Environmental assessment of the state of urban soils in Petrozavodsk, Russia

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Abstract. Urban ecosystems are exposed to heavy adverse technogenic pressure, which can be indicated by the condition of soils. This paper provides an environmental assessment of soils in urban settings with varying degrees of human impact for the case of Karelia’s largest city – Petrozavodsk. To this end, 96 soil samples were collected from the surface layer (0–10 cm) from sites in the city used for different purposes. The samples were tested for total heavy metal content as a key indicator of the detrimental effect of urbanization. Microbiological indices were also determined, including oligonitrophilic microorganism count, catalase and urease activity, rate of cellulose degradation. These parameters are commonly used in monitoring. It was found as a result that soils were the most severely affected in common use land, where pollutant concentrations were the highest. The main soil pollutants among those tested were manganese, zinc, copper, and lead. The numbers of microorganisms involved in nitrogen transformation and soil cellulolytic activity were higher than in the control. The soil microbial community’s response to human impact was manifest in an elevated activity of the studied enzymes. The resultant data can be used in urban soil monitoring, and in working out recommendations for environmental conservation.

1. Introduction
In the modern world, human pressure on the environment has been growing quite rapidly, especially in urban areas. Building density, industrial activity, and intensive traffic result in accumulation of various contaminants in the biosphere. Soil is a critical component of the ecosystem, which stores chemical pollutants. Among the numerous pollutants, a special group is heavy metals, which bind to mineral and organic compounds [1], increasing the overall level of soil toxicity. Heavy metals within pollutants affect the microbial community of soils. In natural undisturbed soils in the North, the leading role in forming the nitrogen balance belongs to oligonitrophilic bacteria, lichens, and cyanobacteria [2]. Heavy metals have oligodynamic effects on microorganisms [3], and alter the composition of the soil biotic component [4]. The data collected so far evidence that microorganism numbers and enzymatic activity change under heavy metal exposure [5–7]. The uneven deposition and accumulation of heavy metals in soils was found to alter the spatial variation of microbial-biochemical indices [8, 9]. The soil is a reflection of the spatio-temporal structure of the urban landscape. Microorganisms have proved their utility in monitoring the natural environment [10].

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This article deals with an environmental assessment of soils in urban areas used for different purposes. It provides an insight into the state of the natural environment in the study area, helps identify the zones most susceptible to human impact, and plan for soil-improving actions in the city.

2. Objects and methods
Meaningful information for the environmental assessment of urban soils can be gained by estimating heavy metal content, catalase and urease activities, and through model experiments in situ.

2.2. Objects
Surveys were carried out in the western part of North European Russia. The area lies in the eastern part of the Baltic Shield, on the terraced slope of Petrozavodsk Bay of Lake Onego, within a half-buried tectonic depression [11]. The study object was soils altered by urbanization in the largest city of Karelia – Petrozavodsk (61.789036 N; 34.359688 E).

2.2. Methods
Samples for chemical and microbiological analyses were taken from the top 10-cm layer of soil in different functional zones [12, 13]:
- Urban and rural development areas – residential sections (yard spaces, pocket parks, daycare centers, schools, etc.);
- Common use land – industrial zone (factories, vehicle parks, heat and power plants, warehouses, gas stations, large roads, airports, railways, etc.);
- Natural recreation zone (urban forest, parks, landscaped boulevards, etc.);
- Reserved land (wastelands, quarries).

Altogether, 96 soil samples were collected. They were tested for total heavy metal contents (Pb, Cu, Zn, Ni, Co, Cr, Mn) by digestion with a mixture of concentrated acids (HNO₃, HCl, HF) with atomic absorption spectrophotometry preceded at the Core Facility “Analytical Laboratory” of the Forest Research Institute KarR RAS.

The level of heavy metal pollution in urban soils was estimated through the empirical pollution load index (PLI), in which both the actual content of pollutants in the soil of the study area and the regional background are taken into account [14, 15, 16, 17]. PLI was calculated as follows:

\[
PLI = \left( \frac{C_F \times C_F \times \cdots \times C_F}{n} \right)^{\frac{1}{n}},
\]

(1)

where CF is the concentration factor calculated for each individual element, n is the number of elements studied. The concentration factor is obtained from the formula:

\[
C_F = \frac{C_i}{C_{bi}},
\]

(2)

where \(C_i\) is the actual content of the metal in the soil, \(C_{bi}\) is the regional background.

It PLI > 1, the soil is said to be chemically contaminated, whereas PLI < 1 means the soil is not contaminated [14]. The concentration factor (CF) was divided into the following grades [18]: CF < 1 indicates low contamination; 1 < CF < 3 is moderate contamination; 3 < CF < 6 is considerable contamination; and CF > 6 is very high contamination.

Another index we calculated was the contamination degree (CD), which represents the general degree of soil contamination. The formula is

\[
CD = C_F + C_F + \cdots + C_F
\]

(3)

According to Hakanson [18], CD is subdivided as follows classes: CD < 6 is low; 6 ≤ CD < 12 is moderate; 12 ≤ CD < 24 is considerable; CD ≥ 24 is very high.

The regional background was set at the mean content of heavy metals in the upper mineral horizons under the forest litter of soils in Karelia [19].
Oligonitrophilic microorganisms were counted in fresh samples as suggested by Kizilkaya [20]. The rate of cellulose degradation was determined in situ according to Hiederer, Micheli and Durrant [21]. Catalase activity was estimated according to Beck [22], and urease activity according to Hoffmann and Teicher [23]. Soil samples for the control were collected from a conventionally “clean” area in the Kivach Strict Nature Reserve (Albic Rustic Podzols (Arenic)).

The results were statistically processed using Microsoft Excel 2013 and Statistica 6.

3. Results and discussion
The studies revealed an extensive scatter of the data on total heavy metal contents in the surface layer of Petrozavodsk soils around the mean, as indicated by high standard deviation values (table 1). Hence, a more reliable and adequate measure of the average content of the elements in the soil would be the geometric mean or median [24, 25]. Based on the latter, average lead, zinc, and copper contents exceeded the regional background 1.5–2 fold. An elevated content of these elements in urban soils has been reported by many other researchers, who attribute it to air emissions input from vehicles, fuel combustion, construction dust, as well as to mineral and organic fertilization [12, 26–30]. Manganese concentrations in the soils were 3–4 times higher than the regional background in all the land-use categories. The reason is that the top organo-mineral horizons of the urban soils contained residues of nemoral plants, which can accumulate this element [31, 32]. Cobalt, chromium, and nickel amounts were within the background levels, suggesting there were no technogenic sources of their input to the urban ecosystem.

| Table 1. Total heavy metal content in soils of Petrozavodsk (in 10 cm layer), mg/kg. |
| P | Pb | Cu | Zn | Ni | Co | Cr | Mn |
|---|---|---|---|---|---|---|---|
| Common use land (n = 37) | | | | | | | |
| Mean | 35.8 | 44.5 | 74.4 | 29.4 | 11.0 | 26.2 | 773.3 |
| Standard deviation | 38.0 | 33.7 | 29.2 | 19.5 | 4.6 | 13.0 | 309.8 |
| Median | 20.0 | 38.2 | 78.3 | 25.7 | 10.2 | 23.3 | 718.0 |
| Urban development area (n = 25) | | | | | | | |
| Mean | 45.1 | 32.6 | 77.7 | 25.3 | 10.4 | 31.3 | 703.8 |
| Standard deviation | 86.8 | 15.7 | 32.5 | 9.8 | 3.9 | 10.3 | 345.3 |
| Median | 20.9 | 29.2 | 77.5 | 24.6 | 9.8 | 30.6 | 613.7 |
| Rural development area (n = 6) | | | | | | | |
| Mean | 28.1 | 29.0 | 70.6 | 22.6 | 11.2 | 26.3 | 691.2 |
| Standard deviation | 11.4 | 10.3 | 21.3 | 4.2 | 2.2 | 7.0 | 102.7 |
| Median | 24.7 | 26.7 | 65.5 | 21.0 | 11.3 | 26.6 | 702.4 |
| Natural recreation zone (n = 24) | | | | | | | |
| Mean | 29.9 | 27.6 | 56.4 | 23.4 | 10.2 | 35.1 | 1034.2 |
| Standard deviation | 41.5 | 21.5 | 22.8 | 11.2 | 5.9 | 13.6 | 873.7 |
| Median | 18.3 | 21.0 | 55.8 | 21.1 | 8.4 | 32.3 | 785.1 |
| Reserved land (n = 4) | | | | | | | |
| Mean | 13.8 | 24.9 | 57.9 | 16.5 | 9.9 | 28.7 | 872.4 |
| Standard deviation | 8.3 | 7.6 | 15.1 | 7.5 | 4.4 | 11.2 | 274.5 |
| Median | 15.1 | 22.8 | 56.7 | 19.9 | 10.6 | 26.4 | 822.3 |
| Regional background | 15.5 | 18.5 | 37.2 | 27.5 | 11.6 | 47.3 | 282 |
Soils in sites in any of the investigated land-use categories were not contaminated with cobalt, chromium, and nickel, as corroborated by their calculated mean concentration factors – $\text{CF} < 1$ (table 2). In the reserved land site, this factor for lead was also $< 1$. This is largely due to the location of the site: the soil sampling points were situated quite far away from built-up urban areas, and hence less exposed to air-borne industrial pollution. For other contaminants, $\text{CF}$ ranged within $1 < \text{CF} < 3$, matching the moderate contamination type.

The contamination degree (CD) of all the studied soils was moderate, irrespective of the land-use category. This index was the highest for common use land, where soils were exposed to the heaviest pollution load.

The pollution load index (PLI) for Petrozavodsk soils was within $1.10 – 1.28$. This corresponds to the baseline level of pollution of soils [16]. The pollution level was not high since air-borne industrial emissions have declined lately [33–35]. Nonetheless, the contribution of emissions from motor vehicles has been growing, and may aggravate the heavy metal contamination of urban soils in the future.

**Table 2.** Calculated pollution indexes of soil samples from the topsoil (10 cm) of Petrozavodsk.

|                  | Pb  | Cu  | Zn  | Ni  | Co  | Cr  | Mn  | CD      | PLI  |
|------------------|-----|-----|-----|-----|-----|-----|-----|---------|------|
| Common use land  | 1.29| 2.06| 2.11| 0.93| 0.88| 0.49| 2.55| 10.30   | 1.28 |
| Urban development area | 1.35| 1.58| 2.08| 0.89| 0.84| 0.65| 2.18| 9.57    | 1.25 |
| Rural development area | 1.59| 1.44| 1.76| 0.76| 0.98| 0.56| 2.49| 9.59    | 1.23 |
| Natural recreation zone | 1.18| 1.14| 1.50| 0.77| 0.73| 0.68| 2.78| 8.78    | 1.11 |
| Reserved land    | 0.97| 1.23| 1.52| 0.72| 0.91| 0.56| 2.92| 8.84    | 1.10 |

Analysis of oligonitrophilic bacteria CFU (Colony-Forming Unit) revealed their elevated numbers in the urban soils versus the control (figure 1). Oligonitrophiles proved to be highly sensitive to lead pollution in soils [36], but the metal concentration in our case was rising quite gradually, so the detrimental effect may take some time to show.

An increase in urease activity was detected in the urban environment compared to the control (figure 2). This can be explained by high organic matter content in plant litter, which can mitigate the negative effect of pollutants emitted into the urban ecosystem [37].
Analysis of the soils’ cellulolytic activity revealed a sharp increase in the rate of cellulose mineralization compared to the control. As we know, the possible sources of cellulose are plants, fungi, and microorganism metabolites [38]. Cellulose is a crucial carbohydrate in soil, the precursor of many chemical compounds. It is a readily available source of carbon for microorganisms to grow [39]. Changes in the rate of cellulose degradation are indicative of changes in the carbon cycle of soils in urban ecosystems.

4. Conclusion
The studies have shown that technogenic pressure on urban soils is the heaviest in common use land, as corroborated by the highest values of the contamination degree and pollution load index. Overall, soils of the city were moderately contaminated, no matter what land-use category they belonged to. The concentration factors of the studied elements reveal the following decreasing sequence of the main contaminants of the urban soils: manganese > zinc > copper > lead.

The stimulatory effect of pollutants on the microbiota and enzymatic activity can be explained by a gradual increase in anthropogenic pressure and heavy metal input to the soil. This is in agreement with other studies, which have demonstrated that the tolerance and resilience of bacteria grow proportionately to the increase in industrial pollution gradients [40]. Microorganisms are closely tied to plants, which can reduce the toxic effect of high heavy metal concentrations in soil [41]. It is worth noting also that heavy metals produce an oligodynamic effect on both Gram-positive and Gram-negative bacteria. However, there are several bacterial strains that contain genetic determinants of resistance to heavy metals [42]. Plants play a momentous role in attenuating the toxic effect on microorganisms: heavy metals can influence the soil–microorganisms–enzymatic activity system either directly or indirectly, and response to concentration rise can come either from the system as a whole or from its individual components [43, 44]. The effect of heavy metals on the activity of the enzymes cycling C, N, P, and S in soil has been highlighted by Shiping Deng [45]. In any case, research needs to be continued to explore the mechanisms through which the microbial community of soils adapts to urbanization pressure.
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