, N. A. Kashulin, V. A. Dauvalter, D. B. Denisov, S. A. Valkova, O. I. Vandysh, Z. I. Slukovskii, P. M. Terentyev, and A. A. Cherepanov, "Long-term environmental monitoring in an Arctic lake polluted by metals under climate change," Environments **7**, 34 (2020).
https://doi.org/10.3390/environments7050034

Translated by V. Klyueva