Assessment of regulating ecosystem functions/services of the urban forests in the Angara region (Eastern Siberia, Russia)

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Abstract. The studies of urban forests were carried out on the territory of the Angara region in cities with a high air pollution index (up to 20) and with a high recreational load. The state of forest biogeocenoses was assessed by the parameters of trees, forest litter, and soil. Morphostructural, physicochemical, biochemical, and toxicological indicators were analysed. It was found that the selected biogeochemical parameters of trees and soils have a high level of correlation relationships under conditions of negative anthropogenic impact. The biogeochemical redistribution of technogenic pollutants in urban forests connects with the accumulating capacity of the soil cover and the regulatory function of trees, namely the ability to purify atmospheric air by accumulating toxicants in the needles and leaves. Regulatory function/service of pollutant absorption and air purification depends not only on the condition of urban forests, it is unequal for forests of different cities and, even more, for different forested territories.

1. Introduction

Urban forests are located on the land of urban settlements and are among the least protected and most exposed to anthropogenic impacts category of forests [1]. Intensive urban development has led to a significant increase of uncontrolled anthropogenic impacts on urban forests and a decrease in their conservation potential [2]. Therefore, a necessary and important direction of urban ecology should be to ensure the conservation of these forest ecosystems and increase their environmental protection potential to optimally perform their ecosystem functions and services. The international program “The Economics of Ecosystems and Biodiversity” considers the ecosystem-forming functions of natural ecosystems from the perspective of ecosystem services, that is, the benefits that people receive from ecosystems [3]. The leaders of the practical accounting of ecosystem services are the countries of the European Union [4-6]. In Russia, this new direction has begun to be covered by scientific researches only last few years, and approaches and methods are still not completely developed [7, 8].

In the urbanized areas of the Angara region, comprehensive environmental studies of naturally preserved forests that form the green frame of cities, have not been conducted so far. In the region, the main negative factors affecting the urban forests are high recreational pressure and industrial pollution [9, 10]. To improve the environmental situation, it is necessary to develop scientifically sound approaches to ameliorating the condition of trees and soils – the environment-forming components of urban forests, which play a critical role in the improvement of the environment. The concept of conservation of urban forests as semi-natural ecosystems of urbanized areas should serve as the basis for sustainable environmental management in the region. In this regard, it is important to obtain informative data on the ecosystem services of the urban forests in the Angara
region in conditions of technogenic pollution and recreational pressure, as they allow assessing the possibilities of optimizing the urban environment.

Our work aimed to investigate the ecosystem functions/services of trees and soil cover of urban forests as the most important components involved in creating a comfortable environment in urbanized areas. This paper considers one of the most relevant regulatory functions/services for cities – purification of urban air environment by accumulation and detoxification of technogenic pollutants by soil cover and absorption and accumulation of toxicants in the needles and leaves of trees.

2. Materials and Methods

Studies of urban forests were performed in the territory of the Angara region (Eastern Siberia, Russia) in cities with a high index of atmospheric pollution (IAP up to 20) and with a high recreational load, especially on the soil cover [9]. Data were obtained for the cities of Irkutsk, Angarsk, and Usolye-Sibirskoye. The state of forest biogeocenoses was assessed taking into account the parameters of trees, forest litter, and soil profile horizons. Morphostructural, physicochemical, biochemical, and toxicological parameters were studied, characterized by a high level of mutual correlations, which reflects their indicative character under conditions of negative anthropogenic impact.

The field studies were performed in July-August 2020. The forest survey was carried out on sample plots (SP) according to the recommendations of the international ICP Forests manual [11] in urban pine and pine-birch forests situated within the urban area and on the outskirts of cities. A total of 27 SPs were set in urban forests on natural grey forest soils. At each sampling area, we used an atmospheric air quality monitor (Air detector AM7P, “Environmental Protection Agency”, US) to determine an air quality index (AQI) by the concentration of PM1, PM2.5, PM10 (PM – particulate matter, diameter less than 1, 2.5, 10 ug/m³). Background SPs, 3 in total, were set in pine forests at a distance of 80 km or more from cities. These areas are characterized by relatively healthy stands and undisturbed soil cover.

During the study of stands (Pinus sylvestris L., Larix sibirica Ledeb., Betula pendula Roth), we recorded their main characteristics (forest type, stand composition, stand completeness, crown density), conducted standard geobotanical relevés on the SPs, and measured the thickness of forest litter [11]. The percentage of crown defoliation and dechromation, the crown volume and assimilating phytomass in the crown [11, 12], and trunk height and volume were determined for trees at each SPs. In addition, morphostructural indices were determined: degree of needle and leaf damage, weight and area of assimilating surface (needles, leaves). Samples of pine and larch needles and birch leaves were taken from 5-6 trees at all SPs. Further the content of biogenic elements, the content of pollutants, as well as polycyclic aromatic hydrocarbons (PAHs), and the number of other parameters in the plant assimilating organs were determined [13, 14].

The soils were formed on the Quaternary loamy deposits which have been genetically connected with the Jurassic sandstones and slates. For sampling grey forest soils, profiles were laid down to the depth of the parent rock at each SPs. These soils are also classified as Albic Luvisol [15]. The soil type name and horizon indices were established following the generally accepted classification and the Unified State Register of Soil Resources of Russia [16]. The soil profile is represented by a set of horizons: AO – A1 – A2 – A2B – B1 – B2 – BC – C, reflecting zones of organic matter (forest litter), humus, and eluvial-illuvial accumulation of substances. At each SPs, soil samples were taken and morphological and physicochemical properties (density, moisture, porosity, aeration, natural acidity, electrical conductivity, and total amount of salts) of forest litter and upper humus horizons (“envelope” method used), and all horizons of the soil profile were studied. Soil features indicating the detoxifying capacity were determined by the complex of acid-base, cation-exchange, humification properties of soils, and the activity of pollutant migration in the soil profile horizons [11, 17]. To assess sulfur and other elements migration capacity in the soil profile, mobile sulfur in salt extract (1M KCl) was measured by turbidimetric method with barium chloride [17]; exchangeable forms of calcium (Ca²⁺), magnesium (Mg²⁺), potassium (K⁺), sodium (Na⁺) included in the soil-absorbing complex (SAC) were measured in acetate-ammonium extract (1M CH₃COONH₄) with pH 4.8 [18].
The actual acidity of the soil solution was determined by the potentiometric method. The study of the physical parameters of the soils was carried out according to traditional methods [17]. The structure of soil aggregates was studied using a stereoscopic microscope Biolar (“PZO”, Poland).

To determine the elemental chemical composition of plants and soils the flame photometry, atomic absorption spectrophotometry, and photocolorimetry the certified methods using equipment of the Baikal Analytical Centre of the Siberian Branch of the Russian Academy of Sciences were applied, in particular, AAS Vario 6 (“Analytik Jena AG”, Germany), spectrophotometer Spectrum One FT-IR, (“PerkinElmer Life and Analytical Sciences”, US), Agilent 6890/5973 GC/MSD System (“Agilent Technologies”, US). The data set obtained was subjected to statistical and correlation analysis (“Statistical computing environment R, MapInfo”) to find out interdependence and dynamics of soil and plant parameters changes. Reported statistics are arithmetic means ± standard deviation. Pearson’s correlation coefficient ($r$) was used to measure the degree of correlation between element concentrations [19].

3. Results and Discussion

The ability of forests to perform a regulating ecosystem function is primarily related to the processes of redistribution of biogeochemical fluxes of elements and their compounds in the ecosystem. Since the process of migration of substances is largely determined by acid-alkaline conditions of the environment, changes in these conditions in the “soil-plant” system were studied in urban forests in parallel in the needles and leaves of trees, forest litter, above-ground and underground biomass, humus, mineral, soil-forming horizons of soils. The results showed a change in the acid-alkaline balance towards an increase in alkalinity, which is especially pronounced in the humus horizons and forest litter ($pH_w$ reaches the maximum 8.1-8.5). In the upper humus horizons, the actual acidity of soils varies from 5.80 to 7.70, in the lower mineral horizons from 5.50 to 6.90. Disturbance of acid-alkaline conditions in soils led to changes in the content of exchangeable cations ($K^+; Na^+; Ca^{2+}; Mg^{2+}$) in the SAC. It has been established that on the background territories the sum of exchangeable forms of elements changes in clear dependence on the thickness of forest litter, humus-accumulative thickness layers of soils, and the content of humus ($r$ = 0.84-0.92). The study of SAC of soils in urban forests shows a pronounced change in the ratio of exchangeable cations [$K^+; Na^+; Ca^{2+}; Mg^{2+}$] and an increase in their total sum – $\sum[K^+, Na^+, Ca^{2+}, Mg^{2+}]$ in comparison with the background (table 1).

### Table 1. Content (mg/kg×10²) of exchangeable forms of elements in the upper soil horizons (A1+A2) in the urban and background areas of the Angara region.

| Geographic coordinates of the SPs | $[K^+]$ | $[Na^+]$ | $[Ca^{2+}]$ | $[Mg^{2+}]$ | $\sum[K^+, Na^+, Ca^{2+}, Mg^{2+}]$ |
|---------------------------------|---------|---------|-------------|-------------|----------------------------------|
| **Urban forests with a high recreational load** |         |         |             |             |                                  |
| 52°22'3.13” N 104°06'34.11” E | 39.83 ± 0.16 | 6.15 ± 0.11 | 118.23 ± 1.15 | 37.23 ± 0.12 | 201.44 ± 5.34 |
| 52°33'23.57” N 103°51'21.71” E | 31.58 ± 0.12 | 4.15 ± 0.08 | 96.86 ± 0.93 | 32.18 ± 0.10 | 164.77 ± 2.26 |
| **Urban forests with a low recreational load** |         |         |             |             |                                  |
| 52°13'8.76” N 104°19'27.57” E | 19.73 ± 0.16 | 1.32 ± 0.06 | 52.51 ± 0.28 | 11.64 ± 0.09 | 85.20 ± 1.52 |
| 52°31'33.79” N 103°52'12.99” E | 27.73 ± 0.16 | 2.12 ± 0.07 | 92.48 ± 0.93 | 31.39 ± 0.18 | 153.72 ± 0.75 |
| 52°44'23.29” N 103°36'10.03” E | 28.06 ± 0.17 | 1.82 ± 0.05 | 96.86 ± 0.93 | 36.39 ± 0.18 | 163.13 ± 0.75 |
| **Background (undisturbed) forests** |         |         |             |             |                                  |
| 52°47'23.15” N 103°03'22.10” E | 5.06 ± 0.17 | 0.32 ± 0.04 | 31.51 ± 0.28 | 8.39 ± 0.18 | 45.28 ± 0.75 |
Thus, the maintenance of humus content and thickness of humus horizons are not determining factors \((r \leq 0.35)\) for the cation-exchange ability of soils, as it is established for background territories. The total carbon (TC) of urban soils is ranged from \(1.52 \pm 0.27\) to \(2.44 \pm 0.38\%\), the nitrogen from \(0.11 \pm 0.03\) to \(0.23 \pm 0.06\%\), and the C/N ratio from \(13.6 \pm 0.72\) to \(10.2 \pm 0.54\). In urban conditions, one of the determinants of soil pollution is an increase in the proportion of alkaline cations with increasing alkalinity of the soil solution, which also proves the importance of this process in the regulatory function of soils [20].

Changes in the composition of exchange cations and acid-alkaline balance, determine the accumulation and migration of heavy metals (HMs) and elements-toxicants (sulfur, chlorine, fluorine) in soils. Active movement and accumulation of mobile forms of heavy metals in all genetic horizons of the soil profile have been detected in the urban areas of the Angara region in the studied soils. The results obtained indicate that the level of contamination of urban soils with HMs is determined by two main pedochemical processes – accumulation in the humus horizons and vertical migration through the soil profile. It was found that the HMs content in the forest litter and humus horizons of soils in Irkutsk can exceed the background values of lead by up to 34 times, copper by 23 times, zinc by 18 times, and cadmium by up to 14 times. In the forest soils of Angarsk and Usolye-Sibirskoye cities, background concentration exceeding are approximately equal and amount to 28, 17, 14, and 8 times, respectively, for the above-mentioned HMs. The lysometric studies of lead and cadmium migration in the studied soils of Usolye-Sibirskoye show their high accumulation in humus-accumulative horizons and intensive illuvial redistribution with depth (figure 1).

Thus, in the upper horizons \((A1, A2, A2B)\) of soils of urban forests on the outskirts of the city the content of lead and cadmium exceeds the background level by 7-10 times. In the underlying illuvial B1 horizon, where podzolic process occurs, the concentration of elements is reduced to 4-6 times relative to the upper humus horizons, and the textural B2 horizon. Also, the concentration of HMs increases again in comparison with the overlying organic-mineral A2B and mineral B1 horizons. This process is explained by fixing of HMs ions by illuvial colloids of the lower soil horizons. The specificity of the accumulative capacity of the soil genetic horizons is also manifested regarding other industrial air pollutants of the urban environment.

![Figure 1. Migration of lead and cadmium through the soil profile in urban and background areas.](image)
Studies show that mobile forms of toxic elements can enter from polluted soils into the root systems of plants. Along with foliar contamination of trees, soil absorption of pollutants is important in urban forests. Considering the obtained results indicating the high migration activity of toxicants in the soil profile system their significant receipt in the assimilating organs of plants from all horizons of soils could be assumed. Thus, the rather strong links between the content of the priority toxicants, sulfur, and chlorine in the pine needles and soil horizons were found (table 2).

Table 2. Correlation coefficients between the content of sulfur, chlorine in soil horizons and pine needles in urban forests ($P = 0.05$, $n = 42$).

| Soil horizon index | Irkutsk | Angarsk | Usolye-Sibirsкоye |
|--------------------|---------|---------|------------------|
| AO                 | 0.86 / 0.88$^a$ | 0.82 / 0.94 | 0.79 / 0.92 |
| A1                 | 0.82 / 0.86 | 0.76 / 0.88 | 0.74 / 0.87 |
| A2                 | 0.58 / 0.62 | 0.66 / 0.78 | 0.60 / 0.74 |
| A2B                | 0.42 / 0.58 | 0.58 / 0.65 | 0.49 / 0.67 |
| B1                 | 0.50 / 0.56 | 0.52 / 0.60 | 0.46 / 0.62 |
| B2                 | 0.75 / 0.87 | 0.72 / 0.79 | 0.71 / 0.88 |
| BC                 | 0.65 / 0.69 | 0.69 / 0.63 | 0.65 / 0.72 |
| C                  | 0.55 / 0.68 | 0.58 / 0.59 | 0.52 / 0.68 |

$^a$ The first number in each column is the Pearson correlation coefficient ($r$) for sulfur, the second number is the correlation coefficient for chlorine.

The results indicated that the total content of toxicants (the sum of foliar and soil input) in the assimilating organs of trees of urban forests of Irkutsk in the needles of pine and larch and birch leaves exceeds the background values of sulfur by 1.5-3 times, fluorine 3-6 times, chlorine 2-7 times, lead 8-20 times, cadmium 5-8 times, mercury 1.5-4 times, copper 3-8 times, zinc 2-7 times, iron 2-8 times, arsenic 2-4 times. In addition, trees accumulate many organic pollutants. Thus, it has been shown that pine needles accumulate PAHs – one of the most toxic technogenic pollutants appearing in the emissions of internal combustion engines.

It was determined that exceeding the background level of PAHs in pine needles of the second year of life is from 1.5 to 18 times, in larch needles – from 5 to 17 times. Compounds with 3-4 aromatic rings (phenanthrene, anthracene, fluoranthene, pyrene, benz[a]anthracene, chrysene) dominate in terms of percentage and ratio. In the city of Angarsk, the content of pollutant elements in the needles and leaves of trees is also high. In urban forests, sulfur content exceeds background concentrations 2-3 times, lead 7-15 times, cadmium 4-7 times, mercury 1.5-2 times, copper 2-7 times, zinc 2-6 times, iron 2-5 times, arsenic 1.5-3 times. In the city of Usolye-Sibirsкоye tree pollution is caused by the close location of the industrial zone and disturbance of the soil cover in large areas adjacent to the urban forests. Pine and larch needles and birch leaves contain 1.3-2.5 times more sulfur than background levels, 2-9 times more chlorine, 4-12 times more lead, 3-7 times more cadmium, 1.5-9 times more mercury, and 2-5 times more copper.

It was found that the lowest level of urban forest pollution is observed on the outskirts of cities not subjected to the transfer of industrial and vehicular emissions. In the soils of these areas the lowest coefficients of concentration (CC) HMs were recorded: Pb$_{0.5}$ > Cu$_{4.2}$ > Zn$_{3.2}$ > Cd$_{2.3}$; sulfur and chlorine exceed the background level to 5.5 times. The regulating ecosystem service of trees is to purify atmospheric air from technogenic emissions. In these areas, the following sequence of CC HMs in the assimilative organs of plants was found: Pb$_{4.5}$ > Cu$_{2.8}$ > Zn$_{2.1}$ > Cd$_{1.7}$. Elevated soil contamination is found in most forested territories within urban areas. For these territories, average CC HMs values in soils are much higher and represented as follows: Pb$_{18.8}$ > Cu$_{10.6}$ > Zn$_{8.2}$ > Cd$_{5.1}$; sulfur and chlorine concentrations exceeded 10.2-14.6 times. Regulating service of soils consists in strengthening the cation-exchange capacity of PPC to ions of polluting compounds. Also, the regulating service of soils is confirmed by data on adsorption and chemical fixation of HMs by humus compounds. These processes result in immobilization of toxicants in the substances with low rates of migration through the soil profile, and their entry into the root systems of plants is also reduced.
In the needles and leaves of plants of these territories the content of HMs according to the calculations of CC is: Pb 7.2 > Cu 6.3 > Zn 5.1 > Cd 4.7. At a high level of pollution in urban forests, the regulatory service of soils consists in the immobilization of toxic ions from the soil solution into the complex compounds in an alkaline condition, which significantly reduces their availability to plants. The average content of HMs in the needles and leaves of woody plants according to the calculations of CC is Pb 12.2 > Cu8.3 > Zn7.2 > Cd6.1. The accumulation of pollutants in the assimilative organs of plants is also evidence of air pollution in cities, where the values of Maximum Permissible Concentrations of pollutants are significantly exceeded [6].

4. Conclusion

The study of redistribution of flows of technogenic pollutants in urban forests revealed the most important ecosystem service of soil cover – the ability to accumulate and detoxify pollutants. Also, the important ecosystem service of trees namely the ability to clean atmospheric air by accumulating toxicants in the needles and leaves was evidenced. All the presented features of soils and plants are characterized by a high level of mutual correlations, which reflects their ability to indicate the adverse anthropogenic impact. The biogeochemical processes like changes in acid-alkaline conditions in the forest ecosystem, disturbance of the ratio of biogenic elements in soils and plants, migration and accumulation of pollutant elements in the soil profile, needles, and leaves of trees, are characterized by interdependent changes in the bilateral plant-soil system. In general, the scientific results obtained provide information on ecosystem services/functions of soil and trees, considered as the important components providing purifying and sustainable functioning of semi-natural ecosystems in the urban environment.

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