



Assessment of the level of pollution based on soil and *Tilia × europaea* leaves

Edina Simon^{1,2} · Haziq Bin Ismail¹ · Bianka Sipos^{1,2} · Vanda Éva Abriha-Molnár^{1,2} · Dávid Abriha³ · Dávid Tőzsér^{1,4} · Zsófi Sajtos⁵ · Rafael Boluda⁶ · Luis Roca-Pérez⁶

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Abstract

Anthropic activities related to urbanization release pollutants, including potentially toxic elements which can deposit in soils, water, and vegetation. Thus, soil and plant leaves are widely used as ecological indicators to assess the effect of urbanization. This study aimed to evaluate the impact of urbanization based on the elemental concentration of soil and leaves of *Tilia × europaea* from urban, suburban, and rural areas along an urbanization gradient in Debrecen, Hungary. The rural area was situated near Nagyerdő, a protected area for nature conservation. The suburban area was intermediate between the rural and urban areas regarding urban density. The urban study area was at the centre of the urban community to maximize the observable effect of urban pollution. Using inductively coupled plasma optical emission spectrometry (ICP-OES) technique, the concentration of Ba, Cd, Co, Cr, Cu, Ni, Pb, Sr, and Zn was analysed and based on them, bioaccumulation factor (BAF) was calculated. The highest concentration of all elements was found in soil samples from urban areas, with an increasing tendency along the urbanization gradient. A significant difference was found along the urbanization gradient only for Cr based on the plant leaves. *T. × europaea* showed bioaccumulation capacity for Cr and Sr. Our results suggest that urbanization has a remarkable effect on the elemental concentration of soil, which is a perfect ecological indicator. At the same time, we concluded that the *T. × europaea* was not sufficiently sensitive to detect the effect of urbanization.

Keywords Soil and Air Pollution · Anthropogenic activities · Ecological indicators · Urbanization · Metals

Introduction

Soil and air pollution by metals is one of the most critical environmental problems worldwide (Yuan et al. 2021). Anthropogenic activities cause contamination in soils by certain elements such as Sr, As, Cd, Cr, Cu, Ni, Pb and Zn (Ramos-Miras et al. 2023). Among anthropogenic activities, urbanization is one of the primary sources of polluted soil with heavy metals because of increased road traffic and industrial activities (Yuan et al. 2021). Urbanization has been progressing rapidly between 2000 and 2030, and the urban population is anticipated to grow an average of 2.3% per year in the developing world (Egidi et al. 2020). The effects of urbanization on environmental pollution are different in countries and regions with various degrees of development (Egidi et al. 2020). Earlier studies reported that urbanization directly and indirectly affects soil as an essential resource. Accumulation of metals can modify the quality of soil and agricultural products

✉ Edina Simon
edina.simon@gmail.com

¹ Department of Ecology, University of Debrecen, Egyetem tér 1, Debrecen H-4032, Hungary

² HUN-REN–UD Anthropocene Ecology Research Group, University of Debrecen, Egyetem tér 1, Debrecen H-4032, Hungary

³ Department of Physical Geography and Geoinformatics, University of Debrecen, Egyetem tér 1, Debrecen H-4032, Hungary

⁴ Circular Economy Analysis Center, Hungarian University of Agriculture and Life Sciences, Páter Károly u. 1, Gödöllő H-2100, Hungary

⁵ Environmental Analytical Research Group, Department of Inorganic and Analytical Chemistry, University of Debrecen, Egyetem tér 1, Debrecen H-4032, Hungary

⁶ Facultat de Farmàcia, Departamento de Biología Vegetal, Universitat de València, Valencia, Spain

and, thus, they have adverse effects on humans (Ihenetu et al. 2024). Knowledge of maximum threshold concentrations in different media such as in soil, air, water and vegetables, as reported by WHO/FAO or EPA, is therefore very important for environmental risk assessment (Feyisa et al. 2025). Plant leaves play an essential role in urban areas because they can accumulate air pollutants in high concentrations; air pollutant particles can also be deposited in the leaves of plants due to their stomatal openings and waxy cuticles (Molnár et al. 2020; Simon et al. 2021). The genus *Tilia* is generally used as biomonitors of trace elements to assess the effect of urbanization and industrialization on terrestrial environments (Zeb et al. 2022; Andrianjara et al. 2024).

The bioaccumulation factor can determine the capacity of plants to transfer and accumulate metals or other compounds from soils to the aerial part of the plant (Hosseini et al. 2022). This index has been applied to soil-plant system in mining areas (Roca-Perez et al. 2023) near road networks (Hosseini et al. 2022), rural and urban areas (Pietrelli et al. 2022); in urban areas with species of the genus *Tilia* (Mitrović et al. 2021, 2023).

Therefore, *Tilia × europaea* was chosen for our study, a typically ornamental tree in European countries (Țenche-Constantinescu et al. 2015). Our study aimed to investigate elemental concentration in soil and *Tilia × europaea* plant leaves along an urbanization gradient in Debrecen to assess the level of pollution. Hungary. Our hypotheses are as follows: (i) there are significant differences in pollutant levels along the urbanization gradient (urban, suburban, and rural area), (ii) the highest metal concentration in soil and leaves is in the urban area, while the lowest concentration is in the rural area, (iii) significant correlation is found between the soil and leaves metal concentrations based on the bioaccumulation factor.

Materials and methods

Study area

Debrecen is the second largest city in Hungary, with a population of approximately 200,000 as of 2019. The area allocated for the city is 461 km², which results in a population density of 436/km². Along an urbanization gradient in Debrecen city, three different studied areas were chosen (Fig. 1). The rural area was situated near Nagyerdő, a protected area for nature conservation (47°33'40.9"N 21°37'04.7"E). It was a sparsely built-up area located north of the university campus. The suburban area was intermediate between the rural and urban areas regarding urban density. It was near the northern border of the town, adjacent to a residential district and the Nagyerdő forest (47°32'55.8"N 21°38'30.9"E). The urban study area was at the center of the urban community to maximize the observable effect of urban pollution, and it was surrounded by housing and offices at the center of Debrecen (47°31'43.6"N 21°37'57.3"E).

Along urbanization gradient representing rural, suburban, and urban area 3 individuals of *Tilia × europaea* was randomly chose in the same locations because this species was the most dominant in the studied From each individual 15 leaves were collected at a 1.5 m height. Trees showing any form of disease were avoided, as they could alter the investigation results. Additionally, soil samples ($N=15$) were collected within a 1-meter radius of the tree base to calculate the bioaccumulation factor. At each sampling area, five soil samples were collected. All samples were collected from 0 to 20 cm depth with a small hand spade. Samples were placed into poly bags and kept at −21 °C in the refrigerator (Simon et al. 2014, 2016).



Fig. 1 Studied areas for Debrecen from rural, suburban and urban areas along an urbanization gradient. Notations: The red circle indicates the study areas

Sample preparation

The laboratory process started with a surface wash to remove any surface pollutants from the leaf samples. After washing, the leaf samples were dried in an oven set at 70 °C for 90 min. Soil samples were dried at room temperature, and after that stones, plant roots, and residues were removed with plastic tweezers. Samples were sieved in a 2-mm plastic sieve. Soil and leaf samples were then processed according to Bibi et al. (2023a, b) (Fig. 2). Inductively coupled plasma optical emission spectrometry (ICP-OES 5110 Agilent Technologies) was used for the determination of Ba, Cd, Co, Cr, Cu, Ni, Pb, Sr and Zn concentrations. For quality control 3 replicates, 10 blank samples and Peach leaves (1547) and soil (SQC001) CRM were used, and the recoveries were within 10% of the certified values for the elements (Simon et al. 2013, 2014, 2016, 2021). A six-point calibration procedure with multi-element calibration solution (Merk ICP multi-element standard solution IV) was used. The detection limit of elements was the following: Ba (0.01 µg/L), Cd (0.1 µg L⁻¹), Co (0.6 µg L⁻¹), Cr (0.2 µg L⁻¹), Cu (0.2 µg L⁻¹), Ni (0.9 µg L⁻¹), Pb (2.2 µg L⁻¹), Sr (0.01 µg L⁻¹) and Zn (0.2 µg L⁻¹). When the concentration was below the detection limit, the half of the detection limit concentration was used for the statistical analysis (Wood et al. 2011).

Bioaccumulation factor (BAF)

To study the accumulation of elements in leaves of *T. × europaea*, bioaccumulation factor (BAF) was used. BAF is the ratio of elemental concentration in leaves (C_{plant}) and elemental concentration in soil (C_{soil}) (Van Gestel et al. 2011):

$$BAF = C_{\text{plant}}/C_{\text{soil}}$$

Statistical analyses

Statistical analyses were conducted with SPSS Statistics 20 (IBM) statistical software. The normality of the distribution was tested using the Shapiro–Wilk test. The homogeneity

of variances was tested using Levene's test. The differences among samples were tested with the analysis of variance (ANOVA) for each variable. Tukey's test was performed for pairwise comparison between the groups. We used the canonical discriminant analysis (CDA) because this analysis is a multivariate method for classification, aimed at maximizing group separation through linear combinations of variables based on studies localities. CDA can identify those variables that most efficiently discriminated the study area as the dependent variable based on elemental concentration of soil and leaf (De Sá 2007). The correlation between the elemental concentration of soil and leaves was analysed with the Pearson correlation coefficient (Zar 1996).

Results

There was a clear separation among the studied areas based on the elemental concentration of soil according to the CDA (Fig. 3). The canonical variables were significant ($p < 0.001$) in the first and second discriminant functions. The percentage of variance was 87.0 in the first, while 13.0 was in the second discriminant function. There was significantly higher elemental soil concentration in the urban area than in the rural area (Table 1). The order of contents of potentially toxic elements was: Zn > Ni > Ba > Pb = Sr > Cu > Cr > Co > Cd in rural soil, Ba > Zn > Ni > Sr > Pb > Cu > Cr > Co > Cd in suburban soils, and Ba > Zn > Ni > Sr > Cr > Pb > Cu > Co > Cd in urban.

Similar to the soil, separation was found among the studied areas based on the elemental concentration of *Tilia × europaea* according to the CDA (Fig. 4). The canonical variables were not significant ($p > 0.05$) in the first and second discriminant functions. The percentage of variance was 99.2 in the first, while 0.8 was in the second discriminant function. In rural areas, higher concentrations of Ba, Cu, Ni and Zn were observed in the leaves of *T. × europaea*; however, only Cr in rural and suburban areas showed significantly higher values than in urban areas (Table 2). The Cd, Co, Cr, and Pb concentrations were below the detection limit.

In all studied areas, we did not find any significant correlation between the elemental concentration of soil and leaves

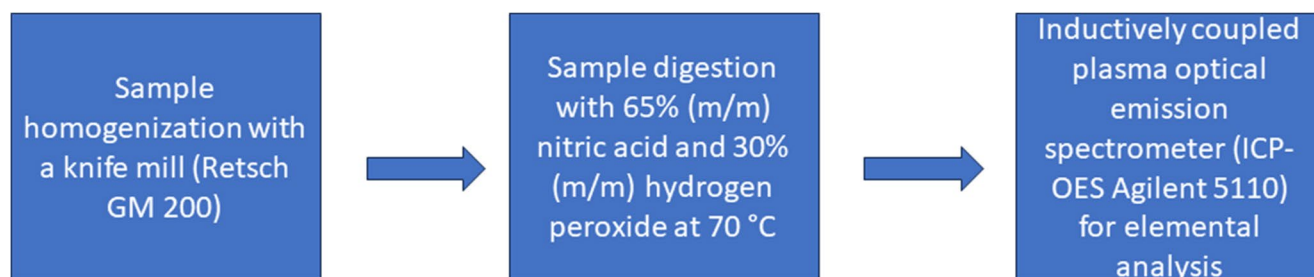


Fig. 2 Sample preparations and elemental analysis for soil and leaves

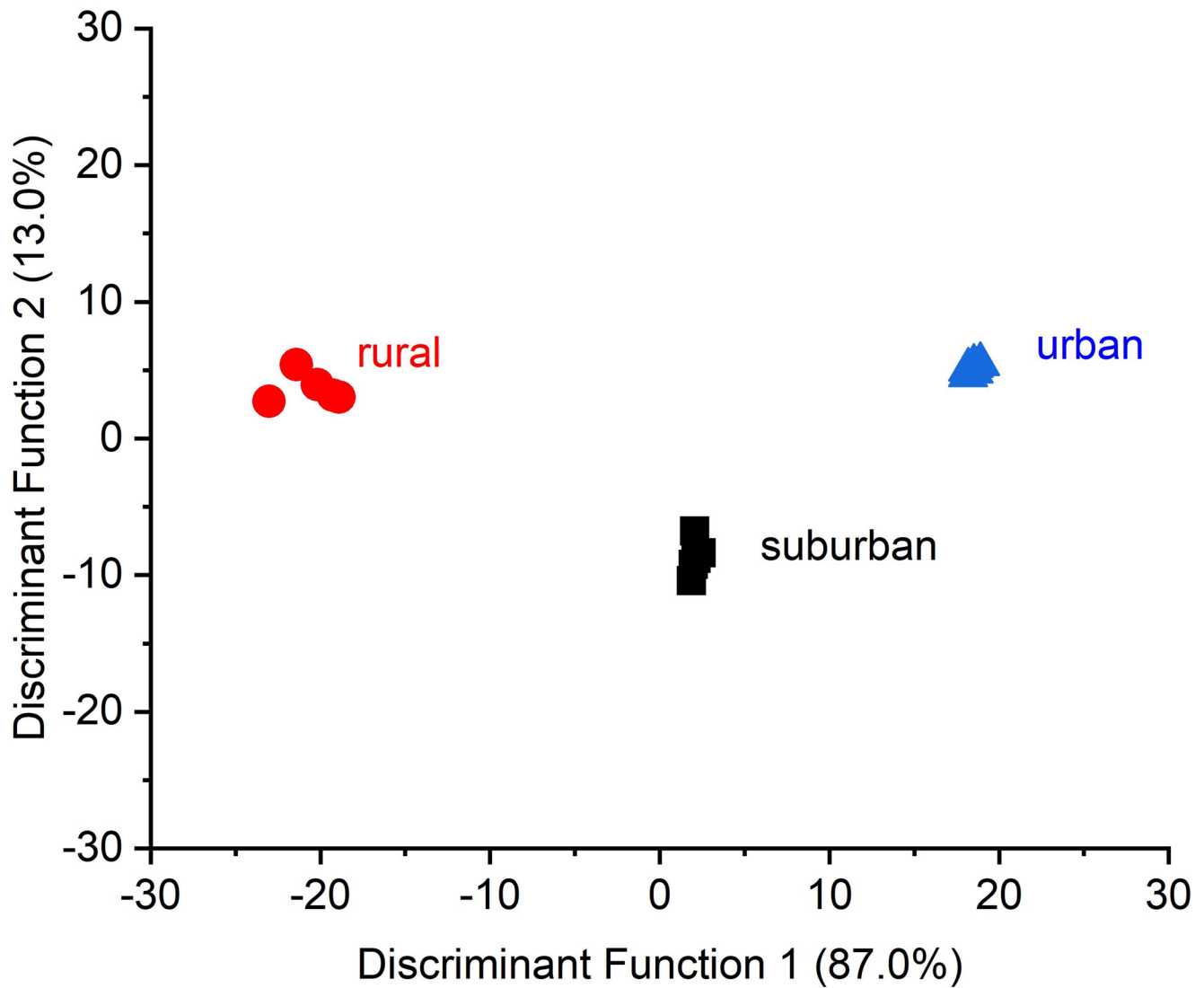


Fig. 3 Scatter plot of canonical discriminant analysis (CDA) based on the elemental concentration of soil among the studied areas

Table 1 Summary statistics of elemental concentration of soil (mg kg^{-1} , mean $\pm$ SE)

Elements	Urbanization gradient			F	p
	rural	suburban	urban		
Ba	14.2 $\pm$ 1.0	67.7 $\pm$ 16.2	97.1 $\pm$ 11.0	13.825	0.001
Cd	0.3 $\pm$ 0.1	0.8 $\pm$ 0.1	1.8 $\pm$ 0.2	55.623	<0.001
Co	1.3 $\pm$ 0.1	2.6 $\pm$ 0.1	6.4 $\pm$ 0.4	96.986	<0.001
Cr	3.1 $\pm$ 0.3	7.3 $\pm$ 0.7	28.0 $\pm$ 6.3	13.081	0.001
Cu	3.7 $\pm$ 0.3	13.8 $\pm$ 2.5	22.3 $\pm$ 2.7	19.031	<0.001
Ni	18.9 $\pm$ 4.5	28.6 $\pm$ 1.5	39.8 $\pm$ 4.2	8.229	0.006
Pb	5.5 $\pm$ 2.3	20.9 $\pm$ 5.5	24.5 $\pm$ 3.9	5.971	0.016
Sr	5.5 $\pm$ 0.7	25.2 $\pm$ 6.8	32.6 $\pm$ 4.3	8.975	0.004
Zn	19.1 $\pm$ 1.2	61.5 $\pm$ 8.1	83.9 $\pm$ 13.7	12.735	0.001

(rural: $r=0.429$, $p=0.397$; suburban: $r=0.486$, $p=0.329$; urban: $r=0.371$, $p=0.468$). The BAF values were higher than 1 for Cu in the rural and for Sr in all studied areas (Figs. 5 and 6). The BAF values of Cu and Sr indicated that trees could accumulate these elements from soil indirectly or directly.

Discussion

As hypothesized, we found differences based on the elemental concentration of soil along the urbanization gradient; significantly higher concentrations were found

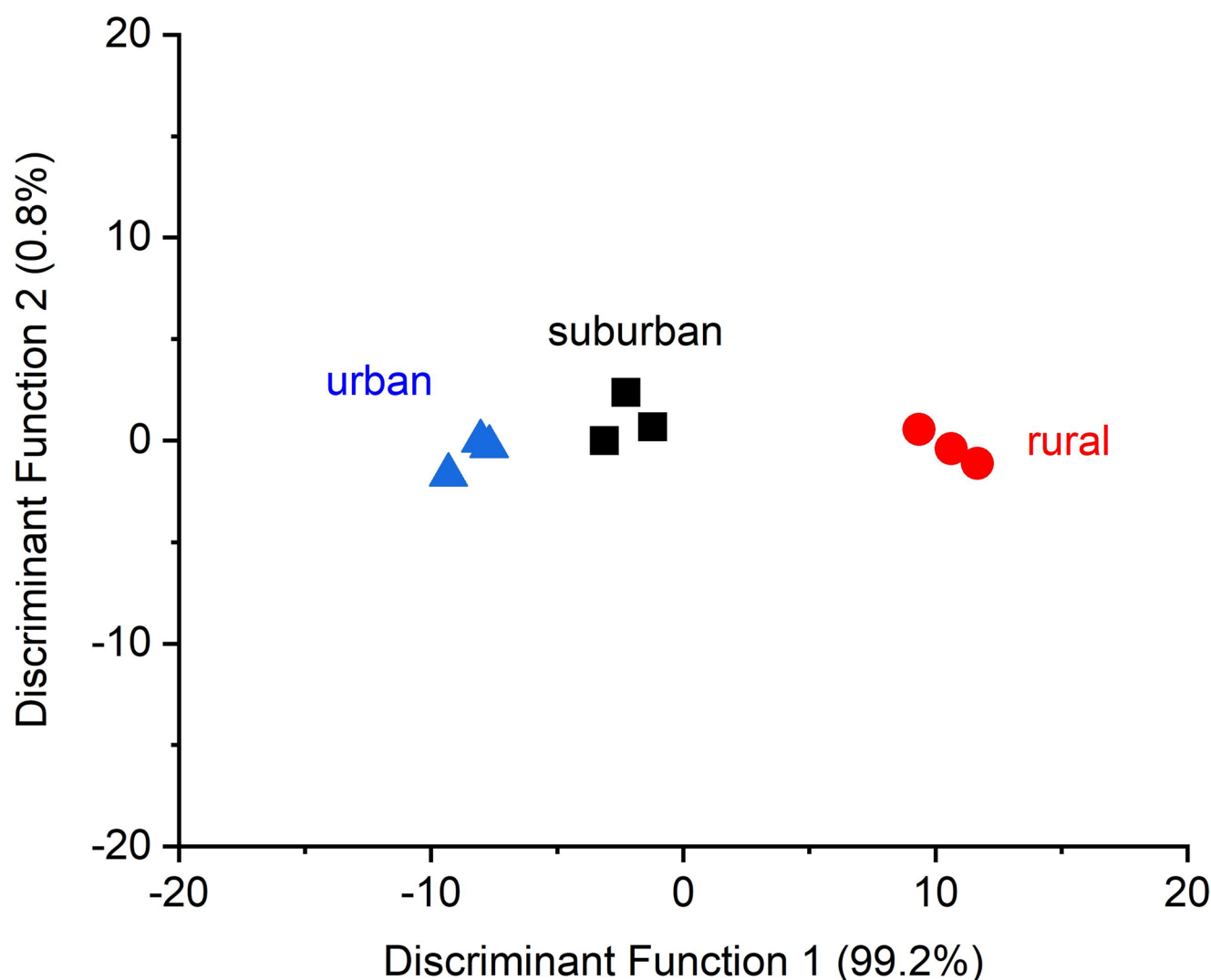


Fig. 4 Scatter plot of canonical discriminant analysis (CDA) based on the elemental concentration of *Tilia × europaea* leaves among the studied areas

Table 2 Summary statistics of elemental concentration of *Tilia × europaea* leaves (mg kg^{-1} , mean $\pm$ SE)

Elements	Urbanization gradient			F	p
	rural	suburban	urban		
Ba	12.9 $\pm$ 4.2	8.1 $\pm$ 0.6	5.6 $\pm$ 2.5	1.663	0.266
Cr	0.3 $\pm$ 0.1	0.3 $\pm$ 0.1	0.2 $\pm$ 0.1	7.426	0.024
Cu	7.7 $\pm$ 0.9	6.2 $\pm$ 0.6	4.9 $\pm$ 1.1	2.709	0.145
Ni	1.5 $\pm$ 0.5	0.6 $\pm$ 0.1	0.5 $\pm$ 0.1	3.844	0.084
Sr	28.8 $\pm$ 4.6	41.9 $\pm$ 1.7	32.1 $\pm$ 5.8	2.456	0.166
Zn	18.5 $\pm$ 1.4	14.4 $\pm$ 0.4	17.5 $\pm$ 0.9	4.85	0.056

in urban areas than in rural ones. Thus, it was indicated that urbanization had a remarkable effect on the metal concentration of soil. Contrary to our hypothesis, the elemental concentration of *T. × europaea* did not differ significantly along the urbanization gradient; only Cr,

a typically anthropogenic element, showed significant variation. At the same time, our results also indicated that *T. × europaea* was not sensitive enough to reveal the effect of urbanization.

Similar to our results, Yuan et al. (2021) also demonstrated the effect of urbanization on the soil elemental concentration change, and they found the highest pollution level and potential ecological risk of surface soil polluted with metals in urban soil. Urbanization may cause an increasing risk of soil pollutants through waste disposal and acid deposition derived from urban air pollution (Hasan et al. 2020). Tešić et al. (2022) also found significantly higher Zn, Cu, Cd, Cr, and Ni in the soil of urban areas in Belgrade than in the rural. Simon et al. (2016) also reported that soil was a suitable bioindicator for monitoring the effects of urbanization and anthropogenic activities on terrestrial ecosystems because

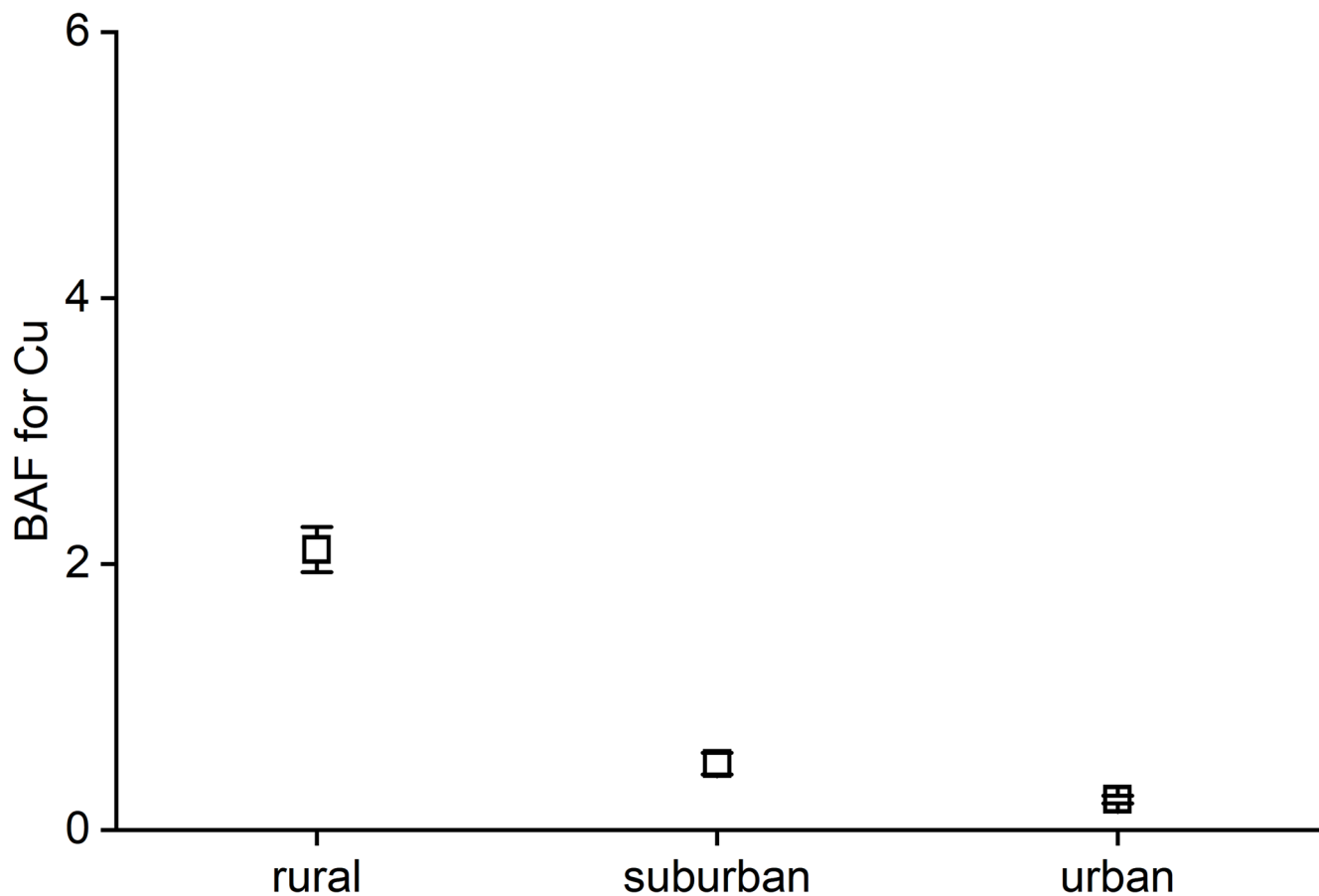


Fig. 5 Value of bioaccumulation factor (BAF) for Cu (mean $\pm$ SE) along the urbanization gradient

they found significant differences among areas based on the concentration of Ba, Cu, Mn, Sr, and Zn in soil. Simon et al. (2013) also confirmed that the elemental analysis of soil samples is one of the best ways to study the effects of urbanization. Bibi et al. (2023a) also showed higher concentrations of Cu, Pb, Sr, and Zn were in the urban and suburban areas than in the rural areas in Wien, Austria. In summary, as indicated by Wang et al. (2024), urbanization intensifies the impact on potential toxic elements in soil. In relation to the higher or lower content of elements in the soil, the elements with the highest concentration in urban area were Ba, Zn and Ni, these results are similar to those performed in urban soils of Vienna (Austria) where the concentrations of Ba and Zn were also among the highest of the elements analyzed (Simon et al. 2013).

Molnár et al. (2020) demonstrated that *T. × europaea* is sensitive to air pollutants based on the air pollution tolerance index (APTI). Serbula et al. (2013) showed that pine needles responded more intensively to pollution than *Tilia*. Serbula et al. (2013) also indicated, based on the bioaccumulation

and translocation index, that the high concentrations of Cu and Pb in aerial parts of pine and linden are mainly a consequence of airborne pollution, which may explain why there was no correlation between the elemental concentration of soil and leaves in our study. Similarly, to our finding, Țenche-Constantinescu et al. (2015) also demonstrated that *Tilia* sp. was very resistant to biotic and abiotic stress because they found a correlation only between traffic intensity and the concentration of Pb in leaves. The study of *Tilia* leaf showed a different capacity for accumulating potentially toxic elements in various locations by Mitrović et al. (2021) in urban areas with varying pollution levels. Jouraeva et al. (2002) studied the accumulation potential of PAHs and metals on the leaves of *Tilia × euchlora* and *Pyrus calleryana*, and they reported that leaves of *T. × euchlora* accumulated higher concentrations of air pollutants than *P. calleryana*. Aničić et al. (2011) studied the metal concentration in the *Aesculus hippocastanum* leaves and *Tilia* spp. Similar to our finding, they also demonstrated that *Tilia* spp. was not so sensitive to assessing Pb and Cu atmospheric

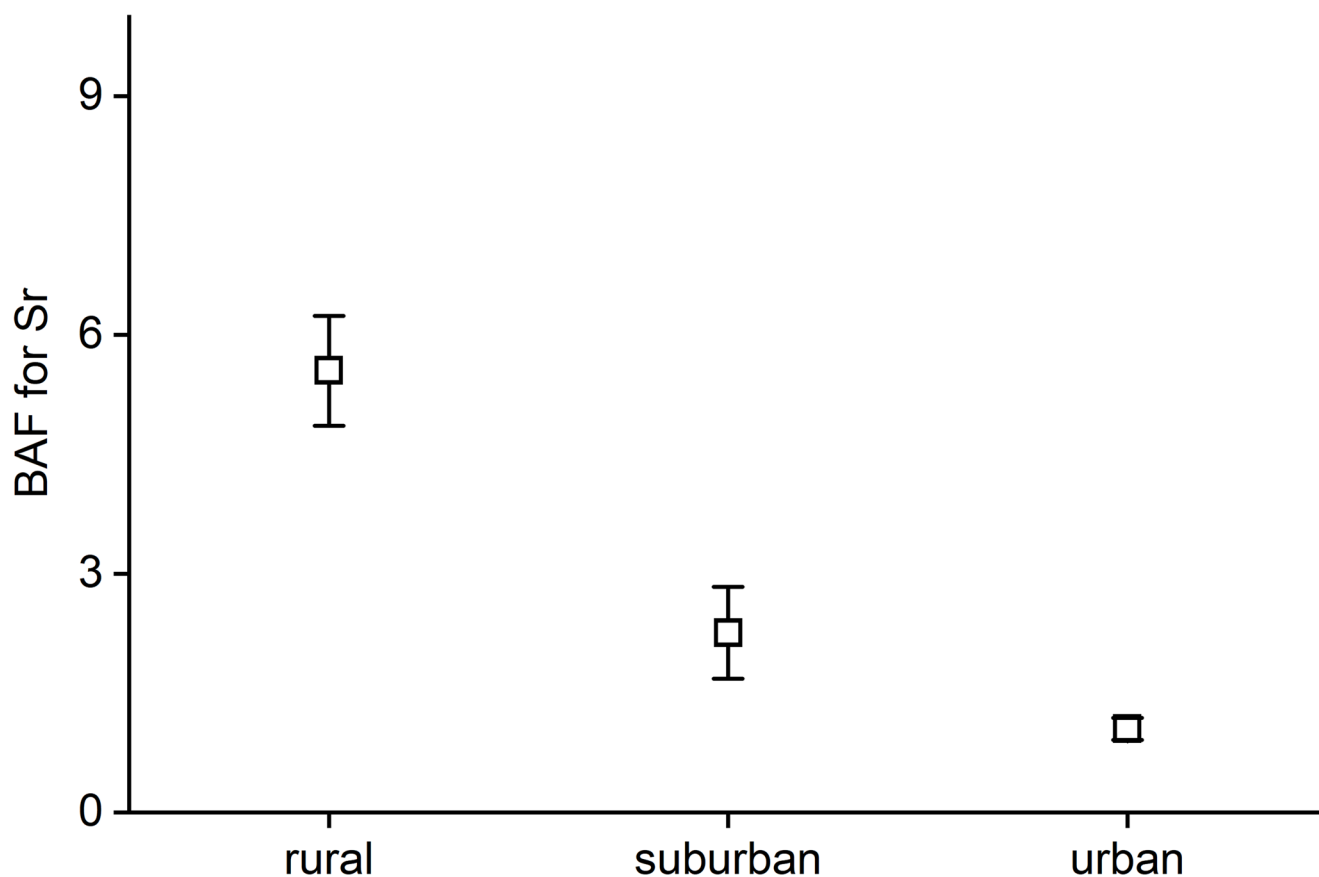


Fig. 6 Value of bioaccumulation factor (BAF) for Sr (mean ± SE) along the urbanization gradient

pollution (Aničić et al. 2019). Urošević et al. (2019) studied the metal concentration of different tree leaves, and they did not recommend *Tilia* sp. as a valuable bioindicator for air pollutants. In the case of plant species, the uptake of the elements may be accompanied by a species-specific pattern of physiological reaction (Drzewiecka et al. 2019). Although we did not detect any pathological changes of plants, Bierza and Bierza (2024) reported problems in chloroplast organization and plasmolysis of the leaf cells in *Tilia* leaves from polluted areas which cause chlorosis and necrosis.

In this study only Sr, in all areas, and Cu, only in rural areas, presented BAF values higher than 1, which indicates that *Tilia x europaea* has the capacity to accumulate these elements in leaves. However, studies with *Tilia tomentosa* (Mitrović et al. 2023), *Tilia argentea* (Greksa et al. 2019) and *Tillia* sp. (Alagić et al. 2013), conducted in different areas with anthropic influence, did not exceed BAF=1 for any elements. Mitrović et al. (2023) reported that there may be defense strategies at the root level of *Tilia cordata* which can decrease the metal toxicity. Plants can reduce the negative effects of heavy metal stress by their increasing antioxidative protection (Schützendübel and Polle 2002) which may be the reason of no correlation with metals in soil.

Conclusion

Our study demonstrated differences in the elemental concentration of soil along the urbanization gradient. Slight difference was found in elemental concentrations of *T. x europaea* only in the case of Cr along the urbanization gradient. Based on the accumulation rate, *T. x europaea* could accumulate the Cu and Sr from soil directly or indirectly. Thus, we concluded that urbanization has a remarkable effect on the elemental concentration of soil, which is a perfect ecological indicator. At the same time, we concluded that the *T. x europaea* was not sensitive enough to indicate the effect of urbanization.

Author contributions Edina Simon: Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Supervision. Haziq Bin Ismail: Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Bianka Sipos: Data curation, Formal analysis, Visualization, Writing – original draft. Vanda Éva Abriha-Molnár: Data curation, Formal analysis, Visualization, Writing – original draft. Dávid Abriha: Writing – review & editing. Dávid Tőzsér: Writing – review & editing. Zsófi Sajtos: Methodology. Rafael Boluda: Writing – review & editing. Luis Roca- Pérez: Writing – review & editing.

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Data availability Data will be made available on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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References

- Alagić SČ, Šerbula SS, Tošić SB, Pavlović AN, Petrović JV (2013) Bioaccumulation of arsenic and cadmium in birch and lime from the Bor Region. *Arch Environ Contam Toxicol* 65:671–682. <https://doi.org/10.1007/s00244-013-9948-7>
- Andrianjara I, Cabassa C, Lata JC, Hansart A, Raynaud X, Renard M, Nold F, Genet G, Planchais S (2024) Characterization of stress indicators in *Tilia cordata* Mill. as early and long-term stress markers for water availability and trace element contamination in urban environments. *Ecol Indic* 158:111296. <https://doi.org/10.1016/j.ecolind.2023.111296>
- Anićić M, Spasić T, Tomašević M, Rajšić S, Tasić M (2011) Trace elements accumulation and temporal trends in leaves of urban deciduous trees (*Aesculus hippocastanum* and *Tilia* spp). *Ecol Indic* 11:824–830. <https://doi.org/10.1016/j.ecolind.2010.10.009>
- Anićić Urošević M, Jovanović G, Stević N, Deljanin I, Nikolić M, Tomašević M, Samson R (2019) Leaves of common urban tree species (*Aesculus hippocastanum*, *Acer platanoides*, *Betula pendula* and *Tilia cordata*) as a measure of particle and particle-bound pollution: a 4-year study. *Air Qual Atmos Hlth* 12:1081–1090. <https://doi.org/10.1007/s11869-019-00724-6>
- Bibi D, Tözsér D, Sipos B, Molnár VÉ, Tóthmérész B, Simon E (2023b) Complex study of air pollution based on tree species in Vienna. *Air Qual Atmos Hlth* 17:417–424. <https://doi.org/10.1007/s11869-023-01452-8>
- Bibi D, Tözsér D, Sipos B, Tóthmérész B, Simon E (2023a) Heavy metal pollution of soil in Vienna, Austria. *Water Air Soil Pollut* 234:232. <https://doi.org/10.1007/s11270-023-06244-5>
- Bierza K, Bierza W (2024) The effect of industrial and urban dust pollution on the ecophysiology and leaf element concentration of *Tilia cordata* Mill. *Environ Sci Pollut Res* 31:58413–58429. <https://doi.org/10.1007/s11356-024-34999-9>
- De Sá JPM (2007) *Applied Statistics Using SPSS. STATISTICA. MATLAB and R*. 2nd ed.; Springer: Berlin/Heidelberg. Germany. ISBN 978-3-540-71971-7
- Drzewiecka K, Piechalak A, Goliński P, Gąsecka M, Magdziak Z, Szostek M, Budzyńska S, Niedzielski P, Mlecze M (2019) Differences of *Acer platanoides* L. and *Tilia cordata* Mill. Response patterns/survival strategies during cultivation in extremely polluted mining sludge A pot trial. *Chemosphere* 229:589–601. <https://doi.org/10.1016/j.chemosphere.2019.05.051>
- Egidi G, Salvati L, Vinci S (2020) The long way to Tipperary: city size and worldwide urban population trends, 1950–2030. *Sustain Cities Soc* 60:102148. <https://doi.org/10.1016/j.scs.2020.102148>
- Feyisa G, Mekassa B, Merga LB (2025) Human health risks of heavy metals contamination of a water-soil-vegetables farmland system in Toke Kutaye of West Shewa, Ethiopia. *Toxicology Reports* 14:102061. <https://doi.org/10.1016/j.toxrep.2025.102061>
- Greksa A, Ljevnaić-Mašić B, Grabić J, Benka P, Radonić V, Blagojević B, Sekulić M (2019) Potential of urban trees for mitigating heavy metal pollution in the city of Novi Sad, Serbia. *Environ Monit Assess* 191:636. <https://doi.org/10.1007/s10661-019-7791-7>
- Hasan SS, Zhen L, Miah Md G, Ahamed T, Samie A (2020) Impact of land use change on ecosystem services: A review. *Environ Dev* 34:100527. <https://doi.org/10.1016/j.envdev.2020.100527>
- Hosseini NS, Sobhanardakani S, Cheraghi M, Lorestani B, Merrikhpour H (2022) Expansive herbaceous species as bio-tools for elements detection in the vicinity of major roads of Hamedan Iran. *Int J Environ Sci Tech* 19:1611–1624
- Ihenetu SC, Li G, Mo Y, Jacques KJ (2024) Impacts of microplastics and urbanization on soil health: an urgent concern for sustainable development. *Green Anal Chem* 8:100095. <https://doi.org/10.1016/j.greeac.2024.100095>
- Jouraeva VA, Johnson DL, Hassett JP, Nowak DJ (2002) Differences in accumulation of PAHs and metals on the leaves of *Tilia×euchlora* and *Pyrus calleryana*. *Environ Poll* 120:331–338. [https://doi.org/10.1016/S0269-7491\(02\)00121-5](https://doi.org/10.1016/S0269-7491(02)00121-5)
- Mitrović M, Blanus T, Pavlović M, Pavlović D, Kostić O, Perović V, Jarić S, Pavlović P (2021) Using fractionation profile of potentially toxic elements in soils to investigate their accumulation in *Tilia* sp. leaves in urban areas with different pollution levels. *Sustainability* 13:9784. <https://doi.org/10.3390/su13179784>
- Mitrović M, Kostić O, Miletić Z, Marković M, Radulović N, Sekulić D, Jarić S, Pavlović P (2023) Bioaccumulation of potentially toxic elements in *Tilia tomentosa* Moench trees from urban parks and potential health risks from using leaves and flowers for medicinal purposes. *Forests* 14:2204. <https://doi.org/10.3390/f14112204>
- Molnár VÉ, Simon E, Ninsawat S, Tóthmérész B, Szabó S (2020) Pollution assessment based on element concentration of tree leaves and topsoil in Ayutthaya Province, Thailand. *Int J Environ Res Public Hlth* 17:5165
- Pietrelli L, Menegoni P, Papetti P (2022) Bioaccumulation of heavy metals by herbaceous species grown in urban and rural sites. *Water Air Soil Pollut* 233:141. <https://doi.org/10.1007/s11270-022-05577-x>
- Ramos-Miras J, Sanchez-Muros MJ, Renteria P et al (2023) Potentially toxic element bioaccumulation in consumed indoor shrimp farming associated with diet, water and sediment levels. *Environ Sci Pollut Res* 30:121794–121806. <https://doi.org/10.1007/s11356-023-30939-1>
- Roca-Perez L, Boluda R, Rodríguez-Martín JA, Ramos-Miras JJ, Tume P, Roca N, Bech J (2023) Potentially harmful elements pollute soil and vegetation around the Atrévada mine (Tarragona, NE Spain). *Environ Geochem Health* 45:9215–9230. <https://doi.org/10.1007/s10653-023-01591-y>
- Schützendübel A, Polle A (2002) Plant responses to abiotic stresses: heavy metal-induced oxidative stress and protection by mycorrhization. *J Exp Bot* 53:1351–1365
- Serbula SM, Kalinovic TS, Ilic AA, Kalinovic JV, Steharnik MM (2013) Assessment of airborne heavy metal pollution using *Pinus*

- spp.* and *Tilia spp.* Aerosol Air Qual Res 13:563–573. <https://doi.org/10.4209/aaqr.2012.06.0153>
- Simon E, Baranyai E, Braun M, Cserhádi C, Fábián I, Tóthmérész B (2014) Elemental concentrations in deposited dust on leaves along an urbanization gradient. Sci Total Environ 490:514–520. <https://doi.org/10.1016/j.scitotenv.2014.05.028>
- Simon E, Harangi S, Baranyai E, Braun M, Fábián I, Mizser S, Nagy L, Tóthmérész B (2016) Distribution of toxic elements between biotic and abiotic components of terrestrial ecosystem along an urbanization gradient: soil, leaf litter and ground beetles. Ecol Indic 60:258–264. <https://doi.org/10.1016/j.ecolind.2015.06.045>
- Simon E, Molnár VÉ, Lajtos D, Bibi D, Tóthmérész B, Szabó S (2021) Usefulness of tree species as urban health indicators. Plants 10:2797. <https://doi.org/10.3390/plants10122797>
- Simon E, Vidic A, Braun M, Fábián I, Tóthmérész B (2013) Trace element concentrations in soils along urbanization gradients in the city of Vienna, Austria. Environ Sci Pollut Res Int 20:917–924. <https://doi.org/10.1007/s11356-012-1091-x>
- Țenche-Constantinescu AM, Madoșă E, Chira D, Hernea C, Țenche-Constantinescu RV, Lalescu D, Borlea GF (2015) *Tilia spp.*-urban trees for future. Not Bot Horti Agrobot Cluj-Napoca 43:259–264. <https://doi.org/10.15835/nbha4319794>
- Van Gestel CAM, Ortiz MD, Borgman E, Verweij RA (2011) The bioaccumulation of Molybdenum in the earthworm *Eisenia andrei*: influence of soil properties and ageing. Chemosphere 82:1614–1619
- Wang S, Xiong Z, Han X, Wang L, Liang T (2024) Unveiling the spatial differentiation drivers of major soil element behavior along traffic network accessibility. Environ Pollut 342:123045. <https://doi.org/10.1016/j.envpol.2023.123045>
- Wood MD, Beresford NA, Coplestone D (2011) Limit of detection values in data analysis: Do they matter? Radioprotection 46:85–90
- Yuan X, Xue N, Han Z (2021) A meta-analysis of heavy metals pollution in farmland and urban soils in China over the past 20 years. J Environ Sci 101:217–226. <https://doi.org/10.1016/j.jes.2020.08.013>
- Zar IH (1996) Biostatistical Analysis. Prentice Hall, N.J
- Zeb J, Tahir H, Othman A, Habeebullah TM, Saygal A, Assaggaf HM, Ahmed OB, Sultan M, Mohiuddin S, Masood SS, Mirza AZ, Hajira B (2022) Geo-environmental approach to assess heavy metals around auto-body refinishing shops using biomonitors. Heliyon 8:e08809. <https://doi.org/10.1016/j.heliyon.2022.e08809>

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