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Soil microbial community of urban green infrastructures in a polar city

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Abstract

Urban and technogenic landscapes in subarctic zones are not considered comfortable habitats for soil microbiota. However, green infrastructures in polar cities can provide a new niche for the development of a microbial soil community. Soil microbial biomass and the diversity of cultivable microfungi have been studied in relation to the chemical and morphological properties of urban soils in the polar city of Apatity. The quantitative indicators based on fluorescence microscopy and PCR real-time methods as well as the qualitative composition of the cultivable microfungal community were used to characterize the microbial community. Changes in the morphological and chemical composition of urban soils included a shift in pH and increased C and N content compared with forest soil. Studies have shown that the biomass of microfungi and actinomycetes in urban soils was lower than in forest soils and equals 0.12–0.19 mg/g and 0.06–0.44 $\times 10^{-3}$ mg/g, respectively. Bacterial biomass, on the contrary, increased in urban soils up to 2.6 $\times 10^{-3}$ – 5.6 $\times 10^{-3}$ mg/g. The number of ITS gene copies of fungi in urban soils varied from 5.0 $\times 10^{9}$ to 1.45 $\times 10^{10}$ copies/g of soil, reaching the highest values in the courtyard. The number of rRNA gene copies of bacteria and archaea in urban soils increased compared with forest soil and amounted to 2.37 $\times 10^{10}$ – 9.99 $\times 10^{10}$ and 0.4 $\times 10^{10}$ – 0.8 $\times 10^{10}$ copies/g of soil, respectively. In urban soils, morphological changes in microfungi, including the predominance of small spores, were revealed in comparison with forest soils, where mycelium prevailed. An increase in the diversity of microfungi in urban soil and changes in the structure of their communities compared with forest soil was noted. Microfungi found in urban soils are not typical of the background soils of the region and would be expected in more southern conditions. Among them, opportunistic fungi species have been identified in humans, which increases the risk of diseases in residents of the northern region.

Keywords Prokaryotes · Fungi · Biomass · Quantitative PCR · Microfungal diversity · Urban ecosystem · Subarctic

Introduction

Urbanization remains a key land-use change trend responsible for irreversible changes in vegetation and soils all over the globe (Sharma et al. 2016; UN 2018). Environmental consequences of urbanization are most remarkable in regions in which ecosystem restoration and development are constrained by climatic and soil conditions. In polar regions, plant growth and soil-forming processes are hampered by low temperatures and nutrient deficiencies (Goryachkin et al. 1999; Grosse et al. 2011). Urbanization here coincides with the substitution of natural soils with urban soils and soil constructions, whose properties and functions are considerably different from their natural counterparts (Korneykova et al. 2021; Polyakov et al. 2018; Saltan and Sviatkovskaya 2020).

Soil microbial properties are highly sensitive to anthropogenic distrubance, and the considerable impact of urbanization on microbial soil activity and diversity was reported for various cities and climates (Deeb et al. 2020; Ivashchenko

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et al. 2019; Piotrowska-Dlugosz and Charzynski 2015). Direct effects of urbanization on soil microbiome include pollution (Vasenev et al. 2013; Yang et al. 2006), salinization (Gavrichkova et al. 2020; Litalien and Zeeb 2020), and overcompaction (Dovletyarova et al. 2017), which retard microbial activity and biomass growth. By contrast, development of urban green infrastructures using artificial soils based on substrates rich in easily mineralizable carbon (e.g., compost, peat, or organic wastes) can increase microbial biomass (Slukovskaya et al. 2019) and enzymatic activity (Ditterich et al. 2016) and trigger microbial succession (Vogel et al. 2014). Indirectly, the soil microbial community can be affected by an urban heat island, a mesoclimatic anomaly with a considerable temperature increase in central and densely built-up areas compared with the suburbs (Konstantinov et al. 2018; Shi et al. 2012). The impact of an urban heat island on soil microbial community can be particularly relevant in polar cities, where low temperatures are the primary limiting factor (Demin et al. 2016; Kirtsideli et al. 2016).

Conventionally, microbiological studies of urban soils have been conducted in temperate climates, neglecting the polar regions (Guilland et al. 2018; Stepanov et al. 2005). A few recent studies focus on industrial and technogenic sites, where a combination of severe climatic conditions and high pollution creates extremely unfavorable conditions for the soil microbial community (Gladkov et al. 2019; Slukovskaya et al. 2020). By contrast, residential activities and the development of green urban infrastructures can create new niches for the microbial soil community. Green zones and courtyards are less exposed to anthropogenic pressure and more favorable in climate and soil conditions (Peltola and Åström 2003). Higher microbial biomass and basal respiration were reported for recreational and residential areas compared with the industrial and roadside areas of Moscow (Demina et al. 2018; Sushko et al. 2019), Beijing (Zhao et al. 2013), and New York (Huot et al. 2017). For polar cities, similar patterns were described for Murmansk (Peretrukhina 2011; Turchanovskaya and Bogdanova 2011), Kandalaksha (Marfenina et al. 2002), and Pyramiden (Mazei et al. 2018).

Most of the previous studies' quantifying of urban soils' microbial community used indirect methods such as the microbiological plating method, on various nutrient media (Ball and Virginia 2014; Bridge and Spooner 2012) or measurement of CO_2 microbial production suppressing bacterial activity by fumigation-extraction (Ananyeva et al. 2006; Oechel et al. 1997). Assessments of fungal biomass by luminescent microscopy are rare (Ananyeva et al. 2006; Ball and Virginia 2014; Schmidt and Bolter 2002). The quantitative parameters of the urban soils' microbiome, including the taxonomic structure of microbial biomass and the number of ribosomal genes, remain overlooked. This methodological bias constrains the assessment of the potential for green urban infrastructures in polar cities to provide such important functions and ecosystem services as habitats for soil microbial community and biodiversity. Therefore, we will docomprehensive analysis of microbial biomass and the activity and diversity of cultivable microfungi in soils of urban green infrastructures in Apatity, a polar city in Russia.

Material and methods

Research area

Apatity (67.5°N, 33.4°E) is located on the Kola Peninsula on the left bank of the Belaya River between Imandra Lake and the Khibiny Mountains. The city area has a low hilly relief with an average elevation of 150–200 m a.s.l. The climate of Apatity is continental, cold, and humid (Kottek et al. 2006). The average monthly temperatures in January and July are –13.5 and + 13.5 °C, respectively; however, the minimum recorded temperature was –47 °C. The average annual precipitation is 853 mm, with a considerable contribution of snow (more than 60%) (https://ru.climate-data.org; https://www.weatheronline.co.uk/). The central part of the city is exposed to the urban heat island effect resulting in an air temperature increase up to 3.2 °C compared with the suburbs (Konstantinov et al. 2015). Natural vegetation is typical for the north taiga subzone, and natural soils are dominated by Podzols and Histosols (Pereverzev 2004); however, urbanized and urban soils and soil constructions are spread inside the city boundaries (Saltan and Sviatkovskaya 2020; Vasenev et al. 2019; Vikhman et al. 2008). Founded in 1926 as an industrial and mining settlement, Apatity today is the fifth largest city in a polar zone with a population over 55,000 people and a population density above 1400 citizens/km^2. Although mining industries dominate the city economy, tourism is becoming more popular (AMAP 2017).

Site description

This research focused on the soils of the urban green infrastructure in Apatity (an urban park with external and inner courtyards) compared with arable and forest sites (Fig. 1). Soil pits were laid on similar geomorphological positions: flat surfaces of hilly plains with gentle slopes (structural terraces and hilltops) outside the zone of erosion processes. Soil pits were excavated at each of the sites for soil description, morphological analysis, and classification according to World Reference Base (IUSS Working group WRB 2015). The sampling was conducted in June 2019. For chemical analysis, the samples were taken from soil horizons, transported to the lab, air-dried (22 °C),

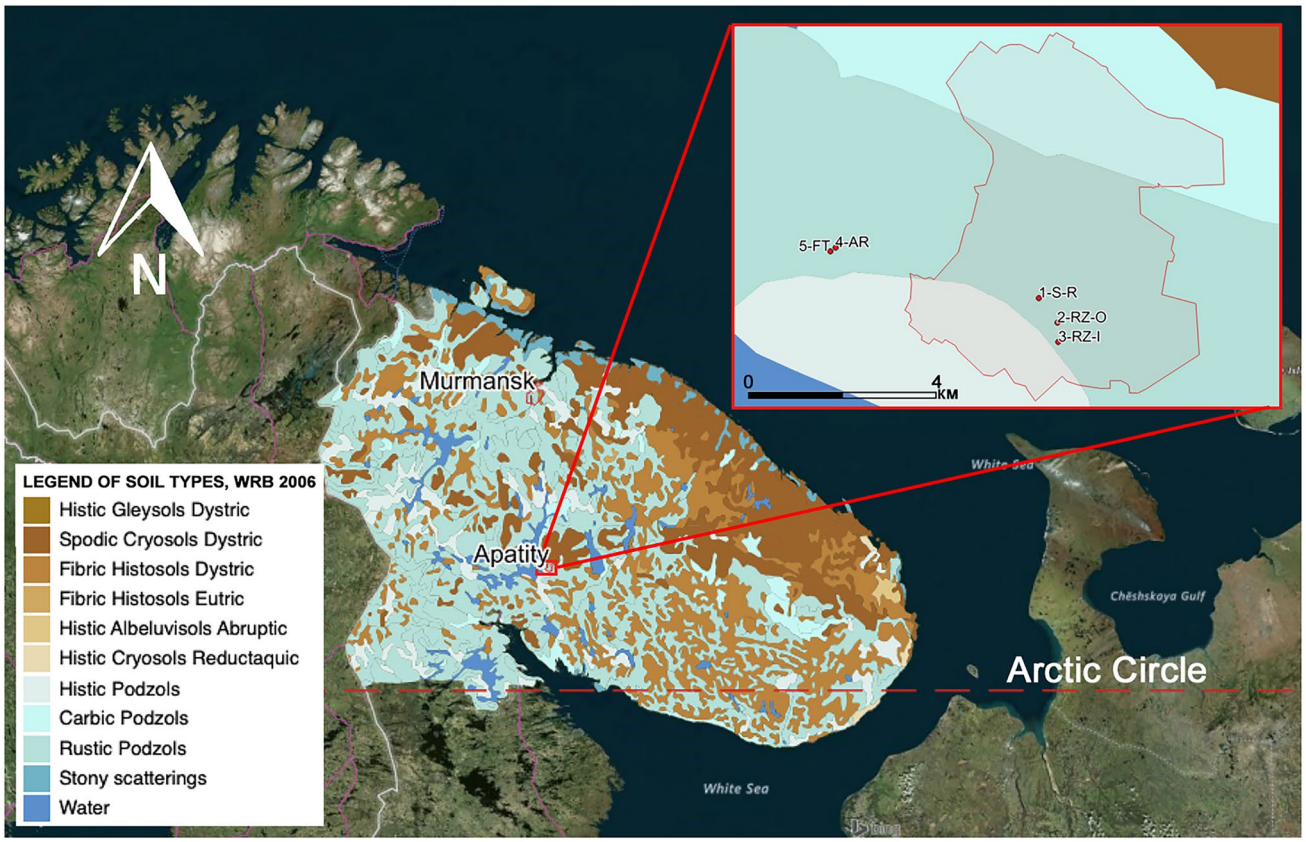

Fig. 1 Regional soil conditions and location of the research sites: an urban park (1-S-R), inner courtyard (3-RZ-I), external courtyard (2-RZ-O), arable (4-AR) and forest (5-FT) areas

and sieved (mesh 2 mm). For the microbiological analysis, the samples were collected from a depth of 0–10 cm and stored at –18 °C for luminescent microscopy and at –70 °C for molecular analyses. Cultivable microfungi were identified in fresh samples the day after collection. Bulk density samples were taken from each horizon by cups and analyzed in the lab using the dry weight approach (Shein et al. 2007).

Soil chemical properties

The pH value (soil: water = 1:5) and hydrolytic acidity (soil: 1 M CH_3COONa = 1:2.5 for mineral and 1:150 for organic soils) were measured by electrometric technique (pH-meter Radelkis OP-300). Soil organic carbon (SOC) and total nitrogen (TN) were determined by dry combustion on a Vario Isotope CNSH analyzer. Carbon and nitrogen stocks were calculated for each layer separately, considering its thickness and bulk density. The concentration of heavy metals (Ni, Cu, and Pb) extracted by 5.0 M HNO_3 was determined by inductively coupled plasma mass spectrometry (ISO/TS 16965 2013).

Microbial biomass

The number of cells and biomass of prokaryotes were determined using the luminescence microscopy method («Zeiss Axioskop 2 plus» microscope [Germany], × 100, oil immersion) using acridine orange fluorescence. Desorption of cells from soil particles was performed by ultrasound «UDNZ-1» device (2 min, 22 kHz, 0.44 A) (Polyanskaya and Zvyagintsev 2005). Six preparations were made from each soil sample, and cells were counted in 30 observation fields. The number of prokaryotic cells per gram of soil was calculated according to Eq. (1):

$$N = S_1 \times a \times n/V \times S_2 \times C, \quad (1)$$

where N is the number of cells per 1 g of substrate; S_1 is the area of the preparation, μm^2; a is the number of cells in one observation field; n is the dilution rate of the bacterial mixture, ml; V is the volume of the drop applied to the glass, ml; S_2 is the area of the observation field of the microscope, μm^2; and C is the soil mass, g.

The number of fungal propagules and the length of the fungal mycelium were also determined by luminescence

microscopy («Biomed 5PR LUM» microscope [Russia], ×40) using calcofluor white fluorescence. Cell desorption from soil particles was conducted with the «MSV-3500» vortex [Latvia] at a speed of 3500 rpm for 10 min) (Polyanskaya and Zvyagintsev 2005). From each sample, 3 preparations were made, and cells were counted in 90 observation fields. The number of fungal cells per gram of substrate was calculated following Eq. (2). The length of the fungal mycelium in grams of the sample was determined following Eq. (3):

$$M = ((4 \times a \times n)/p) \times 10^{10}, \quad (2)$$

where M is the number of cells in 1 g of soil; a is the average number of cells in the field of view; p is the area of the field of view, μm^2; and n is the dilution index.

$$NMA = S_1 a\, n/vS_2 c \times 10^6, \quad (3)$$

In Eq. (3) NMA is the length of the mycelium, m; S_1 is the area of the preparation, μm^2; a is the average length of the fragments of mycelium in the field of view, μm; n is the suspension dilution index, ml; v is the volume of the drop applied to the glass, ml; S_2 is the area of the field of view of the microscope, μm^2; and c is the sample weight, g.

The length of actinomycete mycelium in grams of the sample was determined using Eq. (4):

$$\mathrm{M} = 4\mathrm{an} \times 10^{10}/p, \quad (4)$$

where M is the length of the mycelium in 1 g of soil (m/g), a is the average length of mycelium in the field of view, p is the field of view area (μm2), and n is the dilution index.

Fungal biomass (mg/g of soil) was estimated based on the assumption that the spore density was 0.837 g/cm^3 and the mycelium density was 0.628 g/cm^3 (Polyanskaya and Zvyagintsev 2005). The content of fungal biomass per gram of dry soil was calculated considering its moisture content.

Number of gene copies

Quantitative assessment of the content of ribosomal gene copies of bacteria, archaea, and ITS gene copies of fungi was performed by real-time polymerase chain reaction (PCR). Primers for the 16S rRNA gene were used to account for archaea and bacteria, and primers for the ITS region were used to account for fungi. The reaction was performed in a Real-Time CFX96 Touch amplifier («Bio-Rad»). The reaction mixture was prepared from SuperMix Eva Green («Bio-Rad»). The *Escherichia coli* (Sigma) ribosomal operon was used as the control for bacteria, the FG-07 *Halobacterium salinarum* strain for archaea (Jurgens and Saano 1999), and the *Saccharomyces cerevisiae* Meyen 1B-D1606 yeast strain for fungi. For each sample, the reaction was performed in 3 repetitions. Gene concentrations were calculated using CFX Manager software. The concentration of genes in the DNA preparations was converted into the number of genes per gram of soil, considering the dilutions and weight of the sample.

Diversity of the cultivable microfungi

Diversity of the cultivable microfungi was determined by the plating method on a Chapek´s medium with lactic acid (4 ml/l) to inhibit bacteria (Zvyagintsev 1991). Incubation was performed in a thermostat at a temperature of + 27 °C for 7–10 days and + 5 °C for 5–6 weeks to further isolate psychrotolerant strains. The species diversity of microfungi was performed based on cultural and morphological features (Olympus CX41 microscope) using keys (Domsch et al. 2007; Klich 2002; Seifert et al. 2011). The species name and systematic position were derived from the database: CABI Bioscience Databases (http://www.indexfungorum.org). For the species isolated as sterile mycelium, identification was based on the analysis of the ITS1–5.8 S–ITS2 rDNA site. DNA isolation was performed using the method described by Glushakova et al. (2011), but the strains were subjected to 3 treatment cycles because mycelial fungi are more resistant to external influences than yeast. Sequencing of DNA sections was done using a set of reagents, BigDye Terminator V. 3.1 Cycle Sequencing Kit (Applied Biosystems, USA), with subsequent analysis of reaction products on the applied Biosystems 3130l Genetic Analyzer sequencer at the Syntol research and production center (Moscow). The abundance (density) of microfungi species was determined according to Eq. (5):

$$C = (n/N) \times 100, \quad (5)$$

where C is abundance, %; n is the number of isolates of a particular species; and N is the total number of isolates of all species. The similarity of the microfungal complexes species composition was evaluated by the Sørensen–Czekanowski index.

Statistical analysis

The analytical measurements were carried out in three replicates per sample for chemical and microbiological properties. The significance of differences in experimental data between the studied options (independent groups) was assessed using the Student's t-test. Relationship between chemical and microbiological properties was analyzed using correlation analysis (Pearson's correlation coefficient). The analysis of the qualitative similarity of the species and construct the dendrogram was carried out using cluster analysis.

Experimental data was statistically processed and visualized by Microsoft Office Excel 2016 and Statistica 8.0.

Results

Soil morphological and chemical properties

The soil profile at the natural forest (5-FT) site was classified as Folic Leptic Albic Podzol (Arenic) because of clearly visible albic (E) and spodic (Bs) horizons. Iron migration and accumulation were the main processes of soil formation at the area. The accumulation of litter and its slow mineralization in cold climatic conditions resulted in a folic (O) horizon. At the arable site (4-AR), the soil profile was considerably transformed by long-term ploughing with the addition of fertilizer, resulting in a plaggic horizon (Ap) underlined by a loose spodic (Bs) horizon. Urbanization resulted in considerable soil transformation, clearly visible from soil profiles excavated in Apatity. The soil profile observed at the inner courtyard (3-RZ-I) inherited the main natural features, including albic and spodic horizons. The anthropogenic effect mainly altered the processes of humification and carbon (SOC) accumulation and resulted in the Au horizon. Similar Au horizons were identified in soil profiles at the park (1-S-R) and external yard (2-RZ-O) sites. Soils at these sites were exposed to the longer or more intensive anthropogenic effect, which altered both topsoil and subsoil and resulted in the formation of a mineral Bu horizon. A clear, straight boundary with the underlying buried Bs horizon and inclusions of artifacts (i.e., bricks, glass, and rubber particles) identifies the anthropogenic origin of the Bu horizon. Subsoil horizons (BCg) at all the sites had visible gleyic spots resulting from high precipitation and slow evaporation, which are typical of the subarctic climate, and poor drainage by the rocky parent material (Fig. 2).

The results of physical and chemical soil analysis confirm the anthropogenic effects identified based on soil profile descriptions. Anthropogenic disturbance increased topsoil bulk density with the highest values obtained for croplands. Soil pH in urban sites was significantly higher than in cropland and forest sites. This is a typical feature of urban soils, usually explained by the alkalization effect of lime-containing dust deposition from building construction (Kosheleva et al. 2018; Straigytė et al. 2019; Vasenev et al. 2019). The content of available phosphorus in urban soils was also higher than in the natural and arable soils, likely caused by implementation of fertilizers and deposition from the mining industries (Zhang et al. 2001). The heavy metals' contents at the urban sites did not exceed the health thresholds (approximated permissible concentrations, APC, HS-2.1.7.2511-09 2009) and were comparable to or even lower than cropland and forest sites (Table 1).

The most remarkable effects of urbanization were observed for SOC and N stocks. In urban soils SOC were, on average, 20%–40% higher than in arable lands and twice as high as in forest soils. Profile distributions were also different. In arable and forest soil profiles,

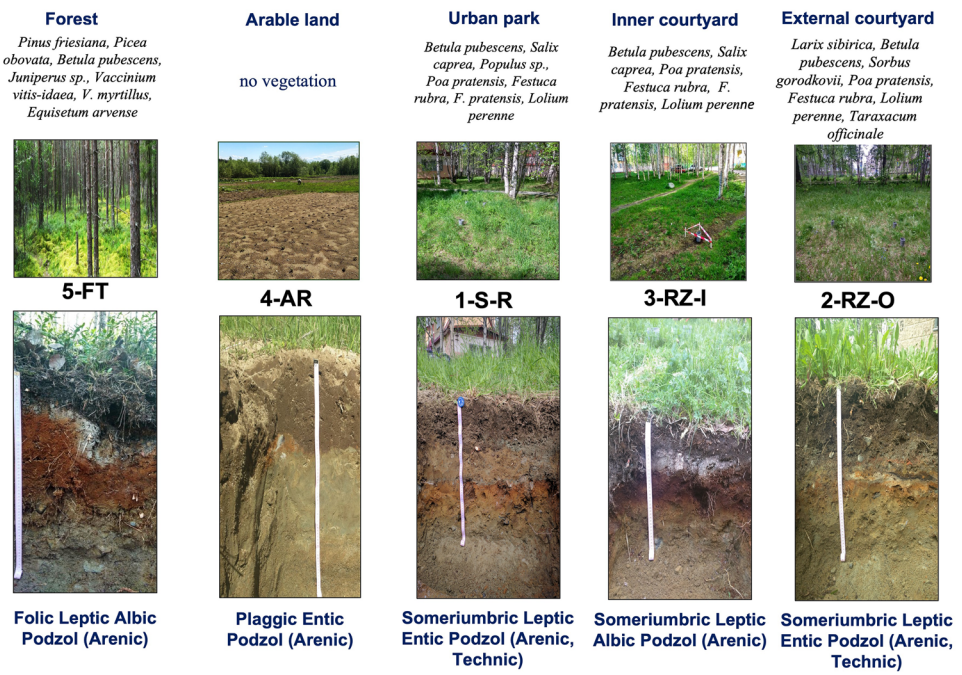

Fig. 2 Vegetation and soil profiles at the research sites (see Fig. 1 for abbreviations)

Table 1 Physical and chemical properties of soils in Apatity and neighboring non-urban sites

Horizon	Depth, cm	Density g/cm^3	pH	AP mg/100 g	Ni mg/kg	Cu	Pb
1-S-R Someriumbric Leptic Entic Podzol (Arenic, Technic)							
Au	0–12	0.98	6.34	46.23	29	30	5
Bu	12–31	1.18	6.87	17.92	15	30	3
Bs	31–45	1.30	6.94	1.23	33	52	3
BCg	45–55	1.30	6.85	16.89	26	54	3
2-RZ-O Someriumbric Leptic Entic Podzol (Arenic, Technic)							
Au	0–15	0.79	6.49	55.66	26	62	11
Bu	15–27	1.00	7.01	2.36	28	75	4
Bs	27–35	1.30	6.98	0.85	17	135	7
BCg	35–55	1.30	7.06	19.43	31	145	3
3-RZ-I Someriumbric Leptic Albic Podzol (Arenic)							
Au	0–5	0.63	6.24	189.62	29	45	17
E	5–10	0.80	5.99	4.25	3	94	6
Bs	10–15	0.75	5.68	13.21	17	84	3
Bs	20–25	1.10	5.62	10.28	27	118	2
BCg	25–35	1.2	5.63	22.26	30	143	3
4-AR Plaggic Entic Podzol (Arenic)							
Ap	0–5	1.18	5.91	26.32	26	155	6
Bs	20–25	1.30	5.42	3.21	15	108	4
BCg	30–35	1.40	5.93	3.21	38	61	4
C	45–50	1.40	5.92	8.77	20	127	3
5-FT Folic Leptic Albic Podzol (Arenic)							
O	0–5	0.32	6.19	50.94	40	112	8
E	7–10	1.00	5.78	1.51	7	86	7
Bs	15–20	1.36	6.03	6.32	33	162	5
BC	40–45	1.53	5.89	29.25	14	74	2

SOC stocks in the top 10 cm were 42% and 57% of total stocks for the whole profiles whereas this contribution was 25%–35%. in urban topsoil similar patterns were observed for N stocks (Fig. 3). The C/N ratio ranged from 17 to 27 with a median of 20. The highest values were observed in forest topsoil, where SOC content was high due to slow litter decomposition. We did not observe a significant difference in the C/N ratio between croplands and urban soils.

Soil microbial biomass

For all the sites, fungi dominated soil microbial biomass. The biomass of fungi and actinomycete in forest soils was significantly higher than in urban soils (*t*-test, $p < 0.05$). By contrast, the biomass of bacteria (4.3×10^{-3}) in urban soils was significantly (*t*-test, $p < 0.05$) higher than in the forest (1.49×10^{-3}) and cropland (2.09×10^{-3}) sites. Among the urban sites, soils in the external courtyard (2-RZ-O) had the

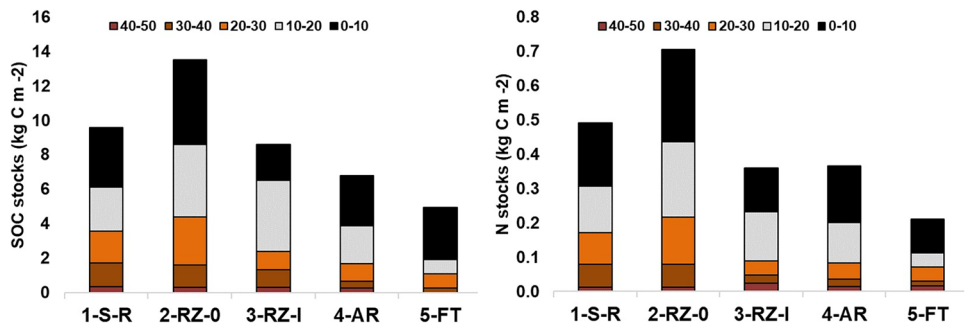

Fig. 3 Profile distribution of soil organic carbon (left) and total nitrogen (right) stocks in Apatity

highest bacterial biomass (5.6×10^{-3}) and the lowest biomass of fungi (13×10^{-2}) and actinomycete (0.063×10^{-3}) compared with the other sites (Fig. 4). The length of the fungal mycelium at different urban sites varied from 27.95 m (3-RZ-O) to 104.16 m (1-S-R), which was 2 to 6 times shorter than at the forest site. Similarly, the length of actinomycete mycelium in forest soil (19.66 m/g) was significantly higher than in arable (0.18 m/g) and urban (7.06 m/g) soils.

The share of resting single- and oligocellular spores and mycelium in fungal biomass characterizes the soil mycobiota (Nikitin et al. 2017). The share of 66%–70% mycelium dominated the fungal biomass in the forest site (5-FT) and in the urban park (1-S-R) whereas the dominating role of spores (up to 80%) was observed at the other sites. The number of fungal spores ranged from several thousand to several hundred thousand per gram of soil (Table 2). Fungal spores were represented by small (2–3 microns) and large (≥ 5 microns) forms. Small spores predominated (10^4–10^5 cells/g of soil) whereas large propagules were no more than 10^3 cells/g of soil. The contribution of large spores to the total number of propagules was 10%–15% for all sites whereas the total mass of large spores was higher than the mass of small propagules. According to the results of the correlation analysis, a significant relationship was found between the number of large spores and SOC content (r = 0.7); and between the number of large spores and pH (r = 0.9). This dependence was noted earlier in a number of other works (Polyanskaya and Zvyagintsev 2005; Nikitin et al. 2017).

The shape of fungal spores was considered a marker to determine a particular taxon. The bio morphological features of the small spores did not differ among the sites. They have spherical or oval shapes without any noticeable irregularities. For the large spores, the specific didymospores and dictyospores, as well as macrospores *Fusarium* and spores *Alternaria, Phoma*, and *Ulocladium,* were observed in urban soils, where they gave 5% of all large spores. The thickness of the fungal hyphae ranged from 2.5 to 4 microns, with larger-diameter mycelium observed only in the forest soil. Buckled basidiomycete mycelium was found only in the soil of the urban park (1-S-R) and forest (5-FT), where its share was 21% and 38%, respectively.

Number of gene copies

The number of rRNA gene copies of bacteria in the urban soil ranged from 2.37×10^{10} to 9.99×10^{10} copies of genes/g of soil, compared with the 6.75×10^{10} copies of genes/g of soil in the forest. Bacteria prevailed over other groups of microorganisms at all sites by the number of gene copies. Their proportion of percentage was up to 80% of the total number of gene copies of all microorganisms. The share of archaea and fungi did not exceed 5%–10%. The average number of rRNA gene copies of archaea (0.89×10^{10}) in urban soils was lower than in forest soil (1.22×10^{10}). The average number of ITS gene copies of fungi (0.63×10^{10}) in urban soils was lower than in arable (0.95×10^{10}) and forest (1.14×10^{10}) soils. The lowest number of microorganism gene copies was found in the park (1-S-R), where it was two and three times lower than in the external and inner yards, respectively (Fig. 5).

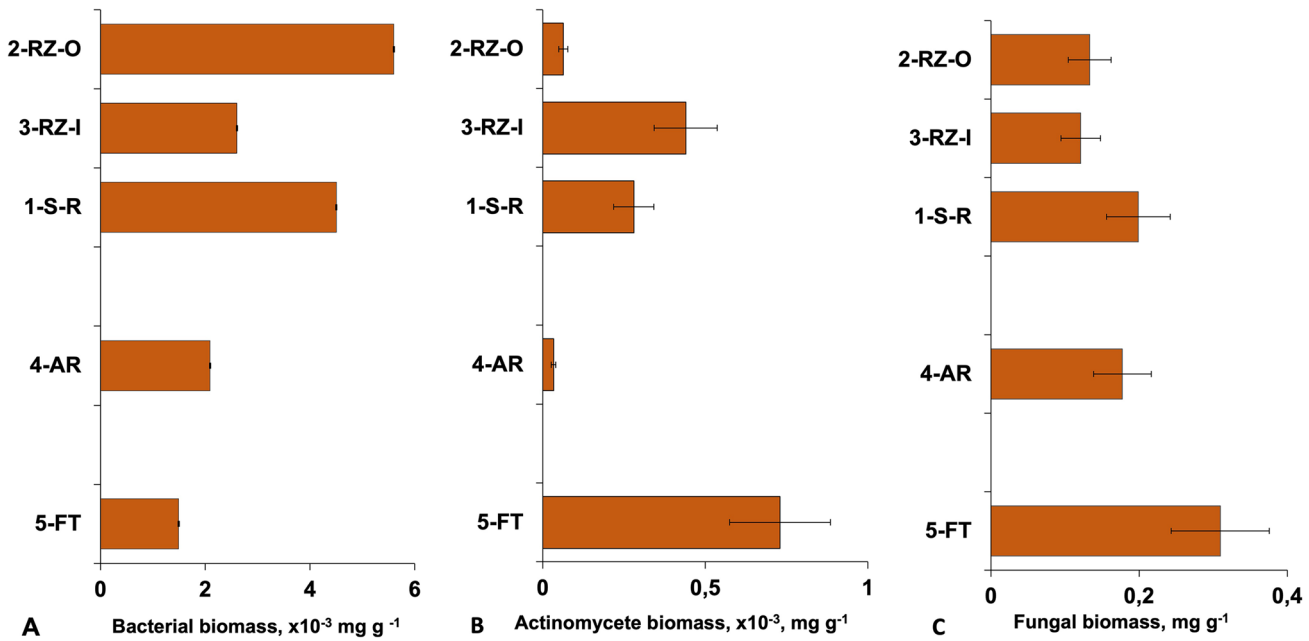

Fig. 4 Bacterial (**A**), actinomycete (**B**) and fungal (**C**) biomass in urban, arable and forest soils

Table 2 Fungal biomass in urban, arable and forest soils

Site	Mycelium (d = 3μ)			Spores (diameter, μ)						Total biomass of spores, mg/g, $\times 10^{-2}$	Total biomass of fungi, mg/g, $\times 10^{-2}$
				≤ 2		2–3		3–5			
	Biomass, mg/g $\times 10^{-2}$	Length, m	Share of mycelium in the total biomass, %	Number, unit/g $\times 10^5$	Mass, mg/g, $\times 10^{-2}$	Number, unit/g $\times 10^4$	Mass, mg/g, $\times 10^{-2}$	Number, unit/g $\times 10^3$	Mass, mg/g		
2 -RZ-O	3.5 ± 0.8	27.95 ± 6.15	26.5 ± 5.8	0.77 ± 0.17	3.6 ± 0.8	2.91 ± 0.64	3.4 ± 0.7	5.20 ± 1.14	0.03 ± 0.01	9.8 ± 2.2	13.3 ± 3.0
3- RZ- I	8.8 ± 1.9	69.58 ± 15.31	27.6 ± 6.1	0.49 ± 0.11	1.7 ± 0.4	0.97 ± 0.21	1.1 ± 0.2	1.04 ± 0.23	0.01 ± 0.001	3.3 ± 0.7	12.1 ± 2.7
1- S-R	13.2 ± 2.9	104.16 ± 22.92	66.1 ± 14.6	1.11 ± 0.24	3.7 ± 0.8	2.58 ± 0.57	3.0 ± 0.7	–	–	6.7 ± 1.5	19.9 ± 4.4
4-AR	3.8 ± 0.8	30.43 ± 6.70	21.6 ± 4.8	1.05 ± 0.23	3.6 ± 0.8	8.38 ± 1.84	9.8 ± 2.1	1.04 ± 0.23	0.006 ± 0.001	13.9 ± 3.1	17.7 ± 3.9
5-FT	21.4 ± 4.7	169.58 ± 37.11	69.3 ± 15.3	1.26 ± 0.28	4.3 ± 0.9	3.07 ± 0.68	3.6 ± 0.8	3.12 ± 0.69	0.017 ± 0.004	9.5 ± 2.1	30.9 ± 6.6

Diversity of soil microfungi

The diversity of cultivable microfungi was represented by 22 species belonging to 11 genera, 9 families (*Aspergillaceae, Ceratocystidaceae, Chaetomiaceae, Hypocreaceae*, *Mortierellaceae, Nectriaceae, Stachybotryaceae, Torulaceae*, *Umbelopsidaceae*), 7 orders (*Eurotiales, Hypocreales, Microascales*, *Mortierellales, Pleosporales*, *Sordariales, Umbelopsidales*), 5 classes (*Dothideomycetes, Eurotiomycetes, Mortierellomycetes, Sordariomycetes, Umbelopsidomycetes),* and 3 divisions (*Ascomycota, Mortierellomycota, Mucoromycota*) (Table 3). The *Mortierellomycota* division was represented by the genera *Mortierella* and the *Mucoromycota* division was represented by the genera *Mortierella* and *Umbelopsis*. The *Ascomycota* division was represented by 8 anamorphic genera (*Acremonium, Aspergillus, Berkeleyomyces, Fusarium, Penicillium, Stachybotrys, Torula, Trichocladium*). One type of sterile mycelium isolates of uncertain taxonomic position was reported because of the difficult cultivation.

The total number of species isolated from the arable soils was half that of all the other sites, where 7 to 10 species were found. In total, 17 species of microfungi were isolated from urban soils, which was considerably higher than in the forest and arable soils, indicating additional ecological niches and increased microfungal diversity in urban green infrastructures. According to cluster analysis, the species diversity of microfungi differed significantly between the sites. The value of the Sørensen coefficient was low for different sites (34%–43%), with the exception of 3-RZ-I and S-R zones (Fig. 6). Some species were not site specific; for example, *Trichocladium griseum*, a typical phytopathogen and cellulolytic (Domsch et al. 2007), was isolated from all the studied sites excluding 3-RZ-I. Many others were typical only for urban (e.g., *Penicillium spinulosum* and *P. simplicissimum*), arable (e.g., *Aspergillus fumigatus* and *Trichoderma koningi*), or forest (e.g., *Penicillium aurantiogriseum*, *P. decumbens*, *Acremonium felinum* and *Berkeleyomyces basicola*) soils. Microfungi *P. nalgiovense* and *Stachybotrys echinatus* were isolated only from urban park soil (S-R) whereas *P. canescens* was found only in the inner courtyard and *P. dierckxii*, *Torula sp.* were found in the external courtyard soil.

Discussion

Urbanization effects on soil properties in subarctic zone

The comparative analysis of forest, arable, and urban soils in Apatity revealed the effects of urbanization on soil formation and functioning. The observed changes in morphological and basic chemical properties, including formation of Au

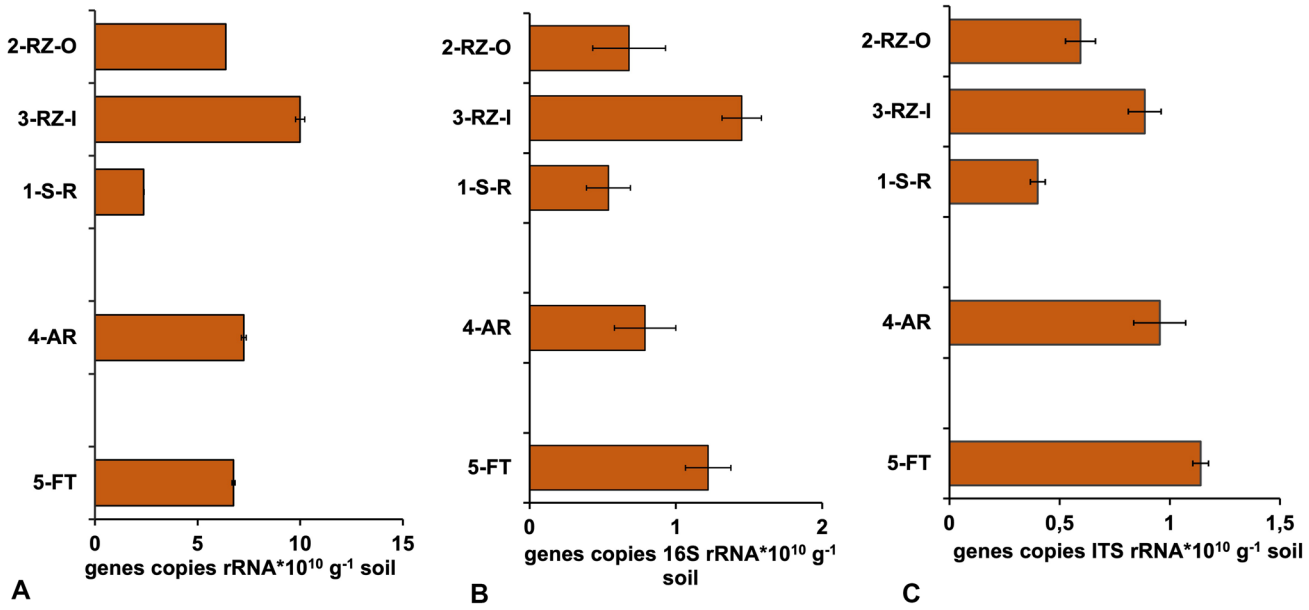

Fig. 5 The number of ribosomal gene copies of bacteria (**A**) and archaea (**B**) and ITS gene copies of fungi (**C**) in urban, arable and forest soils

horizons, an increased number of artifacts, and a shift in pH, were similar to those described for Moscow (Prokofyeva et al. 2011, 2014), St. Petersburg (Aparin and Sukhacheva 2014; Pashkevich et al. 2020), Stuttgart (Lehmann and Stahr 2007), and other cities with temperate climates. Mainly, the urban topsoil was anthropogenically transformed, and the subsoil horizons remained without considerable disturbances. In general, the Apatity soils were less disturbed than soils in many other studies in bigger cities with longer histories, such as Moscow (Stroganova et al. 1997), Kursk (Sarzhanov et al. 2017), or New York (Deeb et al. 2020). This can be explained by a relatively short period of historical development, limited resources, and few demands for large-scale and expensive greening and landscaping projects. However, even these limited anthropogenic effects were enough to have a considerable impact on soil biogeochemistry, primarily on C and N cycles. The average topsoil C stocks in urban sites were 15% higher than in the forest and 20% higher than in the cropland site. When summarized for the profile (0–50 cm), urban soil C and N stocks were twice as high as the natural forest areas. The development of artificial soil constructions, the maintenance and management of urban green infrastructures, and the disposal and management of organic wastes are the main sources of C and N input to urban soils, reported for different cities of the world (Lorenz et al. 2008; Lorenz and Lal 2015; Richter et al. 2020). However, the difference in C and N stocks between urban and natural soils reported for Apatity was much higher than those reported for cities in temperate (Vasenev et al. 2013) and especially arid (Gorbov and Bezuglova 2014) or tropical climates (Yang et al. 2017). This can partially be explained by additional C input from fuel combustion for central heating, typical in northern cities (Dymov et al. 2013; Vasenev and Kuzyakov 2018). However, the main factor is likely the cold climate, which hampers the mineralization of organic matter and preserves C stocks (Karelin et al. 2016, 2020). These considerable C and N stocks and neutral pH create favorable conditions for soil microbial community. Moreover, the low content of heavy metals in the investigated sites exclude the limitation from soil pollution. Heavy metals are often reported in urban and technogenic soils (Yang et al. 2006; Zhao et al. 2013; Ivashchenko et al. 2019; Slukovskaya et al. 2019).

Soil microbiome in a polar city

Urban soils are unique habitats for microorganisms because of the following processes and properties: extremely high spatial heterogeneity and dynamics (Vasenev et al. 2014); the permanent anthropogenic impact of compaction, warming, etc. (Guilland et al. 2018; Ivashchenko et al. 2019); Stroganova et al. 1997), and the introduction of easily decomposable substrates such as peat–sand mixtures, compost, oil products, and waste (Stoma et al. 2020; Vasenev and Kuzyakov 2018). As a result, urban environments provide a unique variety of ecological niches for microbial communities (Ferreira et al. 2018; Stepanov et al. 2005). In a polar city, temperature becomes the primary driver for soil microbial activity, and additional sources of heat in urban ecosystems have a strong stimulating effect on the development of the soil microbiome and its taxonomic diversity

Table 3 The diversity of soil microfungi

Species	Soil pit				
	5-FT	1-S-R	4- AR	2- RZ-O	3-RZ-I
Ascomycota, Pezizomycotina, Dothideomycetes, Pleosporomycetidae, Pleosporales,Torulaceae					
Torula sp.					+
Eurotiomycetes, Eurotiomycetidae, Eurotiales, Aspergillaceae					
Aspergillus fumigatus Fresen			+		
Penicillium aurantiogriseum Dierckx	+				
P. canescens Sopp				+	
P. decumbens Thom	+				
**P. dierckxii* Biourge					+
**P. melinii* Thom	+	+			
**P. miczynskii* K.W. Zaleski			+	+	
P. nalgiovense Laxa		+			
**P. simplicissimum* (Oudem.) Thom		+			+
P. spinulosum Thom		+		+	
Sordariomycetes, Hypocreomycetidae, Hypocreales, Hypocreaceae					
**Trichoderma koningii* Oudem			+		
Incertae sedis					
Acremonium felinum (Marchal) Kiyuna, K.D. An, R. Kigawa & Sugiy	+				
A. sp.				+	
Nectriaceae					
Fusarium sp.	+		+		
Stachybotryaceae					
**Stachybotrys echinatus* (Rivolta) G. Sm		+			
Microascales, Ceratocystidaceae					
Berkeleyomyces basicola (Berk. & Broome) W.J. Nel, Z.W. de Beer, T.A. Duong & M.J. Wingf	+				
Sordariomycetidae, Sordariales, Chaetomiaceae					
**Trichocladium griseum* (Traaen) X. Wei Wang & Houbraken	+	+	+	+	
Mortierellomycota, Mortierellomycotina, Mortierellomycetes, Incertae sedis, Mortierellales, Mortierellaceae					
Mortierella alpina Peyronel		+		+	
Mucoromycota, Umbelopsidomycetes, Incertae sedis, Umbelopsidales, Umbelopsidaceae					
Umbelopsis isabellina (Oudem.) W. Gams	+			+	
U. longicollis (Dixon-Stew.) Y.N. Wang, X.Y. Liu & R.Y. Zheng	+	+			
Incertae sedis					
Mycelia Sterilia	+	+	+	+	+

*fungi, identified by molecular-genetic method

(Tepeeva et al. 2018). Urbanization in Apatity doubled the biomass of soil bacteria whereas the biomass of microfungi in urban soils was 40%– 60% less than the forest soils. Similar patterns emerged obtained on the number of ribosomal gene copies. These patterns are often reported for regions dominated by soils with acid or slightly acid pH (e.g., Podzols, Retisols) and can be explained by a shift in pH to neutral or slightly alkaline in urban areas (Semenov et al. 2018; Tripathi et al. 2019; Zhelesova et al. 2019). However, the correlation between the detected biomass of bacteria and actinomycete mycelium and the content of copies of ribosomal genes was not always identified. For example, the biomass of actinomycetes is extremely low at sites 2-RZ-O and 4-AR whereas the content of gene copies in these sites is sufficient and comparable to site 1-SR. In stress conditions, most actinomycetes are not in the form of mycelium, but in the form of spores. Spores, unlike mycelium, contain a low number of nucleic acids. However, during germination, the amount of DNA and RNA (the content of gene copies) in actinomycete spores increases sharply. Thus, there can simultaneously be a large length of hyphae of actinomycetes in the soil but a low content of copies of their genes. Similarly, unicellular bacteria in a

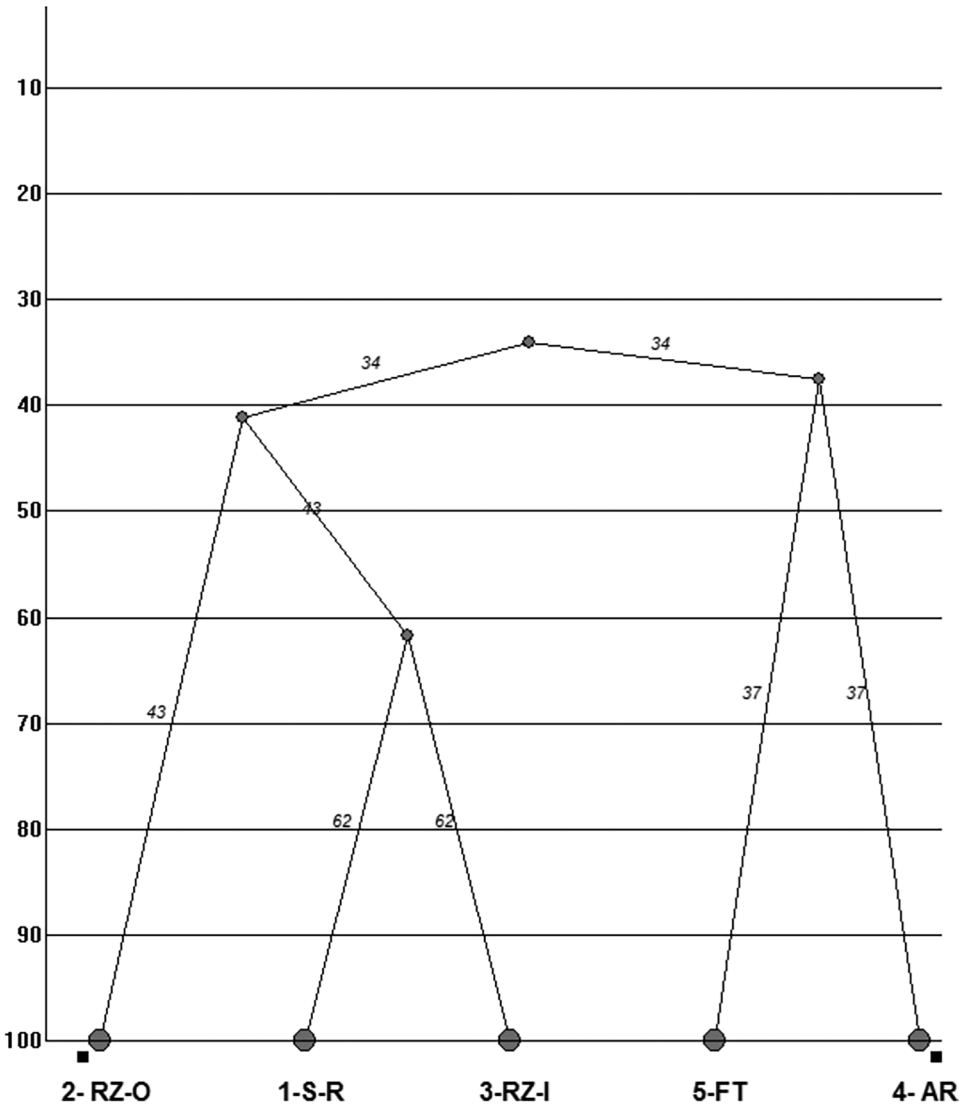

Fig. 6 Similarity dendrogram of microfungal species composition in the forest and urban soils. On the abscissa axis – land use zones; on the ordinate axis – % of species composition similarity according to the Sørensen coefficient

dormant state (spores, cysts, akinetes, etc.) contain few nucleic acids, but upon awakening to an active state, the amount of DNA and RNA increases dramatically. Thus, one method (fluorescence microscopy) can detect many microorganism cells, but another method (quantitative PCR) can detect a low number of copied microbial genes. The morphological properties of microfungi, characterized by the domination of small spores and thin mycelium, were also typical of cold ecosystems (Nikitin et al. 2019; Polyanskaya and Zvyagintsev 2005). The biomass of actinomycetes in urban soils was 2–4 times smaller than the forest soils, confirming their high sensitivity to the anthropogenic impact reported in previous studies (Sharkova et al. 2011; Stepanov et al. 2005). At the same time, it was 3 to 10 times higher than in arable soils, indicating more favorable conditions provided by green infrastructures.

For all groups (i.e., fungi, bacteria, and actinomycetes), the microbial biomass in the urban green infrastructure of Apatity was considerably smaller than in cities with warmer climates (Ivashchenko et al. 2019; Marfenina and Danilogorskaya 2017; Polyanskaya and Zvyagintsev 2005), however higher than in technogenic and even some natural areas in the subarctic zone (Evdokimova et al. 2011; Nikonov et al. 2006). The microfungal diversity also increased considerably. In general, the list of genera isolated from urban and forest soil was typical for the Murmansk region (Korneikova 2018; Korneikova et al. 2018). *Penicillium*, being the dominant genus among the cultivable microfungi of Northern taiga soils (Domsch et al. 2007; Marfenina et al. 2002; Seifert and Gams 2011), prevailed in the urban soils (40%–70% of the total number of species). Some of the cultivated species (e.g., *Aspergillus, Stachybotrys,* and *Fusarium*) are typical of more southern locations and are rarely found in natural areas of the subarctic

zone. Their abundance in the urban soils of Apatity is likely driven by the warmer climate caused by the urban heat island effect (Konstantinov et al. 2015). A similar positive effect of urbanization on the diversity of microfungi (Marfenina and Danilogorskaya 2017; Tepeeva et al. 2018) and bacteria (Lysak and Lapygina 2018) was previously reported for the other northern cities. Although, the increased microbial diversity is an ecosystem service, the "quality" and functions of the urban-specific species shall be considered. Some species additionally cultivated from urban soils compared with natural soils can be conditionally pathogenic for humans (Li et al. 2018; Marfenina and Danilogorskaya 2017). In Apatity, at least three species (i.e., *P. canescens*, *P. nalgiovense*, and *Stachybotrys echinatus*) cultivated only from urban soils were pathogenic.

Environmental and anthropogenic factors influencing soil microbial biomass and microfungal diversity in Apatity

The soil sampling design with a limited number of excavated and thoroughly analyzed soil pits aimed to investigate the effects of morphological and chemical soil properties on microbiomes in urban and nonurban soils rather than studying the spatial variability of soil microbial properties inside the city. However, even for a limited number of urban sites, the obtained variability was quite high and corresponded with the level of anthropogenic disturbance. For example, judging by direct microscopy, the highest biomass of microfungi, the biggest number of large spores, and the greatest abundance of basidiomycetes were reported in the park compared with other urban sites. This can be explained by high C content (Nikitin et al. 2017; Polyanskaya and Zvyagintsev 2005) and by the composition of the vegetation (Dobrovol'skaya et al. 2015; Dominguez-Nuñez et al. 2016; Nilsson et al. 2005). The abundance of trees in the forest compared with the urban areas and in the park compared with the courtyards could contribute to the abundance of ectomycorrhizal fungi, in which mycelium often makes a significant contribution to the biomass of soil mycobiota (Cairney 2012; Högberg et al. 2020; Polyanskaya and Kalimova 2017). By contrast to urban sites, soil fungal mycelium dominated the spores in the forest soils, which is a widely accepted indicator of the undisturbed taiga ecosystems (Khabibullina et al. 2014; Korneikova 2018). The patterns obtained for prokaryotes differed considerably from those shown for the mycelial microorganisms: the highest bacterial biomass was in the external courtyard whereas in the park and in the forest, it was respectively 40% and 50%. This can be partly explained by the antagonism of many groups of bacteria to fungi (Mille-Lindblom and Tranvik 2003; Shirokih and Shirokih 2019).

The general patterns revealed by the PCR analysis were consistent with those obtained by direct microscopy: a higher number of ribosomal gene copies of bacteria and a lower number of fungi in urban areas than in forest sites. The number of bacterial ribosomal gene copies were comparable to other studies on subarctic ecosystems like the Bolshezemelskaya tundra (Zhelezova et al. 2019) and Northern Alaska (Kim et al. 2014; Tripathi et al. 2019). The spatial pattern in the number of archaea genes was similar to the one reported for the fungi; however, the absolute number was ten times smaller. This is a typical ratio reported for soils of different biomes (Semenov et al. 2018; Zhelezova et al. 2019). Inside the city, the patterns obtained by different methods were not always similar. For example, the smallest number of gene copies of all the microorganism groups was observed in the park based on the PCR whereas the number of fungi revealed by direct microscopy in the park was higher than in the residential areas. This can be explained by methodological specifics like the uneven distribution of genetic material in fungal hyphae (Glöckner et al. 2017) and by the high complexity of environmental and urban factors, such as bulk density; C, N, and P contents; and pH, which can have a local impact on soil microbiomes (Bergkemper et al. 2016; Guilland et al. 2018; Zak et al. 2019).

Microfungal diversity also differed between the sites considering the number of species and cultivating species specific to each site. Such heterogeneity is usually reported for urban soils and explained by variability in soil properties and specific substrates for microfungi (Khabibullina et al. 2014; Ivashchenko et al. 2019; Marfenina et al. 2017). For example, the highest number of fungal species was isolated from the forest and park areas. They were characterized by polydominant structure, including *P. melinii, P. simplicissimum,* and *Stachybotrys echinatus* in the parks and *P. decumbens*, P. *melinii*, and *Umbelopsis isabellina* in the forest soil. The taxonomic structure of the sites was similar, likely following the similarity in soil properties, vegetation cover, and low level of anthropogenic load (Ivanova et al. 2015). The monodominant structure was clearly observed in the inner and external courtyards, dominated by *P. dierckxii* (82%) and *Trichocladium griseum* (64%), respectively. In previous studies, *Trichocladium griseum* in the regional soils was described only as a random or rare taxon. The development of the *T. griseum* cellulolytic in the urban soils of Apatity can be explained by the abundance of plant residue and easily mineralizable organic substrates (Domsch et al. 2007; Seifert et al. 2011) as well as by warmer conditions driven by the urban heat island effect and climate change (Demin et al. 2016). Soils of all the urban sites were dominated by dark-pigmented micromycetes. The pigmentation could be a protective

function against negative effects (Marfenina et al. 2017; Nosanchuk et al. 2015), but at the same time, most of the melanized micromycetes are conditionally pathogenic for humans (Marfenina and Danilogorskaya 2017).

Conclusion

Urbanization and the development of urban green infrastructures in Apatity coincided with remarkable changes in the morphological and chemical properties and processes of soil. Constructing soil using easily mineralizable organic substrates doubled soil C and N compared with forest and arable areas and shifted soil pH from acid to slightly alkaline and neutral. The availability of organic substrates and a warmer climate created new niches for the development of the soil microbial community. As a result, the biomass and the number of ribosomal gene copies of bacteria in urban soils more than doubled whereas the opposite occurred for fungi. Moreover, the morphological properties of microfungi were affected by urban disturbance, including domination of the small pores in urban soils compared with forest soils dominated by mycelium. These effects were clearly visible for the courtyard soils, whereas the morphology of microfungi in the parks was similar to the undisturbed forest site.

Increased microfungal diversity was another important urbanization outcome. A total of 17 species were cultivated from urban soils in Apatity, including several urban-specific species. These species included taxa, which are rarely described in the subarctic region and are typical for the warmer conditions. At least three species conditionally pathogenic for humans were also cultivated from urban soils in Apatity, which can be considered a drawback of the increased microfungal diversity in urban areas. Microbial biomass and the diversity of the microfungi described in Apatity were considerably higher than many other studies on technogenic soils in subarctic conditions. In the study, we purposely excluded more disturbed industrial areas and roadsides from the analysis; in addition, analyzed soils may not be representative of all the urban soils of Apatity. This focus on recreational and residential areas allowed confirmation of the potential for urban green infrastructures to be hotspots for soil microbial growth and diversity in a polar city.

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

AMAP (2017) Adaptation Actions for a Changing Arctic (AACA) - Barents Area Overview report. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway

Ananyeva ND, Susyan EA, Chernova OV, Chernov IY, Makarova OL (2006) The ratio of fungi and bacteria in the biomass of different types of soil determined by selective inhibition. Microbiology 75(6):702–707. https://doi.org/10.1134/S0026261706060130

Aparin BF, Sukhacheva EY (2014) Principles of soil mapping of a megalopolis with St. Petersburg as an example. Eurasian Soil Sci 47(7), 650–661. https://doi.org/10.1134/S1064229314070035

Ball BA, Virginia RA (2014) Microbial biomass and respiration responses to nitrogen fertilization in a polar desert. Polar Biol 37(4):573–585. https://doi.org/10.1007/s00300-014-1459-0

Bergkemper F, Schöler A, Engel M, Lang F, Krüger J, Schloter M, Schulz S (2016) Phosphorus depletion in forest soils shapes bacterial communities towards phosphorus recycling systems. Environ Microbiol 18(6):1988–2000. https://doi.org/10.1111/1462-2920.13188

Bridge PD, Spooner BM (2012) Non-lichenized Antarctic fungi: Transient visitors or members of a cryptic ecosystem? Fungal Ecol 5(4):381–394. https://doi.org/10.1016/j.funeco.2012.01.007

Cairney JW (2012) Extramatrical mycelia of ectomycorrhizal fungi as moderators of carbon dynamics in forest soil. Soil Biol Biochem 47:198–208. https://doi.org/10.1016/j.soilbio.2011.12.029

Climatic data of cities worldwide (2021) https://ru.climate-data.org/. Accessed 20 Feb 2021

Deeb M, Groffman PM, Blouin M, Egendorf SP, Vergnes A, Vasenev V, Cao DL, Walsh D, Morin T, Séré G (2020) Using constructed soils for green infrastructure–challenges and limitations. Soil 6(2):413–434. https://doi.org/10.5194/soil-6-413-2020

Demin VI, Kozelov BV, Elizarova NI, Men'shov YuV (2016) Geomorphological factors of the formation of the "heat island" in Apatity. Phys Auroral Phenom 39(1):154–157 (in Russ.)

Demina S, Vasenev V, Ivashchenko K, Ananyeva N, Plyushchikov V, Hajiaghayeva R, Dovletyarova E (2018) Microbial properties of urban soils with different land-use history in New Moscow. Soil Sci 183(4):132–140. https://doi.org/10.1097/SS.0000000000000240

Ditterich F, Poll C, Pronk GJ, Heister K, Chandran A, Rennert T, Ellen IK-K, Kandeler E (2016) Succession of soil microbial communities and enzyme activities in artificial soils. Pedobiologia 59(3):93–104. https://doi.org/10.1016/j.pedobi.2016.03.002

Dobrovol'skaya TG, Zvyagintsev DG, Chernov IY, Golovchenko AV, Zenova GM, Lysak LV, Manucharova NA, Marfenina OE, Polyanskaya LM, Stepanov AL, Umarov MM (2015) The role of microorganisms in the ecological functions of soils. Eurasian Soil Sci 48(9):959–967. https://doi.org/10.1134/S1064229315090033

Dominguez-Nuñez JA, Benito B, Berrocal-Lobo M, Albanesi A (2016) Mycorrhizal fungi: role in the solubilization of potassium. In: Meena V, Maurya B, Verma J, Meena R (Eds.), Potassium solubilizing microorganisms for sustainable agriculture. Springer, New Delhi, p 77–98. https://doi.org/10.1007/978-81-322-2776-2_6

Domsch KH, Gams W, Anderson TH (2007) Compendium of Soil Fungi. IHW-Verlag, Germany, Eching

Dovletyarova EA, Mosina LV, Vasenev VI, Ananyeva ND, Patlseva A, Ivashchenko KV (2017) Monitoring and assessing anthropogenic influence on soil's health in urban forests: the case from Moscow City. In: Rakshit A, Abhilash P, Singh H, Ghosh S (Eds.), Adaptive Soil Management: From Theory to Practices. Springer, Singapore, p 531–557. https://doi.org/10.1007/978-981-10-3638-5_24

Dymov AA, Kaverin DA, Gabov DN (2013) Properties of soils and soil-like bodies in the Vorkuta area. Eurasian Soil Sci 46:217–224. https://doi.org/10.1134/S1064229313020038

Evdokimova GA, Mozgova NP, Kalabin GV (2011) Contents and toxicity of heavy metals in soils of the zone affected by aerial emissions from the Severonikel Enterprise. Eurasian Soil Sci 44(2):237–244. https://doi.org/10.1134/S1064229311020037

Ferreira CS, Walsh RP, Ferreira AJ (2018) Degradation in urban areas. Curr Opin Environ Sci Health 5:19–25. https://doi.org/10.1016/j.coesh.2018.04.001

Gavrichkova O, Brykova RA, Brugnoli E, Calfapietra C, Cheng Z, Kuzyakov Y, Liberati D, Moscatelli MC, Pallozzi E, Vasenev VI (2020) Secondary soil salinization in urban lawns: Microbial functioning, vegetation state, and implications for carbon balance. Land Degrad Dev 31(17):2591–2604. https://doi.org/10.1002/ldr.3627

Gladkov G, Kimeklis A, Zverev A, Pershina E, Ivanova E, Kichko A, Andronov E, Abakumov E (2019) Soil microbiome of the postmining areas in polar ecosystems in surroundings of Nadym, Western Siberia. Russia Open Agric 4(1):684–696. https://doi.org/10.1515/opag-2019-0070

Glöckner FO, Yilmaz P, Quast C, Gerken J, Beccati A, Ciuprina A, Bruns G, Yarza P, Peplies J, Westram R, Ludwig W (2017) 25 years of serving the community with ribosomal RNA gene reference databases and tools. J Biotechnol 261:169–176. https://doi.org/10.1016/j.jbiotec.2017.06.1198

Glushakova AM, Kachalkin AV, Chernov IY (2011) Specific features of the dynamics of epiphytic and soil yeast communities in the thickets of Indian balsam on mucky gley soil. Eurasian Soil Sci 44(8):886–892. https://doi.org/10.1134/S1064229311080059

Gorbov SN, Bezuglova OS (2014) Specific features of organic matter in urban soils of Rostov-on-Don. Eurasian Soil Sci 47(8):792–800. https://doi.org/10.1134/S1064229314080043

Goryachkin SV, Karavaeva NA, Targulian VO, Glazov MV (1999) Arctic soils: Spatial distribution, zonality and transformation due to global change. Permafr Periglac Process 10(3):235–250. https://doi.org/10.1002/(SICI)1099-1530(199907/09)10:3%3c235::AID-PPP320%3e3.0.CO;2-4

Grosse G, Harden J, Turetsky M, McGuire AD, Camill P, Tarnocai C, Frolking S, Schuur EAG, Jorgenson T, Marchenko S, Romanovsky V, Wickland KP, French N, Waldrop M, Bourgeau-Chavez L, Striegl RG (2011) Vulnerability of high-latitude soil organic carbon in North America to disturbance. J Geophys Res Biogeosci 116(3):G00K06. https://doi.org/10.1029/2010JG001507

Guilland C, Maron PA, Damas O, Ranjard L (2018) Biodiversity of urban soils for sustainable cities. Environ Chem Lett 16(4):1267–1282. https://doi.org/10.1007/s10311-018-0751-6

Högberg MN, Skyllberg U, Högberg P, Knicker H (2020) Does ectomycorrhiza have a universal key role in the formation of soil organic matter in boreal forests? Soil Biol Biochem 140:107635. https://doi.org/10.1016/j.soilbio.2019.107635

HS-2.1.7.2511-09 (2009) Hygienic standards. Approximate permissible concentration (APC) of chemicals in the soil

Huot H, Joyner J, Córdoba A, Shaw RK, Wilson MA, Walker R, Muth TR, Cheng Z (2017) Characterizing urban soils in New York City: profile properties and bacterial communities. J Soil Sediment 17(2):393–407. https://doi.org/10.1007/s11368-016-1552-9

Index Fungorum (2021) A nomenclatural database. http://www.indexfungorum.org. Accessed 09 May 2021

ISO/TS 16965. Soil quality (2013) Determination of trace elements using inductively coupled plasma mass spectrometry (ICP-MS). International Organization for Standardization Geneva

IUSS Working Group WRB (2015) World Reference Base for Soil Resources 2014, update 2015. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No 106. FAO, Rome.

Ivanova AE, Nikolaeva VV, Marfenina OE (2015) Changes in the cellulolytic activity of urban soils induced by the removal of plant litter (using Moscow as an example). Eurasian Soil Sci 48(5):501–508. https://doi.org/10.1134/S1064229315030059

Ivashchenko K, Ananyeva N, Vasenev V, Sushko S, Seleznyova A, Kudeyarov V (2019) Microbial C-availability and organic matter decomposition in urban soils of megapolis depend on functional zoning. Soil Environ 38(1):31–41. https://doi.org/10.25252/SE/19/61524

Jurgens G, Saano A (1999) Diversity of soil Archaea in boreal forest before, and after clear-cutting and prescribed burning. FEMS Microbiol Ecol 29(2):205–213. https://doi.org/10.1111/j.1574-6941.1999.tb00612.x

Karelin D, Goryachkin S, Zazovskaya E, Shishkov V, Pochikalov A, Dolgikh A, Sirin A, Suvorov G, Badmaev N, Badmaeva N, Tsybenov Y, Kulikov A, Danilov P, Savinov G, Desyatkin A, Desyatkin R, Kraev G (2020) Greenhouse gas emission from the cold soils of Eurasia in natural settings and under human impact: Controls on spatial variability. Geoderma Reg 22:e00290. https://doi.org/10.1016/j.geodrs.2020.e00290

Karelin DV, Goriachkin SV, Zamolodchikov DG, Dolgikh AV, Zazovskaya EP, Shishkov VA, Pochikalov AV, Sirin AA, Suvorov GG, Kraev GN (2016) The influence of local anthropogenic factors on soil emission of biogenic greenhouse gases in cryogenic ecosystems. Zh Obshch Biol 77(3):167–181 (in Russ.)

Khabibullina FM, Kuznetsova EG, Vaseneva IZ (2014) Micromycetes in podzolic and bog-podzolic soils in the middle taiga subzone of northeastern European Russia. Eurasian Soil Sci 47(10):1027–1032. https://doi.org/10.1134/S1064229314100044

Kim HM, Jung JY, Yergeau E, Hwang CY, Hinzman L, Nam S, Hong SG, Kim OS, Chun J, Lee YK (2014) Bacterial community structure and soil properties of a subarctic tundra soil in Council, Alaska. FEMS Microbiol Ecol 89(2):465–475. https://doi.org/10.1111/1574-6941.12362

Kirtsideli IY, Abakumov EV, Teshebaev SB, Zelenskaya MS, Vlasov DY, Krylenkov VA, Ryabusheva YV, Sokolov VT, Barantsevich EP (2016) Microbial communities in regions of arctic settlements. Gig Sanit 95(10):293–299 (in Russ.)

Klich MA (2002) Identification of common Aspergillus species. CBS Fungal Biodiversity Centre, Utrecht, Netherlands

Konstantinov P, Varentsov M, Esau I (2018) A high density urban temperature network deployed in several cities of Eurasian Arctic.

Environ Res Lett 13(7):075007. https://doi.org/10.1088/1748-9326/aacb84
Konstantinov PI, Grishchenko MY, Varentsov MI (2015) Mapping urban heat islands of arctic cities using combined data on field measurements and satellite images based on the example of the city of Apatity (Murmansk Oblast) Izv. Atmos Ocean Phys 51(9):992–998. https://doi.org/10.1134/S000143381509011X
Korneikova MV (2018) Comparative analysis of the number and structure of the complexes of microscopic fungi in tundra and taiga soils in the north of the Kola Peninsula. Eurasian Soil Sci 51(1):89–95. https://doi.org/10.1134/S1064229318010106
Korneikova MV, Redkina VV, Shalygina RR (2018) Algological and mycological characterization of soils under pine and birch forests in the Pasvik Reserve. Eurasian Soil Sci 51(2):211–220. https://doi.org/10.1134/S1064229318020047
Korneykova MV, Vasenev VI, Nikitin DA, Soshina AS, Dolgikh AV, Sotnikova YL (2021) Urbanization affects soil microbiome profile distribution in the Russian arctic region. Int J Environ Res Pub Health 18(21):11665. https://doi.org/10.3390/ijerph182111665
Kosheleva NE, Dorokhova MF, Kuzminskaya NYu, Ryzhov AV, Kasimov NS (2018) Impact of motor vehicles on the ecological state of soils in the western district of Moscow. Vestn Mosk Univ 5(2):16–27 (in Russ.)
Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World Map of the Köppen-Geiger climate classification updated. Meteorol Z 15(3):259–265. https://doi.org/10.1127/0941-2948/2006/0130
Lehmann A, Stahr K (2007) Nature and significance of anthropogenic urban soils. J Soil Sediment 7(4):247–260. https://doi.org/10.1065/jss2007.06.235
Li G, Sun GX, Ren Y, Luo XS, Zhu YG (2018) Urban soil and human health: a review. Eur J Soil Sci 69(1):196–215. https://doi.org/10.1111/ejss.12518
Litalien A, Zeeb B (2020) Curing the earth: a review of anthropogenic soil salinization and plant-based strategies for sustainable mitigation. Sci Total Environ 698:134235. https://doi.org/10.1016/j.scitotenv.2019.134235
Lorenz K, Lal R (2015) Managing soil carbon stocks to enhance the resilience of urban ecosystems. Carbon Manag 6(1–2):35–50. https://doi.org/10.1080/17583004.2015.1071182
Lorenz K, Lal R, Shipitalo MJ (2008) Chemical stabilization of organic carbon pools in particle size fractions in no-till and meadow soils. Biol Fertil Soils 44(8):1043–1051. https://doi.org/10.1007/s00374-008-0300-8
Lysak LV, Lapygina EV (2018) The diversity of bacterial communities in urban soils. Eurasian Soil Sci 51(9):1050–1056. https://doi.org/10.1134/S1064229318090077
Marfenina OE, Danilogorskaya AA (2017) Effect of elevated temperatures on composition and diversity of microfungal communities in natural and urban boreal soils, with emphasis on potentially pathogenic species. Pedobiologia 60:11–19. https://doi.org/10.1016/j.pedobi.2016.11.002
Marfenina OE, Kul'ko AB, Ivanova AE, Sogonov MV (2002) The microfungal communities in the urban outdoor environment. Mikol Fitopatol 36(4):22–32 (in Russ.)
Marfenina OE, Lysak LV, Ivanova AE, Glushakova AM, Kachalkin AV, Nikolaeva VV, Karlsen AA, Tepeeva AN (2017) Biodiversity in urban soils: threats and opportunities (on the example of cultivated microorganisms). In: Abstract book of 9th international congress Soils of Urban Industrial Traffic Mining and Military Areas. "Urbanization: a challenge and an opportunity for soil functions and ecosystem services" 22–26 May 2017, Moscow, Russia, p 98–100
Mazei YA, Lebedeva NV, Taskaeva AA, Ivanovsky AA, Chernyshov VA, Tsyganov AN, Payne RJ (2018) What role does human activity play in microbial biogeography?: The revealing case of testate amoebae in the soils of Pyramiden, Svalbard. Pedobiologia 67:10–15. https://doi.org/10.1016/j.pedobi.2018.02.002
Mille-Lindblom C, Tranvik LJ (2003) Antagonism between bacteria and fungi on decomposing aquatic plant litter. Microb Ecol 45(2):173–182. https://doi.org/10.1007/s00248-002-2030-z
Nikitin DA, Marfenina OE, Kudinova AG, Lysak LV, Mergelov NS, Dolgikh AV, Lupachev AV (2017) Microbial biomass and biological activity of soils and soil-like bodies in coastal oases of Antarctica. Eurasian Soil Sci 50(9):1086–1097. https://doi.org/10.1134/S1064229317070079
Nikitin DA, Semenov MV, Semikolennykh AA, Maksimova IA, Kachalkin AV, Ivanova AE (2019) Biomass of fungi and species diversity of the cultivated mycobiota of soils and substrates in Northbrook Island (Franz Josef Land). Mikol Fitopatol 53(4):210–222 (in Russ.)
Nikonov VV, Lukina NV, Polyanskaya LM, Fomicheva OA, Isaeva LG, Zvyagintsev DG (2006) Population and biomass of microorganisms in soils of pyrogenic succession in the northern taiga pine forests. Eurasian Soil Sci 39(4):433–442. https://doi.org/10.1134/S1064229306040107
Nilsson LO, Giesler R, Bååth E, Wallander H (2005) Growth and biomass of mycorrhizal mycelia in coniferous forests along short natural nutrient gradients. New Phytol 165(2):613–622. https://doi.org/10.1111/j.1469-8137.2004.01223.x
Nosanchuk JD, Stark RE, Casadevall A (2015) Fungal melanin: What do we know about structure? Front Microbiol 6:1463. https://doi.org/10.3389/fmicb.2015.01463
Oechel WC, Vourlitis G, Hastings SJ (1997) Cold season CO2 emission from arctic soils. Global Biogeochem Cy 11(2):163–172. https://doi.org/10.1029/96GB03035
Pashkevich MA, Bech J, Matveeva VA, Alekseenko AV (2020) Biogeochemical assessment of soils and plants in industrial, residential and recreational areas of Saint Petersburg. J Min Inst 241(1):125–130. https://doi.org/10.31897/PMI.2020.1.125
Peltola P, Åström M (2003) Urban geochemistry: a multimedia and multielement survey of a small town in northern Europe. Environ Geochem Health 25(4):397–419. https://doi.org/10.1023/B:EGAH.0000004553.56489.0c
Peretrukhina AT (2011) Sanitary and microbiological studies of soils in Murmansk city and the Murmansk region. Mezhdunar Zh Eksp Obraz 6:14–16 (in Russ.)
Pereverzev VN (2004) Forest soils of the Kola Peninsula. Nauka, Moscow (in Russ.)
Piotrowska-Długosz A, Charzyński P (2015) The impact of the soil sealing degree on microbial biomass, enzymatic activity, and physicochemical properties in the Ekranic Technosols of Toruń (Poland). J Soil Sediment 15(1):47–59. https://doi.org/10.1007/s11368-014-0963-8
Polyakov V, Petrova A, Kozlov A, Abakumov E (2018) Toxicological state and chemical properties of soils in urbanized ecosystems of Murmansk. Czech Polar Rep 8(2):230–242. https://doi.org/10.5817/CPR2018-2-19
Polyanskaya L, Kalimova I (2017) A new method for determining the number and biomass of spores and mycelius of fungi. In: Danilova MA, Geraskina AP, Gornov AV, Lukina NV, Plotnikova AS, Tebenkova DN, Kuznetsova AI, Dulina AA, Nikitina AD (Eds.), Materialy VIII vserossiyskoy nauchnoy konferentsii s mezhdunarodnym uchastiyem "Lesnyye pochvy i funktsionirovaniye lesnykh ekosistem" (Mater. VIII All-Russ. Sci. Conf. with Int. Part. "Forest soils and functioning of forest ecosystems"). Moscow, p 37–38 (in Russ.)
Polyanskaya LM, Zvyagintsev DG (2005) The content and composition of microbial biomass as an index of the ecological status of soil. Eurasian Soil Sci 38(6):625–633
Prokofyeva TV, Gerasimova MI, Bezuglova OS, Gorbov SN, Bakhmatova KA, Matinyan NN, Gol'eva AA, Zharikova EA,

Nakvasina EN, Sivtseva NE (2014) Inclusion of soils and soil-like bodies of urban territories into the Russian soil classification system. Eurasian Soil Sci 47(10):959–967. https://doi.org/10.1134/S1064229314100093

Prokofyeva TV, Martynenko IA, Ivannikov FA (2011) Classification of Moscow soils and parent materials and its possible inclusion in the classification system of Russian soils. Eurasian Soil Sci 44(5):561. https://doi.org/10.1134/S1064229311050127

Richter S, Haase D, Thestorf K, Makki M (2020) Carbon pools of Berlin, Germany: Organic carbon in soils and aboveground in trees. Urban Urban Green 54:126777. https://doi.org/10.1016/j.ufug.2020.126777

Saltan NV, Sviatkovskaya EA (2020) Assessment of soil pollution with heavy metals in urban areas of the Kola Arctic. In: Vasenev V, Dovletyarova E, Cheng Z, Valentini R, Calfapietra C (Eds.), Green Technologies and Infrastructure to Enhance Urban Ecosystem Services. SSC 2018. Springer Geography. Springer, Cham, p 12–17. https://doi.org/10.1007/978-3-030-16091-3_3

Sarzhanov DA, Vasenev VI, Vasenev II, Sotnikova YL, Ryzhkov OV, Morin T (2017) Carbon stocks and CO2 emissions of urban and natural soils in Central Chernozemic region of Russia. Catena (amst) 158:131–140. https://doi.org/10.1016/j.catena.2017.06.021

Schmidt N, Bölter M (2002) Fungal and bacterial biomass in tundra soils along an arctic transect from Taimyr Peninsula, central Siberia. Polar Biol 25(12):871–877. https://doi.org/10.1007/s00300-002-0422-7

Seifert K, Morgan-Jones G, Gams W, Kendrick B (2011) The genera of Hyphomycetes. CBS, Reus, Utrecht

Seifert KA, Gams W (2011) The genera of Hyphomycetes–2011 update. Persoonia Mol Phylogeny Evolut Fungi 27:119–129. https://doi.org/10.3767/003158511X617435

Semenov MV, Chernov TI, Tkhakakhova AK, Zhelezova AD, Ivanova EA, Kolganova TV, Kutovaya OV (2018) Distribution of prokaryotic communities throughout the Chernozem profiles under different land uses for over a century. Appl Soil Ecol 127:8–18. https://doi.org/10.1016/j.apsoil.2018.03.002

Sharkova SYu, Parfenova EA, Polyanskova EA (2011) Bioindication of the urban environment by the state of the microbial complex of soils. Ekol Prom Ross 11:44–47

Sharma RC, Tateishi R, Hara K, Gharechelou S, Iizuka K (2016) Global mapping of urban built-up areas of year 2014 by combining MODIS multispectral data with VIIRS nighttime light data. Int J Digit Earth 9:1004–1020. https://doi.org/10.1080/17538947.2016.1168879

Shein EV, Karpachevskii LO, Sudnitsyn II (2007) Theory and methods of soils physics. Grif and K Moscow, Russia (in Russ.)

Shi B, Tang C-S, Gao L, Liu C, Wang B-J (2012) Observation and analysis of the urban heat island effect on soil in Nanjing. China Environ Earth Sci 67(1):215–229. https://doi.org/10.1007/s12665-011-1501-2

Shirokikh IG, Shirokikh AA (2019) Antagonism and resistance to antibiotics of Actinomycetes from soils of three specially protected natural territories. Eurasian Soil Sci 52(10):1227–1233. https://doi.org/10.1134/S1064229319100132

Slukovskaya MV, Kremenetskaya IP, Drogobuzhskaya SV, Novikov AI (2020) Sequential extraction of potentially toxic metals: Alteration of method for Cu-Ni polluted peat soil of industrial barren. Toxics 8(2):39. https://doi.org/10.3390/toxics8020039

Slukovskaya MV, Vasenev VI, Ivashchenko KV, Morev DV, Drogobuzhskaya SV, Ivanova LA, Kremenetskaya IP (2019) Technosols on mining wastes in the subarctic: Efficiency of remediation under Cu-Ni atmospheric pollution. Int Soil Water Conserv Res 7(3):297–307. https://doi.org/10.1016/j.iswcr.2019.04.002

Stepanov AL, Manucharova NA, Smagin AV, Kurbatova AS, Myagkova AD, Bashkin VN (2005) Characterization of the biological activity of the microbial complex in urban soils. Eurasian Soil Sci 38(8):864–869

Stoma GV, Manucharova NA, Belokopytova NA (2020) Biological activity of microbial communities in soils of some Russian cities. Eurasian Soil Sci 53(6):760–771. https://doi.org/10.1134/S1064229320060125

Straigytė L, Vaidelys T, Þalkauskas R, Manton M (2019) Impact of urban green spaces, native tree species and seasons on soil pH in Kaunas, Lithuania. Balt For 25(2):257–262. https://doi.org/10.46490/vol25iss2pp257

Stroganova MN, Myagkova AD, Prokofyeva TV (1997) The role of soils in urban ecosystems. Eurasian Soil Sci 30(1):82–86

Sushko S, Ananyeva N, Ivashchenko K, Vasenev V, Kudeyarov V (2019) Soil CO 2 emission, microbial biomass, and microbial respiration of woody and grassy areas in Moscow (Russia). J Soil Sediment 19(8):3217–3225. https://doi.org/10.1007/s11368-018-2151-8

Tepeeva AN, Glushakova AM, Kachalkin AV (2018) Yeast communities of the Moscow city soils. Microbiology 87(3):407–415. https://doi.org/10.1134/S0026261718030128

Tripathi BM, Kim HM, Jung JY, Nam S, Tae JH, Kim M, Lee YK (2019) Distinct taxonomic and functional profiles of microbiome associated with different soil horizons of a moist tussock tundra in Alaska. Front Microbiol 10:1442. https://doi.org/10.3389/fmicb.2019.01442

Turchanovskaya NS, Bogdanova OYu (2011) Microbiological study of the soil of Murmansk city. Usp Sovrem Estestvozn 8:72 (in Russ.)

UN (2018) The World's Cities in 2018: Data booklet. United Nations (UN), New York

Vasenev V, Kuzyakov Y (2018) Urban soils as hot spots of anthropogenic carbon accumulation: Review of stocks, mechanisms and driving factors. Land Degrad Dev 29(6):1607–1622. https://doi.org/10.1002/ldr.2944

Vasenev VI, Stoorvogel JJ, Vasenev II (2013) Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in the Moscow region. Catena (amst) 107:96–102. https://doi.org/10.1016/j.catena.2013.02.009

Vasenev VI, Stoorvogel JJ, Vasenev II, Valentini R (2014) How to map soil organic carbon stocks in highly urbanized regions? Geoderma 226–227:103–115. https://doi.org/10.1016/j.geoderma.2014.03.007

Vasenev VI, Yaroslavtsev AM, Vasenev II, Demina SA, Dovltetyarova EA (2019) Land-use change in New Moscow: First outcomes after five years of urbanization. Geogr Environ Sustain 12:24–34. https://doi.org/10.24057/2071-9388-2019-89

Vikhman MI, Kislykh EE, Moiseeva MM, Nefedova ES (2008) Agrochemical valuation of urbanozem soils in some towns of the Murmansk region. Agrokhim Vestn 4:17–18 (in Russ.)

Vogel C, Babin D, Pronk GJ, Heister K, Smalla K, Kögel-Knabner I (2014) Establishment of macro-aggregates and organic matter turnover by microbial communities in long-term incubated artificial soils. Soil Biol Biochem 79:57–67. https://doi.org/10.1016/j.soilbio.2014.07.012

Weather Online (2021) https://www.weatheronline.co.uk/. Accessed 20 Feb 2021

Yang J, Yu F, Yu Y, Zhang J, Wang R, Srinivasulu M, Vasenev VI (2017) Characterization, source apportionment, and risk assessment of polycyclic aromatic hydrocarbons in urban soil of Nanjing, China. J Soil Sediment 17(4):1116–1125. https://doi.org/10.1007/s11368-016-1585-0

Yang Y, Campbell CD, Clark L, Cameron CM, Paterson E (2006) Microbial indicators of heavy metal contamination in urban and

rural soils. Chemosphere 63(11):1942–1952. https://doi.org/10.1016/j.chemosphere.2005.10.009

Zak DR, Pellitier PT, Argiroff W, Castillo B, James TY, Nave LE, Averill C, Beidler KV, Bhatnagar J, Blesh J, Classen AT, Craig M, Fernandez CW, Gundersen P, Johansen R, Koide RT, Lilleskov EA, Lindahl BD, Nadelhoffer KJ, Phillips RP, Tunlid A (2019) Exploring the role of ectomycorrhizal fungi in soil carbon dynamics. New Phytol 223(1):33–39. https://doi.org/10.1111/nph.15679

Zhang G-L, Burghardt W, Lu Y, Gong Z-T (2001) Phosphorus-enriched soils of urban and suburban Nanjing and their effect on groundwater phosphorus. J Soil Sci Plant Nutr 164(3):295–301. https://doi.org/10.1002/1522-2624(200106)164:3%3c295::AID-JPLN295%3e3.0.CO;2-T

Zhao D, Li F, Yang Q, Wang R, Song Y, Tao Y (2013) The influence of different types of urban land use on soil microbial biomass and functional diversity in Beijing, China. Soil Use Manag 29(2):230–239. https://doi.org/10.1111/sum.12034

Zhelezova A, Chernov T, Tkhakakhova A, Xenofontova N, Semenov M, Kutovaya O (2019) Prokaryotic community shifts during soil formation on sands in the tundra zone. PLoS ONE 14(4):e0206777. https://doi.org/10.1371/journal.pone.0206777

Zvyagintsev DG (1991) Methods of soil microbiology and biochemistry. P.C. MGU, Moscow (in Russ.)