Regional approach to soil pollution assessment and ecological sustainability of the town soils of Kursk region

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Abstract. The development of a unified approach to environmental assessment of soils is one of the most important goals of applied ecology. This article presents an attempt to implement the strategy of a comprehensive step-by-step ecological assessment of urban soils polluted by heavy metals of technogenic origin. Schematic maps of the spatial distribution of Pb and Cd in the humus-accumulative soil horizons of Kursk are presented (372 samples). The excess of the MAC of the supererecotoxicants under analysis was noted in more than 50% of the soil samples of Kursk. It was revealed that in the industrial zones of Kursk, the excess of the MAC of Pb in soils reaches 1212.5 ppm, Cd – 52.6 ppm. It was noted that in the soils of urban landscapes with powerful anthropogenic burden, heavy metals contaminated deep horizons and exceeded the relative regional standard for heavy metal content in a meter soil column by 3.7–19.3 times. In the course of approbation of the author’s integrated index of ecological comfort of soils (ECI), it was found that an uncomfortable and relatively comfortable ecological situation was typical for 54.6% of the key areas under analysis. The use of the proposed ECI index in the practice of ecological assessment of soils will allow to identify and predict environmental stress in landscapes affected by heavy metals as soon as it is reasonably possible.

1. Introduction

Environmental assessment and environmental regulation requires an integrated approach that takes into account the assessment of the functional state of all components of ecosystems [1–4]. The basic components of terrestrial ecosystems are soils, which regulate the global processes of circulation and migration of substances. One of the frequent types of urban soils pollution, that limits their ecological functions, is pollution by heavy metals (HM) [5–7]. At the present stage of scientific and technical development, the assessment of soil pollution by HM is based on a comparison of the actual content of HM in the surface root layer of the soil with the established sanitary and hygienic standards of MAC (maximum allowable concentration) and APC (approximate permissible concentration) [3, 8]. Thus, managerial decisions concerning the assessment of soil pollution by HM come down to simplified algorithm: determination of the pollutant – determination of the level of pollution – selection and implementation of a program for the elimination or stabilization of pollution. In this case, decisions may be unreasonable, as the amount of data obtained on the state of the soil cover cannot fully reflect the complexity and environmental hazard of the situation, as well as their relative absence [1, 2, 9, 10].
To make rational technological solutions for eliminating accumulated environmental harm and to plan environmental measures aimed at creating environmentally sustainable and safe urban landscapes, a more detailed approach to the ecological assessment of urban soils is required. With this approach, it is necessary to take into account not only the power of anthropogenic burden, but also the regional features of the basic biogeochemical and ecological conditions of urban landscapes, which characterize the stability of the environment. These conditions include: the genesis of soils and their anthropogenic transformation, the spatial heterogeneity of soils and their temporal dynamics, the ecological stability of soils and the ability to self-purification, the difference of anthropogenic burden in various functional zones of the city, the number of species of living organisms and the productivity of ecosystems, the level, nature and the depth of soil pollution by HM, the features of the spatial distribution of migration, sorption and transformation of HM in urban landscapes, the permeability of geochemical barriers [2, 9–11].

The purpose of the work was to develop and test an integrated approach to environmental assessment of the pollution of urban soils by heavy metals and to assessment of the environmental comfort of the urban soils using the example of the cities of Kursk region.

2. Objects and methods of research

The research was carried out in the cities of Kursk region: Kursk, Zheleznogorsk, Lgov. The choice of key sites for the research of soil properties was substantiated by the type of soil, the presence of active technogenic sources of HM emissions and the level of current soil pollution. The assessment of soil HM pollution in the cities was carried out in two stages. At the first stage, sampling of humus-accumulative soil horizons and surface layers of soil-like substrate at a depth of 0–30 cm was carried out. The soil samples were taken in industrial, residential, transport, social-business and recreational zones of the above-mentioned cities. The content of gross and mobile forms of HM (Pb and Cd) in soils was determined by atomic absorption spectrometry (3 replicates). When determining soil pollution by HMs, MAP values [12], the regional background pollution level for Haplic Chernozem (Pachic, Clayic) and background concentrations for certain soil types [7, 11] were used.

On the basis of the obtained empirical data on the content of HM in soils, a spatial database (SD) was created. Using MapInfo Professional v16, georeferencing of coordinates to a raster substrate was done. Using open source GIS QGIS 2.18.7 "Las Palmas", spatial data processing and modeling of geochemical fields was carried out. Interpolated surfaces of heavy metals distribution were constructed by the method of inverse distance weights (IDW). Further, based on the results of comparing the soil map and schematic maps of the spatial distribution of HMs in the humus-accumulative horizons of soils and topsoils of technogenic surface formations (TSF), key areas of different genesis of soils with contrast HM pollution were determined. In course of the second stage of assessing the HM soil pollution at the key areas, the depth of HM penetration into the soil layer was assessed (assessment of profile pollution). The resource approach was used [12] in order to achieve the most accurate reflection of the current ecological situation. The obtained data on HM content in a meter soil column was compared with the conventionally standard values of HM content (MAC g/m²), which were obtained by recalculating the generally accepted MAC and APC into a unit of measurement g/m² [10]. The calculation of the relative MAC standards was made according to the formula (1):

\[ \text{MAC} \ (\text{mg/kg}) \times \rho \ (\text{kg/m}^3) \times h \ (\text{m}) = \text{MAC} \ (\text{g/m}^2) \]

\[ (1) \]

According to the method [12], the average density \( \rho \) of mineral soils in a meter thickness \( h \) is used for conversion – 1.5 g/cm³ (or 1500 kg/m³).

In the soil profiles in the territory of Kursk, the density rarely reaches a value of 1.5 g/cm³. For example, the average density of the humus-accumulative horizons of Kursk soils ranges from 1.05 to 1.21 g/cm³. Thus, in the research it is proposed to take into account the regional features of the physical properties of soils for calculating the relative standards for HM content in soils and for a comprehensive assessment of the ecological state of soil. In this research we used the average density of each individual soil horizon, obtained on the basis of real data on the density of soil composition of the key areas. To
assess the resource pollution of soils, the author's regional relative standard for HM content in a meter soil column is introduced, calculated and adjusted for the soils of the cities of Kursk region (Kursk, Zheleznogorsk, Lgov, Shchigry). This approach will allow to assess the potential of geochemical barriers and their ability to maintain the ecological balance in the cities of Kursk Region and Central Black Earth Region. On the basis of the results of two stages of assessing soil pollution, an intermediate conclusion concerning the environmental stress or the danger of the current situation was drawn.

Further, in the territories with different levels of soil pollution by Pb and Cd, taking into consideration the total complex of edaphic and biocenotic conditions, the ecological comfort of the soil was assessed and a complex index (Ecological Comfort Index – ECI) was calculated [13].

The author's complex ECI index [13] is applicable for soils potentially and actually exposed to HM. ECI is the ratio of the total impact of HMs on soils, plants, and soil biota to the sum of indicators of the ecological resistance of soils to the effects of HMs and the ability of soils to prevent HM pollution of adjacent territories. ECI is calculated using the formula (2):

\[
ECI = \frac{Cm + Qme + Mob + Cfit + Tmb}{H + |\Delta pH| + ST + GB + LT},
\]

where:
- \(Cm\) is the excess of the total HM content in the humus-accumulative horizon over MAC,
- \(Qme\) is the excess of the HM content in a meter soil column over the relative regional standard MAC,
- \(Mob\) (ammonium acetate extract \(pH = 4.8\)) is the proportion of mobile forms of HM relative to the total content,
- \(Cfit\) is the excess of the content of HM in dominant species plants,
- \(Tmb\) – transformation of soil microbiota,
- \(H\) – humus content (%), \(|\Delta pH|\) is the gradient of the acid-base geochemical barrier in a meter soil column \((G = |\Delta pH| / 1)\),
- \(ST\) is the granulometric composition of the soil,
- \(GB\) is the presence of geochemical barriers in the illuvial horizons,
- \(LT\) is the position in the landscape [13].

ECI was rated according to the levels of natural and anthropogenic ecological disfunctions suggested by Russian researchers: "Norm", "Risk", "Crisis", "Disaster". Taking into account the peculiarity of urban ecosystems and the high fragmentation of the structure of land use in relatively small areas, as well as anthropogenic burden, the levels of natural and anthropogenic ecological disfunctions of soils "Norma" and "Risk" can refer to the groups of ecologically comfortable and conventionally comfortable soils. Levels "Crisis" and "Disaster" – refer to the group of ecologically uncomfortable soils. Based on the experimental data obtained in a comprehensive assessment of the degree of ecological comfort of Kursk soils, the following ranges of ECI values should be established: ecologically comfortable soils – 0 < ECI < 0.5, conventionally comfortable – 0.5 < ECI < 1, ecologically uncomfortable – 1 < ECI < 10. Only after establishing the level of ecological comfort of soils management decisions should be made for each specific situation.

3. Mapping and assessment of heavy metal pollution of humus-accumulative soil horizons and surface layers of soil-like substrates

In course of sampling the humus-accumulative horizons of soils and surface layers of soil-like substrates, schematic maps of the spatial distribution of HM were drawn up (figure 1). On the schematic maps it is evident that soil pollution by HM covers a significant area of the city of Kursk. The maximum level of soil pollution by Pb (up to 1212.5 ppm) and Cd (up to 52.6 ppm) was recorded in the southern part of the city, where powerful sources of pollution are concentrated, among which there are existing chemical production enterprises, machine-building enterprises and heat power engineering enterprises. Polluted by Cd (4–10 ppm) and Pb (64–160 ppm) are the soils of the historical (central) part of the city, which is due to the development of the road transport network and its traffic, as well as the work of instrument making and heat power engineering enterprises (figure 1).
The soils of the northeastern and eastern parts of Kursk had a 2-fold excess of the background values in terms of the Pb and Cd content. However, areas with the content of the HMs under analysis within limits of the background values were noted. The low level of soil pollution with ecotoxicants can be explained by sufficient development of green infrastructure with predominance of forested landscapes (forest parks, parks and miniparks), which serve as a natural barrier that prevents the dispersion of elements. HM polluted soils were found in the northern and northwestern parts of the city. This is due to the northern and northwestern air mass transmission, which makes up 31.7% of the average wind pattern. Soils polluted by Pb are also located in the eastern part of Kursk, in the impact zone of the Schetmash and Pharmstandard plants and out-of-production plant APZ-20. A zone of severe pollution from 5 to 10 MAC was noted, with pollution decreasing to 1 - 2 MAC at the rim (figure 1).

Figure 1. Map diagram of the spatial distribution of gross forms of Pb (A) and Cd (B) in humus-accumulative soil horizons and surface layers of soil-like substrates in the city of Kursk (372 samples)

On the schematic maps of the spatial distribution of Pb and Cd, there can be noted local areas with soils and soil-like substrates that have a background content of Pb and Cd. As a rule, these areas refer to forest park landscapes, or to areas where recultivation activities were carried out, for example, changing soil or adding clean soil.

4. Assessment of the heavy metals profile pollution of soils in the cities of Kursk region

Based on the analysis of the schematic maps of the distribution of Pb and Cd in the cities of Kursk region (Kursk, Zheleznogorsk, Lgov), areas with contrasting soil pollution by the HMs under analysis were identified, as well as non-polluted areas with an excess of background values. Afterwards, the content of Pb and Cd was in the meter soil column (table 1).

Profile pollution, as a rule, was noted in highly transformed soils (Technosols). Thus, the content of Pb and Cd in technosols of Kursk in the zone of high emission (southern part of the city of Kursk), exceeded the conventional regional standard by 3.7–19.3 times. However, in the southern part of the city, areas with no excess of the relative regional standard for Pb and Cd content in a meter soil column were also noted, despite the high level of pollution of surface soil horizons with Pb and Cd. This can be explained both by the protective soil characteristics – infiltration and the work of geochemical barriers (humus, acid-base, biogeochemical), and by timely remediation measures. In soils with a low geochemical capacity (Carbic Podzols), while the level of pollution in the humus-eluvial horizon was 2–5 MAC, profile pollution was not noted, due to intense vertical migration of HMs. With a low level
of pollution in U1 horizons (1–2 MAC), the values of Pb content in the meter soil column of Technosols in the city of Lgov exceeded the relative regional standard by 2 g/m² (table 1).

| № | City       | Soil                      | Pollution rate of in humus-accumulative soil horizons, MAC | Content Pb, g/m² min – max | Content Cd, g/m² min – max |
|---|------------|---------------------------|----------------------------------------------------------|-----------------------------|----------------------------|
| 1 | Kursk      | Technosols                | >10                                                      | 33.2 – 142.6                | 0.7 – 23.2                 |
| 2 | Kursk      | Carbic Podzols            | 2 – 5                                                    | 13.1 – 14.8                 | 0.2 – 0.3                  |
| 3 | Kursk      | Umbric fluvisolsoxyaquic  | 1 – 2                                                    | 19.3 – 20.4                 | 0.3 – 0.8                  |
| 4 | Kursk      | Technosols                | 1 – 2                                                    | 20.6 – 23.8                 | 0.4 – 0.5                  |
| 5 | Kursk      | Technic Greyzemic Phaeozems Loamic | 1 – 2                                               | 21.8 – 32.5                 | 0.2 – 0.4                  |
| 6 | Lgov       | Technosols                | 1 – 2                                                    | 22.7 – 40.6                 | 0.3 – 0.7                  |
| 7 | Zheleznogorsk | Technic Greyzemic Phaeozems Loamic | 1 – 2                                           | 8.1 – 11.8                  | 0.1 – 0.2                  |
| 8 | Kursk      | Greyzemic Phaeozems Loamic | <1                                                      | 16.6 – 19.0                 | 0.2 – 0.3                  |
| 9 | Kursk      | Carbic Podzols            | <1                                                      | 1.7 – 5.5                   | 0.1 – 0.2                  |
| 10 | Lgov      | Umbric fluvisolsoxyaquic  | <1                                                      | 11.3 – 31.6                 | 0.2 – 0.3                  |
| 11 | Zheleznogorsk   | Greyzemic Phaeozems Loamic | <1                                                      | 8.1 – 11.6                  | 0.1 – 0.2                  |

The humus content in the humus-accumulative soil horizons varies from 1.7 to 7.0%. Intraprofile variations in pH (KCl) ranged from 0.3 to 1.4 units (table 2). Areas with soil pollution by Pb up to 7.4 MAC, Cd up to 1.4 MAC were noted. The share of mobile forms of Pb (8.6 – 44.0%) and Cd (4.3 – 51.0%) (element mobility) varied greatly relative to the total content of these HMs in the soils of Kursk. HM mobility significantly increased in soils with high technogenic burden and soils with low geochemical capacity. It was also revealed that the content of the heavy metals under analysis in the aboveground plant biomass were 1.1 to 8.0 times higher.

In most cases, in soils with a low level of pollution in humus-accumulative horizons, no excess of the relative regional standard for Pb and Cd content in a meter soil column was found (Greyzemic Phaeozems Loamic, Technic Greyzemic Phaeozems Loamic, Umbric fluvisolsoxyaquic, Carbic Podzols) It should be noted that the index of HM content in a meter soil column can serve as an indicator of the formation or increase in ecological risk when soils with a high geochemical capacity (humus soils of loamy and clayey texture) are polluted by HMs. For soils with a low geochemical capacity, it does not always reflect the real ecological risks for the landscape.

5. Assessment of the ecological comfort of soils of urban ecosystems
The ecological safety of the components of urban landscapes provides the quality of life for the public and business. The assessment of the ecological comfort of soils should be based not only on the presence or absence of chemical pollution, but also the whole set of parameters that determine both the form and degree of pollution and the functional resistance of soils to this pollution should be taken into account.

While carrying out the research, a significant level of spatial heterogeneity of the characteristics of urban soils was established (table 2).
Table 2. Assessment of the degree of ecological comfort of soils in urban landscapes of Kursk according to the integrated index of ecological comfort through the ratio of indicators of the impact of heavy metals on soils, vegetation and biota to the ecological stability of soils.

| №  | Soil type / texture / landscape<sup>a</sup> | ECI value | Degree of ecological comfort<sup>*</sup> | Humus content, % | Acid-base barrier gradient, ApH<sub>mac</sub> | Pb content nMAC | Soil | Cd nMAC | Soil | Dominant vegetation | HM content in meter soil column g<sup>-1</sup> | Transformation of microbiota (+ noted / - is not noted) | HM mobility, %<sup>b</sup> | Kursk |  |
|----|------------------------------------------|---------|------------------------------------------|------------------|---------------------------------|----------------|------|---------|------|---------------------|---------------------------------|---------------------------------------------------|------------------|--------|------|
| 1  | Technosols / MLS / E                     | 0.36    | UC                                       | 5.9              | 3.9                             | 1.39           | 3.75 | +       | 18.0 | 26.1                |                                                |  
| 2  | Technosols / MLS / T                     | 2.45    | UC                                       | 2.6              | 7.4                             | 1.43           | 0.87 | +       | 33.5 | 31.0                |                                                |  
| 3  | Carbic Podzols / SS / T                  | 1.51    | UC                                       | 1.7              | 4.27                           | 1.26           | 0.54 | +       | 32.8 | 32.2                |                                                |  
| 4  | Technic Greyzemic Podzols Loamic / MLS / E | 0.24    | RC                                       | 2.9              | 1.23                           | 0.3            | 1.07 | +       | 44.0 | 30.2                |                                                |  
| 5  | Umbric fluvisol oxyaqic / MLS / A        | 0.61    | RC                                       | 2                | 1.02                           | 0.75           | 0.8  | +       | 7.0  | 12.1                |                                                |  
| 6  | Greyzemic Phaeozems Loamic / MLS / T      | 0.10    | C                                        | 4.5              | 0.56                           | 0.15           | 0.7  | -       | 41.0 | 7.0                 |                                                |  
| 7  | Umbric fluvisol oxyaqic / MLS / A        | 0.18    | C                                        | 6.1              | 1.06                           | 0.4            | 0.85 | -       | 17.0 | 41.4                |                                                |  
| 8  | Technosols / MLS / A                     | 0.51    | RC                                       | 4.4              | 1.4                            | 0.4            | 1.0  | +       | 29.0 | 51.0                |                                                |  
| 9  | Technosols / MLS / E                     | 0.21    | C                                        | 7.0              | 1.1                            | 0.2            | 0.6  | +       | 23.1 | 40.2                |                                                |  
| 10 | Umbric fluvisol oxyaqic / MLS / A        | 0.08    | C                                        | 4.1              | 1.5                            | 0.2            | 0.8  | -       | 13.0 | 4.3                 |                                                |  
| 11 | Greyzemic Phaeozems Loamic / MLS / A      | 0.16    | C                                        | 2.7              | 0.4                            | 0.1            | 0.3  | -       | 8.6  | 24.0                |                                                |  

<sup>a</sup> nMAC – coefficient of excess, C – comfortable, RC – relatively comfortable, UC – uncomfortable, A – accumulative landscape, T – transeluvial landscape, E – eluvial landscape, MLS – medium loamy soil, SS – sandy soil.

Approbation of the complex index of ecological comfort of soils (ECI) on the territory of Kursk region showed the following results (table 2). 45.4% of the soils of the key areas in Kursk region can be considered environmentally comfortable (0.10 < ECI < 0.39). The relatively comfortable soils are 27.2% of key plots (0.51 < ECI < 0.74). Uncomfortable ecological situation was recorded at 27.2% of key areas (1.30 < ECI < 3.56) (table 2). The use of ECI makes it possible to accurately and timely identify and predict the facts of formation of environmental stress in landscapes polluted by heavy metals. An example is the key plots No. 3 and No. 8 (table 2), where the soils experience less significant anthropogenic burden, but due to their low ecological stability are incapable to neutralize it.
There were cases where soils are considered to be uncomfortable in terms of two HMs at once (key plots No. 2 and No. 5), which was due to the complex technogenic impact of numerous sources of pollution. As a rule, the soils of the recreational functional zones were ecologically comfortable, due to their low anthropogenic transformation and relative protection from the objects of HM emission into the environment. The ecological comfort of soils of other functional zones depends on their geochemical capacity and the level of anthropogenic burden. For example, in the cities of Lgov and Zheleznogorsk, ECI was significantly lower than in similar landscapes of Kursk.

6. Conclusion

Assessment of the ecological comfort of soils polluted by HM requires an integrated step-by-step approach and should be based on the ratio of the sum of indicators of the impact of heavy metals on the soil and vegetation cover and soil biota to the sum of indicators of the ecological resistance of soils and the ability of soils to prevent HM pollution. The comprehensive assessment of the soils of the cities of Kursk region made it possible to assess the scale of soil pollution by HM in urban landscapes and to identify areas of soils with a "hurricane" content of Pb (1212.5 ppm) and Cd (52.6 ppm). The high index of HM content in a meter soil column is an indicator of the formation or increase in ecological risk for soils with a high geochemical capacity. The ecological comfort of urban soils depends on the level of anthropogenic burden, the geochemical capacity of soils and the adaptability of the biocenosis.

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