Water Air Soil Pollut (2023) 234:232
https://doi.org/10.1007/s11270-023-06244-5

Heavy Metal Pollution of Soil in Vienna, Austria

Dina Bibi · Dávid Tőzsér · Bianka Sipos ·
Béla Tóthmérész · Edina Simon

Received: 23 November 2022 / Accepted: 17 March 2023

Abstract Along an urbanization gradient, we explored the soil metal pollution in Vienna, Austria. We analyzed the physical and chemical parameters of topsoil from urban, suburban, and rural areas. The following elements were quantified using ICP-OES technique: Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, S, Sr, and Zn. For heavy metals, *PI* (pollution index) values were used to assess the level of pollution. We found that the concentration of Cu, Pb, Sr, and Zn was higher in the urban and suburban area than in the rural area. The *PI* values indicated a moderate level of pollution by Cd ($1 \leq PI \leq 2$) along the urbanization gradient. We found a low level of pollution for Cr, Cu, Ni, Pb, and Zn ($PI \leq 1$) in studied areas. Our findings demonstrated the presence of anthropogenic contamination, and it is likely that traffic emission may be the major source of metal pollution in Vienna. Our findings also demonstrated that the elemental analysis of soil and the values of *PI* are adequate indicators of the level of pollution based on soil sample analysis in urban ecosystems.

Keywords Pollution index · Heavy metals · Urbanization; Physical-chemical parameters

1 Introduction

Soil heavy metal pollution is in the focus of research globally due to its toxicity, high level of bioaccumulation, and persistence (Zhang and Wang 2020). Heavy metals can accumulate significantly in soils and can leak into the groundwater, rivers, the atmosphere, and crops, posing a serious threat to humans and ecosystems (Jia et al., 2020). The sources of heavy metals may be both natural (lithogenic inputs) and anthropogenic origin (Li et al., 2019). Traffic emissions, industrial discharge, and municipal wastes are all anthropogenic sources of soil heavy metals in metropolitan settings. Mining, smelting, vehicle exhaust, and pesticide and fertilizer applications are the main sources of heavy metals in agricultural soils (Bhuiyan et al., 2021; Liu et al., 2021). Soil is a living, non-renewable resource and its ecological condition has an impact on food production and environmental efficiency. Soil quality is influenced by its inherent composition as well as changes brought about by anthropogenic use and management (De Paul Obade, 2019).

Among minor elements in soil, the estimated Cu concentration in the Earth crust is 55 mg kg^{-1}. In

---

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11270-023-06244-5.

D. Bibi · D. Tőzsér · B. Sipos · E. Simon
Department of Ecology, University of Debrecen, Egyetem square 1, Debrecen H-4032, Hungary

B. Sipos · E. Simon (✉)
ELKH-DE Anthropocene Ecology Research Group, Egyetem square 1, Debrecen H-4032, Hungary
e-mail: edina.simon@gmail.com

B. Tóthmérész
MTA-DE Biodiversity and Ecosystem Services Research Group, Egyetem square 1, Debrecen H-4032, Hungary

Austria, due to contamination Cu concentration is 332 mg kg^{-1} in local rivers (Pirkl and Kralik, 1988). The mean crust concentration for Zn is 70 mg kg^{-1} in the soil, while earlier studies demonstrated that the soil contamination threshold limit for Zn is 300 mg kg^{-1} in Austria (Sager, 2007). In the Earth crust, the Cd concentration is 0.2 mg kg^{-1}, and the threshold limit of Cd is 1.0 mg kg^{-1} for contamination (Sager 2007). The median concentration of Pb in Austrian soil is 6–33 mg kg^{-1}, while the average concentration of Pb in the Earth crust is 18 mg kg^{-1} (Sager 2007).

Pfleiderer et al. (2012) demonstrated local anomaly threshold limit for minor elements in the soil in Vienna. In local level, the following threshold concentrations were reported for minor elements: Cd: 0.8 mg kg^{-1}, Cu: 60 mg kg^{-1}, Cr: 45 mg kg^{-1}, Ni: 33 mg kg^{-1}, Pb: 100 mg kg^{-1}, and Zn: 200 mg kg^{-1} (Pfleiderer et al., 2012). These concentrations are not higher than the national guideline values for uncontaminated urban soils (Eikmann & Kloke, 2004). Zeiss (2021) also reported that the minor element concentrations were below guideline thresholds, but in some garden sites the Pb, Cd, and Zn concentration exceeded Austrian recommended limits. Pfleiderer et al. (2010) reported that the main source of minor elements (Cd, Cu, Pb, and Zn) was anthropogenic, especially traffic. Pfleiderer et al. (2010, 2012) also demonstrated that the concentrations of these elements increased in the past years. Thus, the concentrations of these elements in the soil in Vienna are therefore considered to be caused by anthropogenic contamination (Pfleiderer et al.2010, 2012).

Our study aimed at to investigate element concentrations, particularly metal concentrations in soil along an urbanization gradient in Vienna, Austria. Using the *PI* (pollution index), we explored the pollution levels based on macro- and microelement concentrations of soil samples. We hypothesized that pollutant levels increased dramatically along urbanization gradients (rural, suburban, and urban), and the pollution index is useful indicator of the ecological condition of the soil.

2 Material and Methods

2.1 Study Sites

Sampling areas were in and around the city of Vienna, Austria. The population size is two million people, with a density of around 4000 persons per square kilometer. The average annual temperature is 10–20 °C, and the rainfall is 1000–2000 mm. The main pollution source is traffic emission, which is created by multiple roads and highways with heavy traffic. The effect of urbanization on the soil was studied along an urbanization gradient. Along the gradient, three areas were selected: rural, suburban, and urban area. The rural area was Lainzer Tiergarten along the Lainz district (48°16′N, 16°25′E). The suburban area was Kurpark in the district of Oberlaa (48°14′N, 16°40′E). The urban area was Stadtpark (48°20′N, 16°38′E) near the city center (Fig. 1).

2.2 Sample Collection and Pre-treatment

Soil samples ($N = 45$) were collected along an urbanization gradient representing rural, suburban, and urban areas. At each sampling area, five soil samples were collected from five places. All samples were taken from a depth of 0–20 cm with a small hand spade. Samples were placed into poly bags and kept at −21 °C in the refrigerator.

2.3 Soil Parameter Analysis

To measure the pH and electrical conductivity of the soil samples, soil solutions were prepared from 5.00 ± 0.03 g soil samples and 30 ml distilled water. The pH and electrical conductivity were measured with a pH meter and electrical conductivity meter (Hach HQd Field Case No. 58258-00). To the determination of soil moisture content, 5.00 ± 0.01 g of soil samples were measured in beakers, followed by the drying of the samples for 24 h at 105 °C and by a re-weighting of all the samples (Simon et al., 2013, 2016; Valkó et al., 2013). Arany-type plasticity index was calculated by the following equation: $PA = 100 * V/M$, where “V” is the amount of deionized water used, while “M” is the weight of the soil. The measured soil water capacity can be assigned to the following soil texture categories: $PA < 25$: coarse sand, $PA = 25–30$: sand, $PA = 31–37$: sandy loam, $PA = 38–42$: loam, $PA = 43–50$: clay loam, $PA = 51–60$: clay, and $PA > 60$: heavy clay soils.

For organic matter content determination, the samples (0.100 ± 0.001 g) were cremated at 550 °C for 4 h in a muffle furnace (Nabertherm L5/C6, Germany). To determine the organic matter content of sediment, the loss on ignition method was used. The loss on ignition was calculated with the following equation:

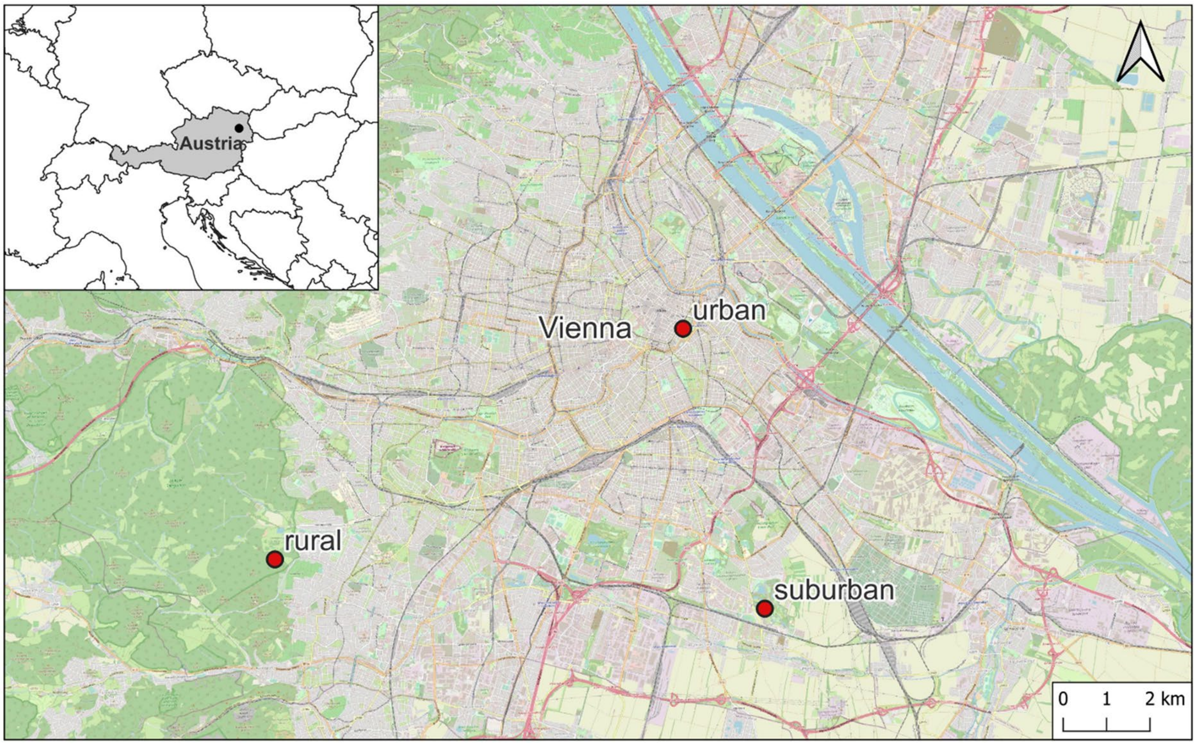

Fig. 1 Map of the studied areas in Vienna

$$\mathrm{LOI}_{550} = \left(\frac{\left(\mathrm{DW}_{105} - \mathrm{DW}_{550}\right)}{\mathrm{DW}_{105}} \right) * 100$$

where LOI_{550} was the percentage of loss on ignition at 550 °C, DW_{105} was the dry weight of samples at 105 °C, and DW_{550} was the weight of the sample at 550 °C (Bengtsson and Enell 1986; Heiri et al. 2001; Balogh et al. 2016). For the calcium-carbonate content analysis, three samples (0.2 g) were cremated at 950 °C for 2 h in a muffle furnace and the calcium carbonate content was calculated in triplicate based on the following equation:

$$\mathrm{LOI}_{950} = \left(\frac{\left(\mathrm{DW}_{550} - \mathrm{DW}_{950}\right)}{\mathrm{DW}_{105}} \right) * 100$$

where LOI_{950} was the percentage of loss on ignition at 950 °C, DW_{105} was the dry weight of samples at 105 °C, DW_{550} was the weight of the sample at 550 °C, and DW_{950} was the dry weight of samples at 950 °C (Bengtsson and Enell 1986; Heiri et al. 2001; Santisteban et al. 2004; Balogh et al. 2016).

Before the elemental analysis, soil samples were dried; stones, plant roots, and residues were removed with plastic tweezers. Samples were sieved in 2-mm plastic sieve. Then the samples were homogenized with a knife mill (Retsch GM 200) and stored in plastic tubes until pre-treatment. For elemental analysis, 0.1000 ± 0.0017 g of dried soil samples were digested using the 4.5 ml 65% (m/m) nitric acid and 0.5 ml 30% (m/m) hydrogen peroxide at 70 °C. Digested samples were diluted to 25 ml with deionized water. The following elements were analyzed with an inductively coupled plasma optical emission spectrometer (ICP-OES Agilent 5110): Al, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Na, Ni, P, Pb, S, Sr, and Zn. Soil (SQC001-30G) CRM was used, and the recoveries were within 10% of the certified values for the elements (Molnár et al., 2020; Simon et al., 2013, 2016).

2.4 Pollution Index

The *PI* was used to assess the pollution levels of urban soils, which was defined as a ratio of metal concentration in the soil and the geochemical concentration of metals (Faiz et al., 2009; Wei and Yang, 2010):

$$\mathrm{PI} = \frac{\mathrm{C_n}}{\mathrm{B_n}}$$

where C_n is the measured concentration and B_n is the background concentration. The following pollution categories were: $PI \leq 1$ low level, $1 \leq PI \leq 2$ moderate level, $2 \leq PI \leq 5$ high level, $PI \geq 5$ extremely high level of pollution (Faiz et al, 2009; Lu et al., 2007; Wei and Yang, 2010). The threshold concentration of Cd, Cr, Cu, Ni, Pb, and Zn was used based on earlier reported data by Pfleiderer et al. (2012).

2.5 Statistical Analysis

We assessed the separation between the rural, suburban, and urban area based on the physical and chemical parameters a using canonical discriminant analysis (CDA). The canonical discriminant analysis is a multivariate method which is used to analyze multivariate samples of the elemental concentrations. In the studied case, we analyzed and demonstrated whether the studied areas are different based on the basic physical and chemical parameters and elemental concentrations of soils. The differences among studied areas along the urbanization gradient based on physical and chemical parameters were assessed using variance analysis (ANOVA). The homogeneity of variance was studied using Levene's test (De Sá, 2007).

3 Results

3.1 Basic Physical and Chemical Parameters of Soil

Based on basic physical and chemical parameters of soil, canonical discriminant analysis (CDA) did not show strong separation among the studied areas. The first discriminant functions (CDA1) contributed to 64.6% of the total variance, while the second one (CDA2) contributed 35.4% of the total variance. Furthermore, the canonical correlation was 0.632 for CDA1 and 0.517 for CDA2.

There were significant differences for all the parameters, except the content of calcium carbonate and Arany-type plasticity index (Supplementary Information Table 1). We found higher pH levels in the suburban area than in the rural one. A significant difference was also found in the case of electrical conductivity; its level higher was higher in the suburban and urban areas than in the rural one. The lowest soil moisture and organic matter content were found in the urban area (Table 1).

3.2 Elemental Concentrations of Soil

CDA showed total separation based on the major and minor elements among the studied areas (Figs. 2 and 3). For major elements, a little overlap was found between the suburban and rural areas, while overlap was found between the suburban and rural areas based on the minor element concentration. The first discriminant functions (CDA1) contributed to 56.7% of the total variance, while the second one (CDA2) contributed to 43.3% of the total variance for major elements. In the case of minor elements, CDA1 contributed to 81.3% of the total variance, while CDA2 contributed 18.7% of the total variance. Furthermore, canonical correlation was 0.813 (major elements) and

Table 1 Basic physical and chemical parameters of soil along the urbanization gradient. Notations: different superscripts indicate significant differences ($p < 0.05$)

Parameters	Studied areas		
	Rural	Suburban	Urban
pH	7.1 ± 0.1^{a}	7.8 ± 0.1^{b}	7.5 ± 0.1^{ab}
Electrical conductivity, µS cm^{-2}	372 ± 91^{a}	931 ± 73^{b}	516 ± 67^{b}
Moisture content, %	35 ± 3^{ab}	28 ± 4^{a}	22 ± 3^{b}
Organic matter, %	12.7 ± 0.8^{ab}	12.3 ± 0.5^{a}	10.0 ± 2.6^{b}
Calcium carbonate, %	6.7 ± 2.3	7.8 ± 1.3	6.0 ± 1.5
Arany-type plasticity index	36 ± 4	43 ± 4	41 ± 3
Soil texture	Sandy loam	Clay loam	Loam

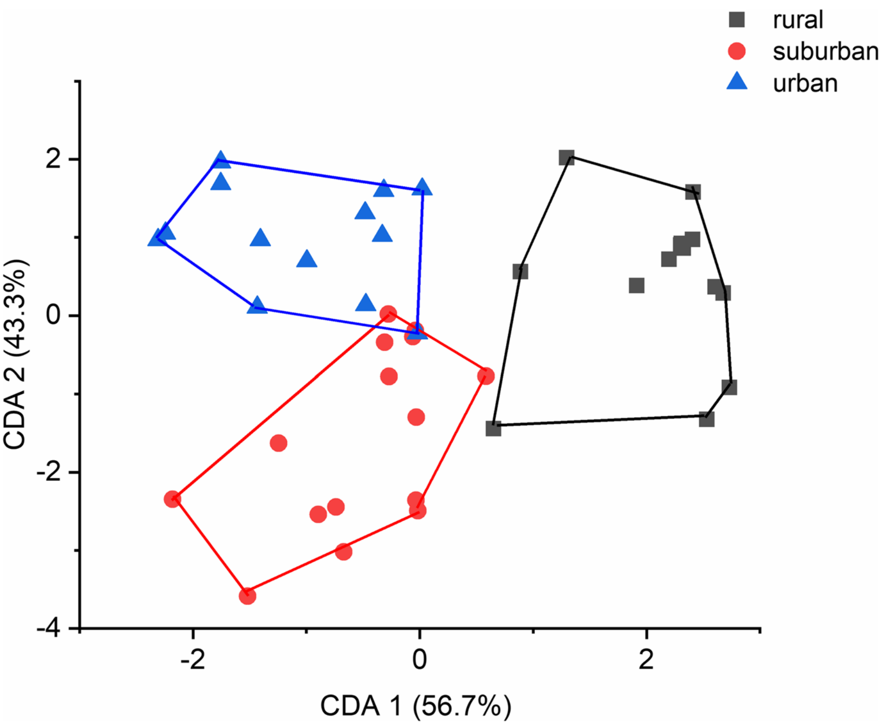

Fig. 2 CDA scatterplot based on the major element concentration of soil

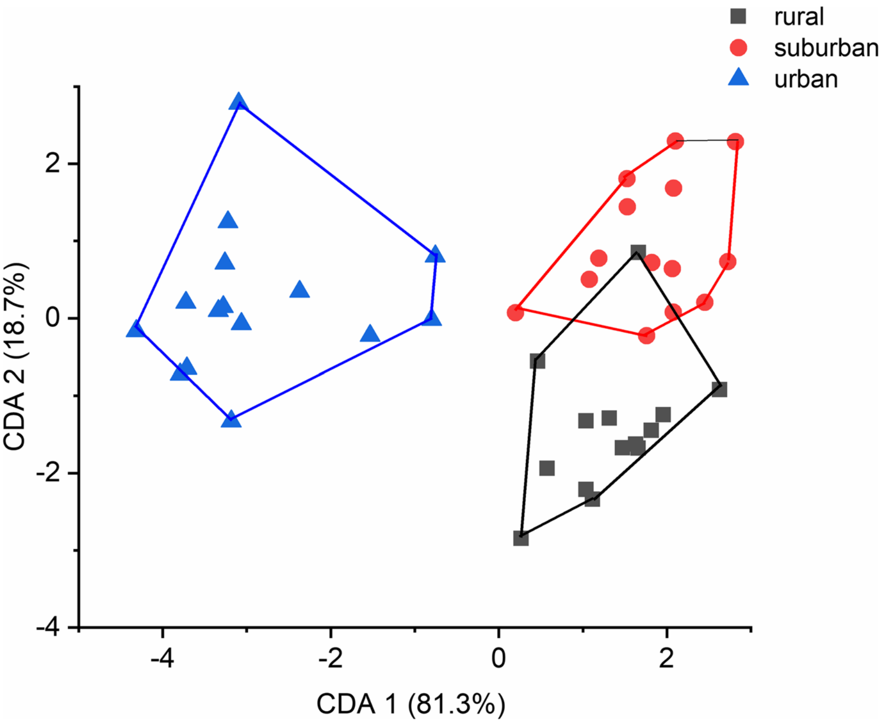

Fig. 3 CDA scatterplot based on the minor element concentration of soil

Table 2 The concentration of major and minor elements (mean ± SD, mg kg^{-1}) in the soil samples along the urbanization gradient. Notations: different legends indicate the significant differences ($p < 0.05$)

Elements	Studied areas		
	Rural	Suburban	Urban
Al	10,128 ± 850^{a}	9787 ± 465^{a}	7096 ± 264^{b}
B	23 ± 3	21 ± 2	28 ± 4
Ba	98 ± 9	103 ± 4	107 ± 4
Ca	35,379 ± 12,468	54,150 ± 4091	47,005 ± 3927
Cd	1.6 ± 0.1	1.5 ± 0.1	1.4 ± 0.1
Co	7.7 ± 0.7^{a}	7.4 ± 0.3^{a}	5.5 ± 0.2^{b}
Cr	19 ± 1	19 ± 1	15 ± 1
Cu	25 ± 3^{a}	39 ± 3^{b}	49 ± 2^{c}
Fe	18,285 ± 1464^{ab}	16,970 ± 713^{a}	14,098 ± 498^{b}
K	1689 ± 158^{a}	2422 ± 146^{b}	1830 ± 81^{ab}
Li	28 ± 2^{a}	29 ± 1^{a}	20 ± 1^{b}
Mg	10,827 ± 2805	12,695 ± 1256	12,121 ± 1146
Mn	623 ± 72	553 ± 22	464 ± 19
Na	210 ± 20	233 ± 17	252 ± 23
Ni	28 ± 2^{a}	26 ± 1^{a}	20 ± 1^{b}
P	459 ± 66^{a}	849 ± 50^{a}	1500 ± 196^{b}
Pb	25 ± 4^{a}	36 ± 3^{a}	79 ± 8^{b}
S	395 ± 30	406 ± 12	422 ± 12
Sr	51 ± 8^{a}	75 ± 3^{b}	69 ± 4^{ab}
Zn	78 ± 7^{a}	88 ± 3^{a}	130 ± 5^{b}

0.906 (minor elements) for CDA1 and 0.773 (major elements) and 0.717 (minor elements) for CDA2.

Along the urbanization gradient, there were significant differences for Al, Co, Cr, Cu, Fe, K, Li, Ni, P, Pb, Sr, and Zn. There were significantly higher Al, Co, Fe, Li, Ni, and P concentrations in the rural area than in the urban one (Table 2). Using the Tukey multiple comparison test, the differences were not significant between the suburban and rural areas for Co, Fe, Ni, and P. In the case of Cu, Pb, Sr, and Zn, the metal concentrations were significantly higher in the urban and suburban area than in the rural one ($p \leq 0.05$). We found that the Al, Co, Fe, and Li concentrations are significantly lower in the urban area than in the suburban and rural ones (Table 2).

3.3 Pollution Index

For Cd, the *PI* value is higher than 1 t along the urbanization gradient in all the areas, indicating a moderate level of pollution (Fig. 4). In the case of other elements (Cr, Cu, Ni, Pb, and Zn), low level of pollution was found (Fig. 5).

4 Discussion

During the research, we focused on the physical and chemical parameters of soil in Vienna, Austria, along an urbanization gradient. We used *PI* (pollution index) values for metals to assess the level of

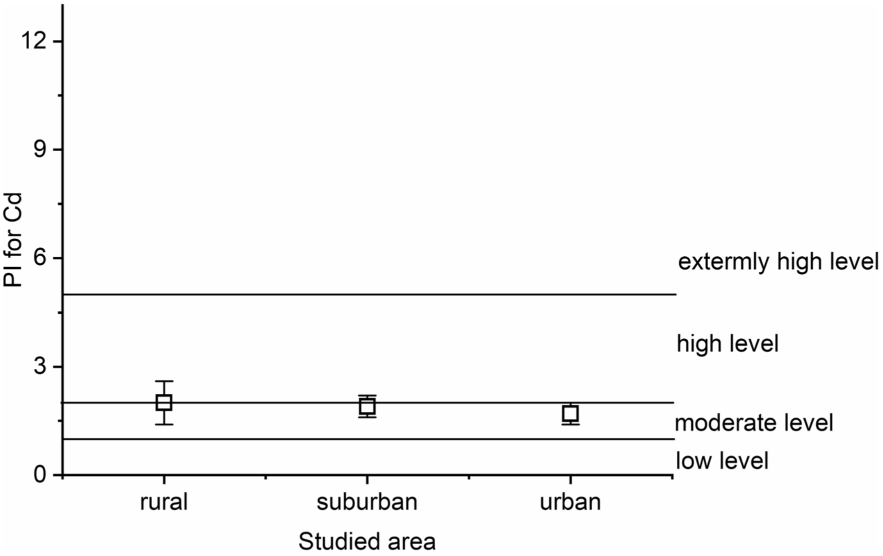

Fig. 4 Value of pollution index (*PI*) which indicated a moderate level of pollution for Cd along the urbanization gradient (mean ± SE)

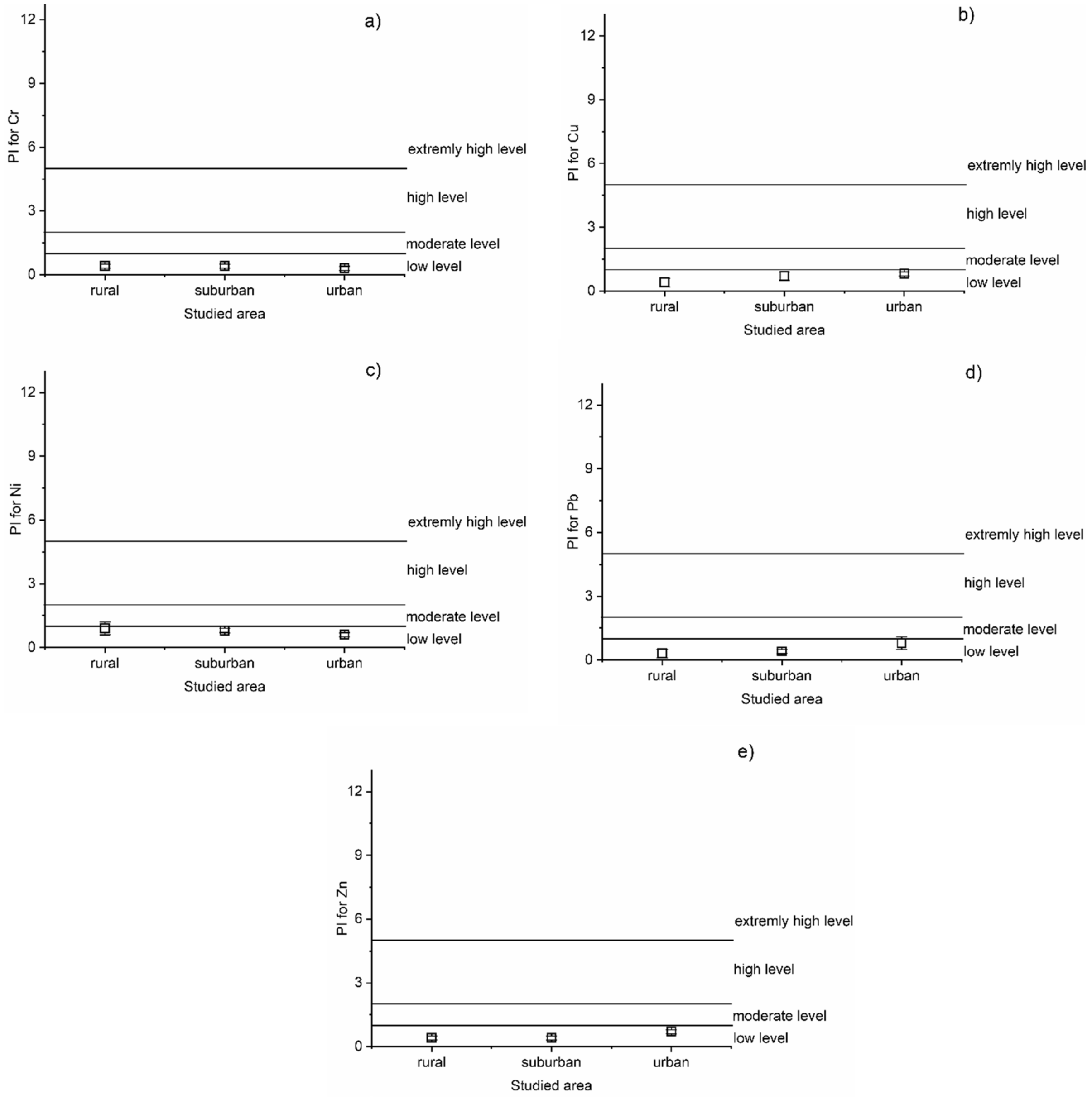

Fig. 5 Value of pollution index (*PI*) for Cr (**a**), Cu (**b**), Ni (**c**), Pb (**d**), and Zn (**e**) which indicated a low level of pollution along the urbanization gradient (mean ± SE)

pollution. We found extremely high level of Cd pollution in each area along the urbanization gradient. We also found a high level of pollution for Cu and Pb in the urban area, while Co, Ni, and Zn showed a moderate level of pollution in urban and rural areas. Similar to earlier studies, we demonstrated that soils are in a good condition in Vienna, but their ecological functionality is at risk due to the diffuse and local accumulation of pollutants (Gentile et al., 2009). Our results also showed that the values of *PI* are adequate indicators to assess the level of pollution based on soil sample analysis in urban ecosystems.

Blum et al. (2005) reported a moderate regional forest soil acidification in Lower Austria, Salzburg, Tyrol, and Vorarlberg. The high P, S, Ca, and Mg concentration and the value of pH in our study did not support it. We demonstrated higher Mn, Al, Fe, and K concentrations in the soil of the urban area, which indicated variations in soil among different parts of Vienna. The relationship between physiochemical parameters and the elemental concentration of soil indicated that the alkaline pH values resulted in higher Ca and Mg concentrations in the urban and suburban areas (Ogbodo, 2012). Soil organic matter is an essential component of soil quality; it has an important role in carbon sequestration, nutrient cycling, distribution of pesticides, and pollutants and water retention (Mehmood et al., 2021; Sündermann et al. 2015). Contradicting earlier studies, we found relatively high organic matter content in Vienna (11.7 ± 1.3%). In Salzburg, the soil organic matter content usually was 8% in the topsoil, whereas in Lower Austria usually it was less than 2% (Blum et al., 2005). The content of soil organic matter depends on the geological and climatic conditions, plant cover, utilization of the soil, and the age of soil layers (Mishra et al., 2010; Schmidt et al., 2011). Kralik (1999) reported that strongly acidic areas were found in Styria and Tyrol, and the organic matter, especially the humus content, was very low in agricultural used soil, which rate was higher in west of Austria than the east part of Austria. Soil cation exchange capacity (CEC) is an important factor controlling the soil buffer capacity, fertilization, and soil nutrient capacity (Chen et al., 2019). Earlier studies reported that metal availability was affected by cation exchange capacity (Zhen et al., 2019). Blum et al. (2005) reported low cation exchange capacity in Lower Austria and Burgenland where the sensitivity of acidification level may be high. Tomašić et al. (2013) demonstrated that pH was positively correlated with CEC and high organic matter content and clay conduced to the higher CEC values because both had a large number of negative charges on their surface which attracted and hold cations. Kobler et al. (2010) reported that the extent of minor elements (Pb and Cd) migration was largely influenced by soil type. Soil texture is loam in Vienna based on the Arany-type plasticity index. Barsova et al. (2019) demonstrated higher metal concentration in neutral loam soil than acid and sandy loam soil types. Rodríguez-Eugenio et al. (2018) reported that heavy metal concentration on the soils depends on the different types of land use and other anthropogenic activities. Urban soils are often reported to have high levels of Cd, Pb, Zn, and Cu (Madrid et al., 2002). Maas et al. (2010) presented that soil acts as a sink for heavy metals through sorption, complexation, and precipitation reactions. Langner et al. (2011) reported that the Cd, Cu, and Pb concentration in soils adjacent to homes increased due to anthropogenic inputs of the elements and organic matter over time. The land uses significantly affected the accumulation of heavy metals in urban soils and the Cd, Pb, Cu, and Zn accumulations would increase linearly with urban age, the number of years since establishment. In Austria, Cu contamination can be detected mostly in the surroundings of industrial sites processing copper ore and in areas with intensive animal husbandry (Gentile et al., 2009). Our results indicated that there are significant differences in the pollution level between the rural, suburban, and urban areas. For lead is exceeded in the soils of Tyro at 9.2% of the of the sites, and in Salzburg at 3.6% of them based on earlier studies in which high transit traffic makes the valley of the Inn River the most polluted region in Tyrol (Kralik, 1999). In the urban area, Cd was found in extremely high concentrations, unlike in the suburban and rural areas. A closer distance to the city center and the vicinity of Austria's most frequented highway may trigger this higher concentration in the sampling areas. On the other hand, the suburban and rural areas also showed high soil contamination levels. This difference may be caused by the soil type and the variations in soil, caused by anthropogenic activities. Traffic and industrial emissions are identified as the main sources of the accumulation of heavy metals in urban soils in Austria. Gentile et al. (2009) indicated that the Cd concentrations exceeded the guidance value in 5% of the monitoring sites in forests and in 6% of the sites in grassland areas. The closest pollution sources are industrial plants in the southeast of Vienna, which are outside the main wind direction (Zehetner et al., 2009). High cadmium contents are partly explained by long-range pollution and subsequent deposition on exposed lopes and the Northern Calcareous Alps may be a naturally elevated content of cadmium (Kralik, 1999). We found higher Cd and Ni concentrations in the topsoil than Zehetner et al. (2009), who studied the distribution of heavy metals across a highway that connects the cities of Vienna, Austria, and Brno, Czech Republic. Zehetner et al. (2009) also highlighted that roadside soil pollution is highly heterogeneous and traffic-borne heavy metals are more mobile than geogenic ones, covering greater distances from the source. Weiss et al. (1994) also demonstrated that the correlation in soil concentrations among the different groups of pollutants was very high, which indicates the existence of identical or adjacent sources for the soil pollution in the Linz area (Upper Austria). Pfleiderer et al. (2012) demonstrated the presence of anthropogenic contamination because the Cd concentration was 25% higher, and the Pb concentration was 36% higher in traffic and industrial areas than in the parks of Vienna (Pfleiderer et al. 2012).

5 Conclusion

In this study, the element concentrations of soils were used to assess the effects of urbanization on the ecological condition of urban ecosystem in Vienna. Using the pollution index, we demonstrated that the level of pollution is moderate for Cd ($1 \leq PI \leq 2$) and low for Cr, Cu, Ni, Pb, and Zn along the urbanization gradient in Vienna. Our findings indicated that the traffic emission may be the major source of the metal pollution in Vienna, because the concentration of these metals was higher than their background concentration. Our findings also demonstrated that the elemental analysis of soil and the values of PI are adequate indicators to assess the level of pollution based on soil sample analysis in urban ecosystems.

Acknowledgements We acknowledge the Department of Inorganic and Analytical Chemistry at the University of Debrecen for elemental analysis with ICP-OES.

Author Contributions All the authors contributed to the study conception and commented on the previous versions of the manuscript. All the authors read and approved the final manuscript.

Funding Open access funding provided by University of Debrecen.

Data Availability The data that support the findings of this study are available from the corresponding author.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Balogh, Z., Harangi, S., Kundrát, J. T., Gyulai, I., Tóthmérész, B., & Simon, E. (2016). Effects of anthropogenic activities on the elemental concentration in surface sediment of oxbows. *Water Air Soil Pollution, 227*, 13–21. https://doi.org/10.1007/s11270-015-2714-x

Barsova, N., Yakimenko, O., Tolpeshta, I., & Motuzova, G. (2019). Current state and dynamics of heavy metal soil pollution in Russian Federation—A review. *Environmental Pollution, 249*, 200–207. https://doi.org/10.1016/j.envpol.2019

Bengtsson, L., & Enell, M. (1986). Chemical analysis. In B. E. Berglund (Ed.), *Handbook of Holocene palaeoecology and palaeohydrology* (pp. 423–445). Chichester.

Bhuiyan, M. A. H., Karmaker, S. C., Bodrud-Doza, M., Rakib, M. A., & Saha, B. B. (2021). Enrichment, sources and ecological risk mapping of heavy metals in agricultural soils of Dhaka district employing SOM PMF and GIS methods. *Chemosphere, 263*, 128339. https://doi.org/10.1016/j.chemosphere.2020.128339

Blum, W. E. H., Englisch, M., Freudenschuß, A., Nelhiebel, P., Pock, H., Schneider, W., Schwarz, S., Wagner, J., & Wandl, M. (2005). Soil survey and soil data in Austria. In R. J. A. Jones, B. Housková, P. Bullock, & L. Montanarella (Eds.), *Soil resources of Europe, second ed. European Soil Bureau Research Report No. 9, EUR 20559 EN* (pp. 47–61). Office for Official Publications of the European Communities.

Chen, L., Wang, G., Wu, S., Xia, Z., Cui, Z., Wang, C., & Zhou, S. (2019). Heavy metals in agricultural soils of the Lihe River Watershed, East China: Spatial distribution, ecological risk, and pollution source. *International Journal of Environmental Research and Public Health, 16*, 2094. https://doi.org/10.3390/ijerph16122094

De Paul Obade, V. (2019). Integrating management information with soil quality dynamics to monitor agricultural productivity. *Science of the Total Environment, 651*, 2036–2043. https://doi.org/10.1016/j.scitotenv.2018.10.106

De Sá, J.P.M. (2007). Applied statistics using SPSS, STATISTICA, MATLAB and R, 2nd ed.; Springer: . ISBN 978-3-540-71971-7.

Eikmann, T., & Kloke, A. (2004). Nutzungs- und schutzgutbezogene Orientierungswerte fu¨r (Schad–)stoffe in Boden Eikmann-Kloke-Werte. In D. Rosenkranz, G. Einsele, & H. M. Harress (Eds.). Bodenschutz.

Faiz, Y., Tufail, M., Javed, M. T., Chaudhry, M. M., & Siddique, N. (2009). Road dust pollution of Cd, Cu, Ni, Pb and Zn along Islamabad Expressway, Pakistan. *Microchemical Journal, 92*, 186–192. https://doi.org/10.1016/j.microc.2009.03.009

Gentile, A. R., Barceló-Cordón, S., & Van Liedekerke, M. (Eds.). (2009). *Soil country analyses Austria. JRC scientific and technical reports. EUR 23959 EN*. OPOCE. https://doi.org/10.2788/2600

Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. *Journal of Paleolimnolgy, 25*, 101–110. https://doi.org/10.1023/A:1008119611481

Jia, X., Fu, T., Hu, B., Shi, Z., Zhou, L., & Zhu, Y. (2020). Identification of the potential risk areas for soil heavy metal pollution based on the source-sink theory. *Journal of Hazardous Materials, 393*, 122424. https://doi.org/10.1016/j.jhazmat.2020.122424

Kobler, J., Fitz, W. J., Dirnböck, T., & Mirtl, M. (2010). Soil type affects migration pattern of airborne Pb and Cd under a spruce-beech forest of the UN-ECE integrated monitoring site Zöbelboden, Austria. *Environmental Pollution, 158*, 849–854. https://doi.org/10.1016/j.envpol.2009.09.026

Kralik, M. (1999). Environmental geology in Austria. *Mitteilungen der Österreichischen Geographischen Gesellschaft, 92*, 313–335 ISSN 0251-7493.

Langner, A. N., Manu, A., & Tabatabai, M. A. (2011). Heavy metals distribution in an Iowa suburban landscape. *Journal of Environmental Quality, 40*, 83–89. https://doi.org/10.2134/jeq2010.0229

Li, C., Zhou, K., Qin, W., Tian, C., Qi, M., Yan, X., & Han, W. (2019). A review on heavy metals contamination in soil: Effects, sources, and remediation techniques. *Soil and Sediment Contamination: An International Journal, 28*, 380–394. https://doi.org/10.1080/15320383.2019.1592108

Liu, H., Zhang, Y., Yang, J., Wang, H., Li, Y., Shi, Y., Li, D., Holm, P. E., Ou, Q., & Hu, W. (2021). Quantitative source apportionment, risk assessment and distribution of heavy metals in agricultural soils from southern Shandong Peninsula of China. *Science of the Total Environment, 767*, 144879. https://doi.org/10.1016/j.scitotenv.2020.144879

Lu, Y., Zhu, F., Chen, J., Gan, H., & Guo, Y. (2007). Chemical fraction of heavy metals in urban soils of Guangzhou, China. *Environmental Monitoring and Assessment, 134*, 429–439. https://doi.org/10.1007/s10661-007-9634-1

Maas, S., Scheifler, R., Benslama, M., Crini, N., Lucot, E., Brahmia, Z., Benyacoub, S., & Giraudoux, P. (2010). Spatial distribution of heavy metal concentrations in urban, suburban and agricultural soils in a Mediterranean city of Algeria. *Environmental Pollution, 158*, 2294–2301. https://doi.org/10.1016/j.envpol.2010.02.001

Madrid, L., & Dı́az-Barrientos, E., Madrid, F. (2002). Distribution of heavy metal contents of urban soils in parks of Seville. *Chemosphere, 49*, 1301–1308. https://doi.org/10.1016/S0045-6535(02)00530-1

Mehmood, T., Liu, C., Niazi, N. K., Gaurav, G. K., Ashraf, A., & Bibi, I. (2021). Compost-mediated arsenic phytoremediation, health risk assessment and economic feasibility using *Zea mays* L. in contrasting textured soils. *International Journal of Phytoremediation, 23*, 899–910. https://doi.org/10.1080/15226514.2020.1865267

Mishra, U., Lalm, R., Liu, D., & Van Meirvenne, M. (2010). Predicting the spatial variation of the soil organic carbon pool at a regional scale. *Soil & Water Management & Conservation, 74*, 906–914. https://doi.org/10.2136/sssaj2009.0158

Molnár, V. É., Simon, E., Ninsawat, S., Tóthmérész, B., & Szabó, S. (2020). Pollution assessment based on element concentration of tree leaves and topsoil in Ayutthaya Province, Thailand. *International Journal of Environmental Research and Public Health, 217*, 5165. https://doi.org/10.3390/ijerph17145165

Ogbodo, E. N. (2012). Assessment of some soil fertility characteristics of Abakaliki urban flood plains of south-east Nigeria, for sustainable crop production. *World Journal of Agricultural Sciences, 7*, 489–495.

Pfleiderer, S., Schedl, A., Neinavaie, H., & Pirkl, H. (2010). *Umweltgeochemie Stadtgebiet Wien*. Report of the Geological Survey of Austria.

Pfleiderer, S., Englisch, M., & Reiter, R. (2012). Current state of heavy metal contents in Vienna soils. *Environmental Geochemistry and Health, 34*, 665–675. https://doi.org/10.1007/s10653-012-9485-8

Pirkl, H., & Kralik, M. (1988). *Ergebnisse einer umweltgeochemischen Flußsedimentbeprobung im südlichen Wiener Becken und Nördlichen Wechsel* (p. 12). Wien: Ber Geol Bundesanst

Rodríguez-Eugenio, N., McLaughlin, M., & Pennock, D. (Eds.). (2018). *Soil pollution: A hidden reality*. FAO.

Sager, M. (2007). Trace and nutrient elements in manure, dung and compost samples in Austria. *Soil Biology and Biochemistry, 39*, 1383–1390. https://doi.org/10.1016/j.soilbio.2006.12.015

Santisteban, J. M., Mediavilla, R., Lopez-Pamo, E., Dabrio, C. J., Zapata, M. B. R., Garcia, M. J. G., Castano, S., & Martínez-Alfaro, P. E. (2004). Loss on ignition: A qualitative or quantitative method for organic matter and carbonate mineral content in sediments? *Journal of Paleolimnology, 32*, 287–299. https://doi.org/10.1023/B:JOPL.0000042999.30131.5b

Schmidt, M. W. I., Torn, M. S., Abiven, S., Dittmar, T., Guggenberger, G., Janssens, I. A., Kleber, M., Kögel-Knaber, I., Lehmann, J., Manning, D. A. C., Nannipieri, P., Rasse, D. P., Weiner, S., & Trumbore, S. E. (2011). Persistence of soil organic matter as an ecosystem property. *Nature, 478*, 49–56. https://doi.org/10.1038/nature10386

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. *Ecological Indicator, 60*, 258–264. https://doi.org/10.1016/j.ecolind.2015.06.045

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. *Environmental Science and Pollution Research, 20*, 917–924. https://doi.org/10.1007/s11356-012-1091-x

Sündermann, A., Solc, R., Tunega, D., Haberhauer, G., Gerzabek, M. H., & Oostenbrink, C. (2015). Vienna soil-organic-matter modeler—Generating condensed-phase models of humic substances. *Journal of Molecular Graphics and Modelling, 62*, 253–261. https://doi.org/10.1016/j.jmgm.2015.10.007

Tomašić, M., Zgorelec, Z., Jurišić, A., & Kisić, I. (2013). Cation exchange capacity of dominant soil types in the Republic of Croatia. *Journal of Central European Agriculture, 14*, 937–951. https://doi.org/10.5513/JCEA01/14.3.1286

Valkó, O., Tóthmérész, B., Kelemen, A., Simon, E., Miglécz, T., Lukács, B. A., & Török, P. (2013). Environmental factors driving seed bank diversity in alkali grasslands. *Agriculture, Ecosystems & Environment, 182*, 80–87. https://doi.org/10.1016/j.agee.2013.06.012

Wei, B., & Yang, L. (2010). A review of heavy metal contaminations in urban soils, urban road dusts and agricultural soils from China. *Microchemical Journal, 94*, 99–107. https://doi.org/10.1016/j.microc.2009.09.014

Weiss, P., Riss, A., Gschmeidler, E., & Schentz, H. (1994). Investigation of heavy metal, PAH, PCB patterns and PCDD/F profiles of soil samples from an industrialized urban area (Linz, Upper Austria) with multivariate statistical methods. *Chemosphere, 29*, 9–11 0045-6535(94)00275-4

Zhang, Q., & Wang, C. (2020). Natural and human factors affect the distribution of soil heavy metal pollution: A Review. *Water Air and Soil Polltuion, 231*, 350–263. https://doi.org/10.1007/s11270-020-04728-2

Zehetner, F., Rosenfellner, U., Mentler, A., & Gerzabek, M. H. (2009). Distribution of road salt residues, heavy metals and polycyclic aromatic hydrocarbons across a highway-forest interface. *Water Air Soil Pollution, 198*, 125–132. https://doi.org/10.1007/s11270-008-9831-8

Zhen, Z., Wang, S., Luo, S., Ren, L., Liang, Y., Yang, R., Li, Y., Zhang, Y., Deng, S., Zou, L., Lin, Z., & Zhang, D. (2019). Significant impacts of both total amount and availability of heavy metals on the functions and assembly of soil microbial communities in different land use patterns. *Frontiers in Microbiology, 10*, 293. https://doi.org/10.3389/fmicb.2019.02293

Ziss, E., Friesl-Hanl, W., Götzinger, S., Noller, C., Puschenreiter, M., Watzinger, A., & Hood-Nowotny, R. (2021). Exploring the potential risk of heavy metal pollution of edible cultivated plants in urban gardening contexts using a citizen science approach in the project "heavy metal city-zen". *Sustainability, 13*, 8626. https://doi.org/10.3390/su13158626