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Assessment of soil fertility in Arctic cities using the soil-ecological index

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Abstract. The fertility of urban soils in the Arctic is limited by harsh climatic conditions and high anthropogenic pressure. In addition to the typical impacts of residential use, recreation, and transportation common in any urbanized areas, the ecosystems of Russian Arctic cities are subject to the technogenic influence of heavy industry hubs, which often serve as the foundation for these cities. Under such conditions, the soil cover of the largest cities in the Russian Arctic — Murmansk, Vorkuta, and Norilsk — has formed. An analysis of the physical and chemical properties of urban soils, an assessment of their fertility, and the limiting factors are necessary for the creation and maintenance of urban green infrastructure, which is one of the key factors in the ecological comfort of city life. This study evaluates the acidity, organic matter and total nitrogen content, availability of mobile forms of phosphorus and potassium in the topsoil of these cities and provides an integrated assessment of their fertility based on the soil-ecological index (SEI) by I.I. Karmanov, adapted within the study for application to northern soils and territories. It is shown that, based on the combination of indicators, the soils of the studied sites form the sequence Murmansk > Vorkuta > Norilsk, from the most fertile to the least fertile. The influence of anthropogenic factors on soil properties is noted, which can be both positive (a decrease in average soil acidity across all sites) and negative (toxic concentrations of mobile phosphorus in the soils of Murmansk). Based on the obtained SEI values, it is concluded that the soils of the studied sites have relatively high overall fertility, comparable to that of soils in the middle and southern taiga.

Keywords: soil fertility indicators, Arctic urban ecosystems, soil bonification

Author contributions: A.I. Losev — statistical processing, analysis, and interpretation of results, graphics generation, text preparation, and source review; V.I. Vasenev — setting goals and objectives, selecting sampling sites and analytical methods, and preparing and editing the text; E.D. Berezhnoy — collecting, preparing, and analyzing soil samples; Yu.L. Sotnikova — organizing the sample preparation and analysis, and preparing and editing the text. All authors reviewed and approved the final version of the manuscript.

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Introduction

Urban ecosystem soils play a key role in maintaining the sustainability of urbanized territories, providing ecosystem services such as carbon sequestration, hydrological regulation, and biodiversity maintenance [1].

Soil fertility is the ability to sustain plant life, thus, it is primarily critical for maintaining sustainable greening and designing green infrastructure, which in northern conditions, besides aesthetic and recreational functions, performs a number of specific utilitarian functions related to natural and technogenic conditions. For example, countering erosion, permafrost thawing, wind, snow, and dust, which within northern regions emphasizes the importance and complexity of maintaining green infrastructure and, consequently, the fertility of soils that must support its viability [2].

Anthropogenic transformation of the soil cover in cities leads to the formation of specific anthropogenically-transformed and artificial soils, the properties of which differ significantly from natural analogues [3]. Under intensive technogenic pressure, urban soils are often characterized by deterioration of organic matter quality, elevated heavy metal content, and altered physical and chemical properties, including soil compaction and sealing, which limits their functional potential [4–6].

In Arctic cities, these processes are exacerbated by extreme climatic conditions, which impose additional constraints on soil formation and ecosystem functioning [7–9]. Low temperatures, a short growing season, and periodic freeze-thaw cycles slow down microbiological activity and humification processes, reducing natural fertility [10]. Furthermore, industrial emissions from mining, steelmaking, and other heavy industries, widespread beyond the Arctic Circle, lead to the accumulation of toxic elements, which additionally suppresses soil biota and destabilizes ecosystems [11–13].

Thus, soil fertility being the key property in Arctic cities is simultaneously limited by all the aforementioned factors, both natural and anthropogenic, including the load inherent to all urbanized areas as well as the technogenic load specific to industrial cities.

Under urbanized conditions, assessing soil status requires particular attention, as reflected in environmental regulation practices, for example, Moscow Government Decree No. 514-PP. However, the lack of developed systems for soil quality regulation and control remains a problem for Arctic cities.

Therefore, a promising approach for the comprehensive assessment of soil status and fertility is the use of integral indices that combine physical, chemical, and often biological indicators [14–16].

Integral indices will allow not only diagnosing the current state of soils but also assessing their potential in comparison with background soils and soils of other cities, including those located in different climatic zones, in order to forecast the possibility of applying these indices in green infrastructure design and resilience to further anthropogenic impact.

One of the most common indices in Russia, that is the soil-ecological index (SEI) of I.I. Karmanov, was developed and is applied primarily for soils of agricultural use, and moreover, soils located in more southern regions [17, 18].

Thus, **the aim of the research** is a comprehensive assessment of the fertility of the soil cover of large urban ecosystems in the Arctic (using the examples of Murmansk, Norilsk, and Vorkuta) under anthropogenic impact, using and adapting the methodology of soil-ecological indices (SEI) by I.I. Karmanov to determine the potential and limitations of their use in greening and landscaping.

Materials and Methods

Study Sites. The soil cover of Russia's three largest cities beyond the Arctic Circle — Murmansk, Norilsk, and Vorkuta, each with populations exceeding 50,000 inhabitants — was examined. These are also among the world's largest settlements in the Arctic, with only Tromsø, Norway, ranking ahead of one of them in population [19].

Information about the study sites and their geographical location is provided in Table 1 and Fig. 1, respectively.

Sampling. Sampling was conducted by genetic horizons (and layers, in case of thick horizons) by digging soil pits/half-pits/small trenches, or by drilling with an Edelman hand auger.

Soil Bulk Density Determination. Bulk density was determined by the cutting ring method, sampling a known volume of soil in its natural structure using a Kachinsky drill/cutting ring, followed by gravimetric measurement of sample moisture and mass.

Soil Total Carbon Determination. Total carbon content was determined using an Elementar Vario TOC Select analyzer by dry catalytic combustion at 950 °C with detection of released CO₂ by a non-dispersive infrared sensor (NDIR).

Soil Organic Matter Determination. Soil organic matter (SOM) was determined by the dichromate oxidation method with heating to 100 °C and photometric endpoint according to GOST 26213–2021¹.

Soil Total Nitrogen Determination. Total nitrogen content was determined by the Kjeldahl method, based on mineralization of a soil aliquot with sulfuric acid heated to 400 °C in the presence of catalysts, distillation of the oxidized (to ammonium form) soil nitrogen in alkaline solution into boric acid, and titration of the formed ammonium-borate complex with sulfuric acid, in accordance with GOST R 58596–2019².

¹ GOST 26213–2021. Soils. Methods for Determining Organic Matter. Introduced on 2022–07–01. Moscow: Standartinform publ., 2021.

² GOST R 58596–2019. Soils. Methods for Determining Total Nitrogen. Introduced on 2020–07–01. Moscow: Standartinform publ., 2019.

Table 1

Soil-geographical characteristics of the study objects

City	$\sum t > 10\text{ }^{\circ}\text{C}$ (GDD)	Days with $t > 10\text{ }^{\circ}\text{C}$	Days with $t > 0\text{ }^{\circ}\text{C}$	Soil-geographical zoning	Number of points
Murmansk (68.970606 N, 33.074749 E)	~800	30...60	~90	Facies of cold, freezing soils (Kola-Karelian province)	76
Vorkuta (67.493512 N, 64.050145 E)	~650	30...60	<65	Facies of very cold, long-freezing soils (Kanin-Pechora province)	37
Norilsk Agglomeration [7]	Norilsk (69.343983 N, 88.210392 E)	~688 [22]	30...60	Boundary between the facies of very cold, long-freezing soils and the mountain Anabar-Putorana province	37
	Talnakh (69.491662 N, 88.390418 E)				17
	Kayerkan (69.351426 N, 87.753701 E)				11
	Oganer (69.358857 N, 88.372239 E)				13
					78

Source: compiled by A.I. Losev using [7, 20, 22].

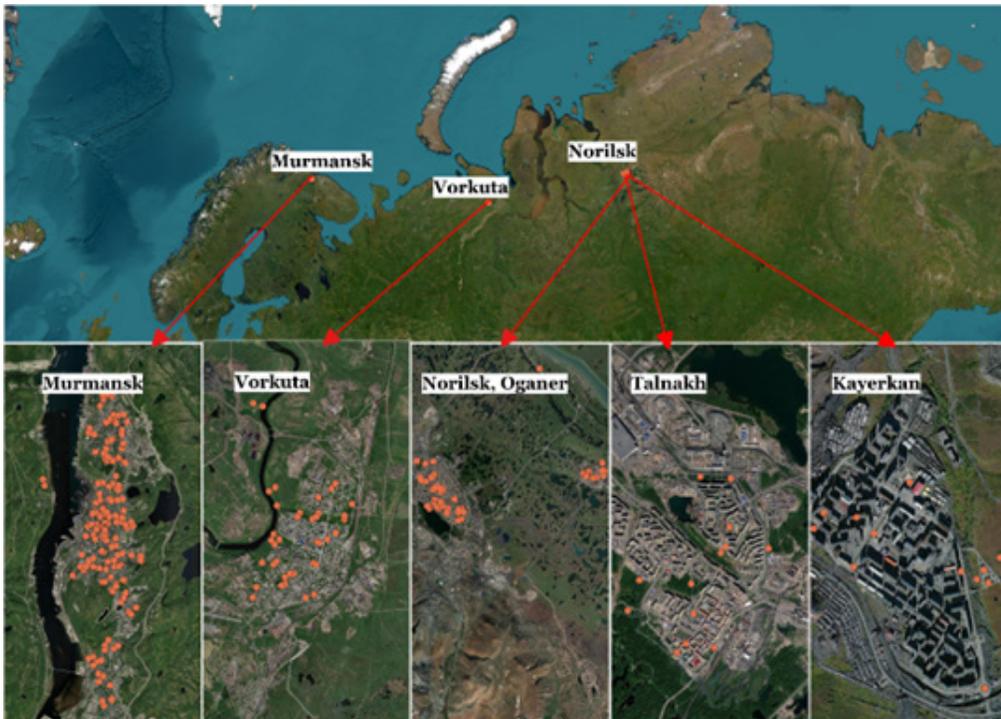


Fig. 1. Study objects and sampling points

Source: compiled by A.I. Losev, QGIS Desktop 3.40.4.

Soil Acidity Determination. The pH of aqueous (soil/solution ratio 1:10) and salt extracts (soil/solution ratio 1:2.5) was determined by the direct potentiometric method using an ECOTEST-2000 pH meter.

Determination of Mobile Forms of Phosphorus and Potassium. Mobile fractions of phosphorus and potassium were determined mainly by the Kirsanov method (extraction with 0.2 mol/L HCl solution) according to GOST R 54650–2011³. For samples containing carbonates, the Machigin method was applied (extraction with 10 g/L ammonium carbonate solution) according to GOST 26205–91⁴. Phosphorus in both extracts was determined photometrically on a Hach Lange DR3900, potassium by ICP-OES on a Perkin Elmer AVIO 200.

Soil Assessment/Bonitation Using Soil Indices. For the integrated assessment of the fertility of the studied soils, the soil-ecological index (SEI) of I.I. Karmanov was used [18, 17]. This index is the product of parameters reflecting the soil (physical, chemical and agrochemical) and climatic features of the studied territory:

- The physico-chemical parameter includes data on humus content, soil density, particle-size distribution, and the level of hydromorphism.
- The agrochemical parameter considers soil pH, mobile phosphorus, and potassium concentrations.
- The climatic parameter is based on the mean annual sum of temperatures above 10 °C, moisture coefficients, and continentality.

The index is calculated using the formula

$$SEI = 12.5(2 - V) \cdot P \cdot AP \cdot A (\sum t > 10 \text{ } ^\circ\text{C} \cdot (MC - 0.05)) / (CC + 1000),$$

where SEI is the soil-ecological index, points; 12.5 is a constant multiplier for all soils; 2 is the maximum possible density at their ultimate compaction, g/cm³; *V* is the density for the meter-thick soil layer, g/cm³; *P* is the coefficient for useful soil volume (considers soil type and particle-size distribution); *AP* are additionally considered soil properties (considers humus status); $\sum t > 10 \text{ } ^\circ\text{C}$ is the mean annual sum of temperatures above 10 °C; *MC* is the moisture coefficient; *CC* is the climate continentality coefficient; *A* is the final agrochemical index (considers acidity, phosphorus and potassium content).

The coefficients for accounting for the listed factors are provided by the index authors [17] for evaluating arable lands in more southern regions, where agriculture and soil bonitation are more common and are limited to the northern part of the taiga-forest soil-bioclimate zone.

In this regard, to conduct an integrated assessment of the studied soils' fertility, we applied this index with a number of modifications for polar belt soils (more details in the "Results and Discussion" section).

Statistical Analysis. To assess the statistical significance of differences in results between cities, multivariate analysis of variance (ANOVA), the Bonferroni criterion

³ GOST R 54650–2011. Soils. Determination of Mobile Phosphorus and Potassium Compounds by the Kirsanov Method as Modified by CIASA. Introduced on 2013–01–01. Moscow: Standartinform publ., 2011.

⁴ GOST 26205–91. Soils. Determination of Mobile Phosphorus and Potassium Compounds by the Machigin Method as Modified by CIASA. Introd. 1993–01–07. Moscow: Standartinform publ., 2015.

for pairwise comparisons (due to comparing samples of different sizes), and Pearson's correlation coefficient were used.

Calculations and chart construction were performed in Microsoft Excel 2024 MSO. Analysis and visualization of cartographic material were performed using QGIS 3.40.

Results and Discussion

Soil Acidity. In Murmansk, the pH of aqueous extracts of upper horizons (Fig. 2) averages 6.31, ranging from 4.18 to 8.40, which is significantly lower than in Vorkuta, where the average pH is 7.50 (ranges from 6.36 to 8.98), and Norilsk with an average pH of 7.36 (ranges from 4.96 to 8.93). In turn, the acidity indicators of Vorkuta and Norilsk soils do not differ significantly; however, a noticeable difference in the magnitude of standard deviations is noted (0.128 and 0.086, respectively), indicating a more homogeneous soil cover in terms of pH within the Norilsk territory.

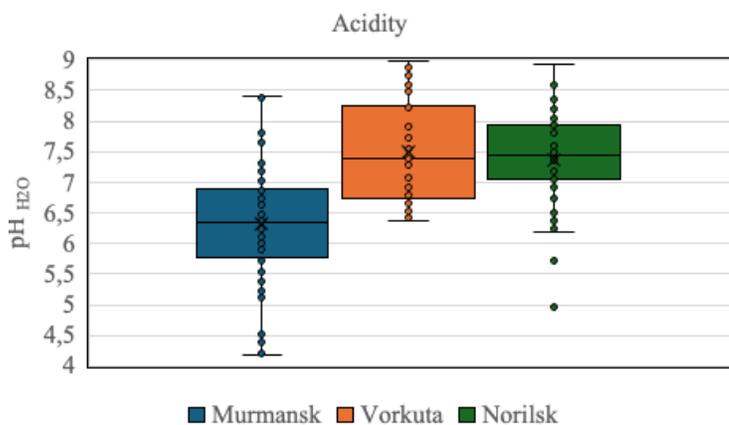


Fig. 2. Acidity of the aqueous extract of the upper soil horizons in Murmansk, Vorkuta, and Norilsk
Source: compiled by A.I. Losev, Microsoft Excel 2024 MSO.

Thus, by acidity value, Murmansk soils are classified in a wide range from strongly acidic to alkaline, while Vorkuta and Norilsk soils range from neutral to alkaline. Given the zonal level of soil pH in the Arctic zone (according to studies of Murmansk [22, 23], Salekhard [24], Vorkuta [25] and surrounding areas [26]) around 3.5...5 (closer to 7 in mountain tundra), the decrease in acidity of the studied sites' soils is explained by various anthropogenic influences, ranging from technogenic pollution to the completely artificial formation of soil horizons [27, 28].

Soil Organic Matter. Due to the high variability of SOM content in the upper horizons (Fig. 3), among which there were both mineral horizons and organomineral ones with completely organic (peat) horizons, no significant differences in this indicator between cities were found. However, a trend towards an increase in the average SOM content in Vorkuta (varies from 3.9 to 51.5%, average 20.9%) compared to Murmansk (varies

from 1.5 to 68.7%, average 15.9%) and Norilsk (varies from 0.3 to 69.7%, average 13.1%) should be noted.

These ranges generally cover the spread of the indicator in zonal soils: 1...3% in non-peat horizons of mountain tundra landscape soils, 5...7% in organo-accumulative horizons of sod-podzolic soils, up to 50% in peatified horizons of podzols [24–26, 29].

In the urbanozems of Arctic cities, SOM content is also described within wide limits from 2 to 50% [22, 27].

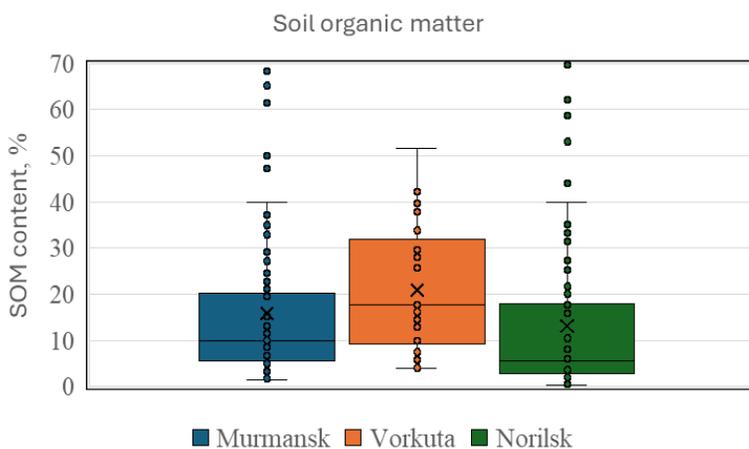


Fig. 3. Organic matter content in the upper soil horizons of Murmansk, Vorkuta, and Norilsk
Source: compiled by A.I. Losev, Microsoft Excel 2024 MSO.

Nutrient Element Content. Descriptive statistics on the content of total nitrogen and mobile forms of phosphorus and potassium in the soils of the sites are presented as $\frac{\text{mean} \pm \text{SD}}{(\text{min} - \text{max})}$. For Norilsk, the contents of phosphorus and potassium by the Machigin method are additionally provided, due to the presence of carbonates in a large number of samples (Table 2).

Table 2

Nutrient content in the upper soil horizons of Murmansk, Vorkuta, and Norilsk

Object	N total, %	P ₂ O ₅ mobile, mg/kg	K ₂ O mobile, mg/kg	P ₂ O ₅ mobile, mg/kg	K ₂ O mobile, mg/kg
		by Kirsanov		by Machigin	
Murmansk	$\frac{0.4 \pm 0.33}{(0.02-1.74)}$	$\frac{1357.6 \pm 987.2}{(42-4674)}$	$\frac{233.5 \pm 138.2}{(49-668)}$	—*	—
Vorkuta	$\frac{0.54 \pm 0.35}{(0.08-1.43)}$	$\frac{280.9 \pm 210}{(10-815)}$	$\frac{199.8 \pm 129}{(19-640)}$	—	—
Norilsk	$\frac{0.25 \pm 0.32}{(0.01-1.7)}$	$\frac{264.3 \pm 256.6}{(11-845)}$	$\frac{312.2 \pm 212.8}{(83-825)}$	$\frac{50.8 \pm 107.9}{(3 - 795)}$	$\frac{213.1 \pm 95.8}{(61 - 572)}$

Note. * — no data.

Source: compiled by A.I. Losev.

Total nitrogen content is well correlated with SOM content (0.93 in Murmansk, 0.85 in Vorkuta, and 0.88 in Norilsk); however, unlike SOM, a statistically significant difference in nitrogen content between Vorkuta (0.54% on average) and Norilsk (0.25% on average) is noted, which also indicates lower organic matter supply in Norilsk soils, in addition to the trend identified earlier.

The C/N ratio in Norilsk is also the highest (41 on average) compared to Vorkuta (24 on average) and Murmansk (22 on average), indicating the lowest nitrogen supply of Norilsk soil SOM. It should be noted that nitrogen supply in all studied soils does not exceed the medium supply class according to Grishina and Orlov ($C/N = 8...11$) and is mainly characterized as very low ($C/N > 14$).

Regarding the content of mobile forms of phosphorus and potassium, strong variability of indicators and, on average, high and very high degrees of element supply are noted at all sites. In the case of phosphorus content by Kirsanov, the supply scale ending at 250 mg/kg is often exceeded at the study sites by 2–4 times, and in Murmansk up to 18 times. This makes Murmansk the site with the highest supply of mobile phosphorus among others. However, according to [35], such phosphorus concentrations may already be toxic to plants.

Given that phosphorus and potassium content for most samples in Norilsk was determined by a method different from the other cities, to conduct a correct comparison of sites by the degree of supply of these elements, coefficients used in SEI calculation were employed, assigned to each sample depending on nutrient content (very low — 0.85, low — 0.93, medium — 1.00, elevated — 1.07, high — 1.13, very high — 1.18).

With such an assessment by the degree of nutrient supply from greater to lesser, the sites form the following series: Murmansk > Vorkuta > Norilsk (Fig. 4).

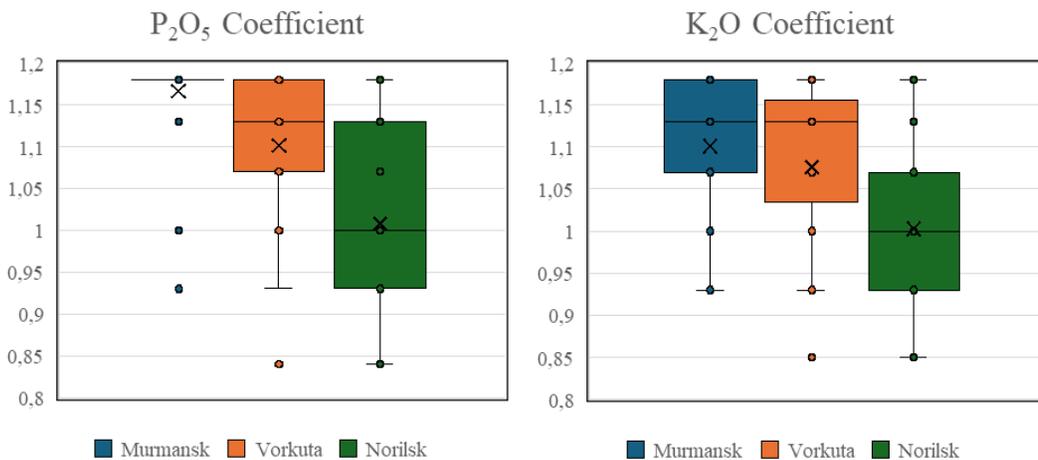


Fig. 4. Coefficients of the degree of provision of the upper soil horizons of Murmansk, Vorkuta, and Norilsk with mobile forms of phosphorus and potassium

Source: compiled by A.I. Losev, Microsoft Excel 2024 MSO.

Soil Assessment/Bonitation Using Soil Indices. For the purpose of assessing soils of Arctic cities, coefficients for a number of indicators were extrapolated to the zone of tundra gley soils and subarctic brown soils of the polar belt (Table 3).

Table 3

Coefficients modified for northern territories used for the SEI calculation

Useful soil volume (coefficient П)					
Clay	Heavy loam	Medium loam	Light loam	Loamy sand	Sand
0.63	0.74	0.85	0.85	0.84	0.71
Supply of mobile forms of phosphorus (included in coefficient A)					
Very low	Low	Medium	Elevated	High	Very high
0.84	0.93	1.00	1.07	1.13	1.18
Supply of mobile forms of potassium (included in coefficient A)					
Very low	Low	Medium	Elevated	High	Very high
0.85	0.93	1.00	1.07	1.13	1.18
Soil Acidity (included in coefficient A)					
Strongly acidic	Moderately acidic	Slightly acidic	Close to neutral		Neutral
0.91	0.98	1.03	1.10		1.18

Source: compiled by A.I. Losev.

Within the assessment of the studied cities, the SEI structure can be represented as four-part:

1. Constant for all cities, which includes the constant multiplier, the difference between the maximum possible and actual density, and the coefficient for useful soil volume. Due to the specifics of the index and limit values for some coefficients, their product for all three cities was equal to 4.57, making the first part of SEI a constant.

2. Humus coefficient, determined by the ratio of actual SOM content to the average value in the studied zone.

3. Agrochemical coefficient, represented by the product of the modified agrochemical property coefficients given in Table 3.

4. Climatic coefficient, calculated based on climatic data provided in the “Materials and Methods” section.

The studied cities differ significantly from each other in the aggregate of SEI calculated for each sampling point, as clearly seen on the graph (Fig. 5). Soils of Murmansk have the highest scores (26 on average, ranging from 17 to 31), followed by soils of Vorkuta (17 on average, ranging from 10 to 20), and the lowest assessment is for Norilsk soils (13 on average, ranging from 10 to 19).

However, when assessing the contribution of each coefficient to the final SEI (Fig 5, stacked chart), it was noted that among the variable coefficients, the contribution of the climatic one was significantly larger (1.5–2 times) than the others in each city.

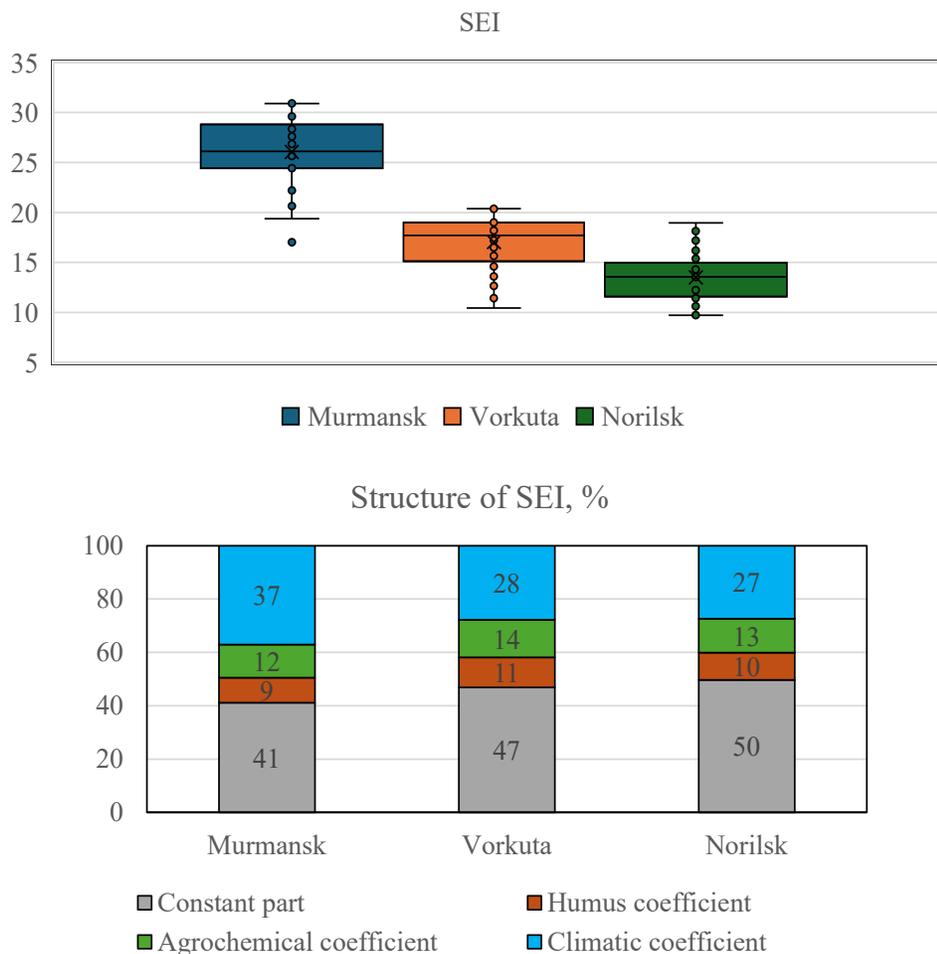


Fig. 5. SEI of Murmansk, Vorkuta, and Norilsk and their structure
 Source: compiled by A.I. Losev, Microsoft Excel 2024 MSO.

Although the climatic factor is critically important in the context of plant vegetation and their productivity (for the assessment of which the SEI was primarily developed), the imbalance it introduces into the SEI structure within this study pushes soil factors into the background. To compare the soil cover of the studied cities in isolation from climatic differences, an SEI was calculated where the climatic coefficient was averaged for all cities. Key climatic features for all three cities, despite differences in absolute values within the SEI, remain the leaching (humid) type of water regime, short and cold growing season, which is why such averaging within soil assessment can be considered relevant.

Comparison of cities by SEI with an equalized climatic coefficient (Table 4) showed less pronounced differentiation of cities by potential fertility level than by the full SEI. Soils of Murmansk (19.7 ± 2.1 points on average) do not differ significantly from soils of Vorkuta (19.6 ± 3.0 points on average); however, Norilsk soils still have reliably the lowest indicators (16.7 ± 2.9 points on average).

Statistical characteristics of coefficients for SEI calculation for Murmansk, Vorkuta, and Norilsk

Indicator	Murmansk	Vorkuta	Norilsk
Constant multiplier	4.57		
Humus coefficient*	$\frac{1.04 \pm 0.17}{(0.70-1.15)}$	$\frac{1.1 \pm 0.11}{(0.78-1.15)}$	$\frac{0.94 \pm 0.20}{(0.70-1.15)}$
Agrochemical coefficient*	$\frac{1.4 \pm 0.10}{(0.91-1.64)}$	$\frac{1.4 \pm 0.20}{(0.84-1.64)}$	$\frac{1.2 \pm 0.20}{(0.84-1.64)}$
Climatic coefficient	4.12	2.71	2.52
SEI*	$\frac{26.1 \pm 2.8}{(17-30.9)}$	$\frac{17 \pm 2.6}{(10.4-20.4)}$	$\frac{13.5 \pm 2.3}{(9.7-19.0)}$
Averaged climatic coefficient	3.12		
SEI with equalized climatic coefficient*	$\frac{19.7 \pm 2.1}{(12.9-23.4)}$	$\frac{19.6 \pm 3.0}{(12.0-23.4)}$	$\frac{16.7 \pm 2.9}{(12.0-23.4)}$

* data are presented as $\frac{\text{mean} \pm \text{SD}}{(\text{min} - \text{max})}$.

Source: compiled by A.I. Losev.

Thus, the extreme levels of heavy metal pollution formed in Norilsk and its surroundings under the influence of the metallurgical industry are reflected in biogeochemical cycles. Through disruption of soil biota activity, deterioration of soil structure, quality and cycles of organic matter mineralization, reduction in the content and availability of macronutrients, soil pollution leads to a decrease in their fertility and natural ecological functions. The SEI of the other studied cities can be viewed as the potential and basis for the remediation of Norilsk soils, improving their properties, and thereby ensuring their more effective involvement in solving urban greening tasks and improving the environmental situation overall.

During the development of the index, an SEI equal to 100 was assigned to the SEI of the non-eroded, non-gleyed, etc., chernozem of the Krasnodar Krai. Actual indices obtained from studies of the chernozem zone soil cover vary within 60...80 in the case of typical and common chernozems [31, 32], can decrease down to 30...40 for leached and podzolized chernozems [33], but generally vary around 50 [34]. For gray forest soils, an index of 20...40 is characteristic within the gradation from light to dark gray forest soils [35]. For sod-podzolic soils, a wide range is described from 15...20 points in the eastern part of Russia [32, 34, 35] to 30...80 in the European part of the country [36–38] (a similar SEI range is characteristic for urbanozems of the Moscow region but can exceed 100 points [36, 39]).

Relying on these values, using the obtained indices (varying on average from 10 to 31), one can not only assess the difference in the soil cover of the sites but also state that, in aggregate, the soils of Arctic cities are comparable in bonitation to the

zonal soils of the southern and middle taiga — sod-podzolic soils, albeit the least fertile representatives within this soil type, but still more fertile than the zonal soils of the Arctic.

Conclusion

Murmansk, Norilsk, and Vorkuta are large urban ecosystems located beyond the Arctic Circle. Characterization of the soil cover of such territories is not widely covered in the literature and represents scientific interest within research on Arctic territories under climate change and urbanization.

As a result of anthropogenic impact, an increase in the pH level of aqueous extracts by 1–2 pH units on average relative to zonal soil values is noted in all cities.

The sites are comparable in organic carbon content; however, based on the aggregate of agrochemical characteristics (content of mobile forms of phosphorus and potassium, nitrogen supply of organic matter), Norilsk soils are characterized as the least fertile.

While all sites generally have good availability of mobile nutrients in the upper horizons, the mobile phosphorus content in Murmansk soils often exceeds the toxicity threshold (> 800 mg/kg).

For an integrated assessment of the fertility of urban soils in the Arctic belt, the methodology of soil-ecological indices by I.I. Karmanov was applied by extrapolating coefficients accounting for various soil properties.

As a result of bonitation, it was found that within the application of the considered index system, the climatic factor makes the maximum contribution to the final score in the territory, which promotes a clear gradation of cities by fertility level in the series: Murmansk $>$ Vorkuta $>$ Norilsk. Assessment of sites without considering the climatic factor statistically equalizes soils of Murmansk and Vorkuta; however, Norilsk soils are still assessed as the least fertile, which is associated with the disruption of natural biogeochemical cycles and processes due to extreme levels of Norilsk soil pollution by technogenic pollutants.

In aggregate, the SEI of Arctic cities varies from 10 to 31 points, which can be approximately compared with the SEI values of virgin sod-podzolic soils of the taiga zone, and this indicates a sufficient potential of the studied cities' soil cover for greening when implementing greening and landscaping projects.

However, key limitations of applying SEI in the assessment of urban soils and soils of Arctic cities, in particular, have been identified: climatic dependence — in Arctic conditions, the temperature factor sharply reduces the overall score, which can mask the real capabilities of soils under local microclimate improvement (e.g., in urbanized zones); lack of consideration for pollution specifics — the methodology does not always reflect the consequences of chemical pollution (e.g., toxicity of phosphorus excess in Murmansk or heavy metals in Norilsk), which requires additional adjustments during regulation; consideration of only surface horizon properties — when assessing city soils, often artificially layered and characterized by high vertical

anisotropy, it would be optimal to account for the structure and characteristics of at least the root-inhabited soil layer.

Nevertheless, the use of SEI as a basis for developing regional standards for urban soil fertility seems promising, especially when adapting coefficients for Arctic conditions.

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Оценка плодородия почв арктических городов с применением почвенно-экологического индекса

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Аннотация. Плодородие городских почв Арктики лимитируется суровыми климатическими условиями и высокой антропогенной нагрузкой. Кроме типичного для любых урбанизированных территорий воздействия селитебного использования, рекреации и транспорта экосистемы арктических городов России испытывают техногенное воздействие очагов тяжелой промышленности, зачастую являющихся градообразующими. В таких условиях формируется почвенный покров крупнейших городов Российской Арктики: Мурманска, Воркуты и Норильска. Анализ физико-химических свойств городских почв, оценка их плодородия и лимитирующих его влияний необходимы для создания и содержания городской зеленой инфраструктуры — одного из ключевых факторов экологической комфортности жизни в городе. Приведена оценка кислотности, содержания органического вещества и общего азота, обеспеченности подвижными формами фосфора и калия верхнего слоя почв этих городов, а также дана интегральная оценка их плодородия на основе почвенно-экологического индекса (ПЭИ) И.И. Карманова, адаптированного в рамках исследования для применения к северным почвам и территориям. Показано, что по совокупности показателей почвы объектов формируют ряд Мурманск > Воркута > Норильск от наиболее плодородных к менее плодородным. Отмечено влияние антропогенного фактора на свойства почв, которые имеют как положительный (уменьшение средней кислотности почв на всех объектах), так и отрицательный (токсичные концентрации подвижного фосфора в почвах Мурманска) характер. По величине полученных ПЭИ сделан вывод об относительно высокой совокупной плодородности почв объектов исследования, сопоставимой с плодородностью почв средней и южной тайги.

Ключевые слова: показатели плодородия почв, арктические урбоэкосистемы, бонитировка почв

Вклад авторов: Лосев А.И. — статистическая обработка, анализ и интерпретация результатов, построение графики, подготовка текста, работа с источниками; Васенев В.И. — постановка целей и задач, выбор точек отбора образцов и методов анализа, подготовка и редакция текста; Бережной Е.Д. — отбор, пробоподготовка и анализ почвенных образцов; Сотникова Ю.Л. — организация работы по пробоподготовке и анализу образцов, подготовка и редакция текста. Все авторы ознакомились с окончательной версией рукописи и одобрили ее.

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