Variations in Sr, Tl, and V Concentrations at Copper Mining Sites Based on Soil Depth, Plant Species, and Plant Organ

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The concentrations of Sr, Tl, and V in soils and plant organs were evaluated at a copper mining site. These are heavy metals that are extremely dangerous and harmful to human and environmental health and, therefore, are on the ATSDR substance priority list. Within the scope of the study, soil samples were taken from different soil depths in the spoil area, the rehabilitation area where planting was performed and adult trees that were at least 20 years old, and the forest area. Soil samples were taken from the rehabilitation and forest areas where *Pinus nigra* Arnold., *Pinus sylvestris* L., and *Robinia pseudoacacia* L. species grow, and leaf, bark, wood, and root samples were taken from trees in the same areas. The study evaluated variations in heavy metal concentrations in soils based on species and soil depth and in plants based on plant species and organs. The study found that the heavy metal concentrations in soils and plant organs generally varied depending on plant species, while these variations were insignificant depending on soil depth. The highest concentrations by species were generally obtained for Sr in *Robinia pseudoacacia* and for Tl and V in *Pinus nigra*.

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INTRODUCTION

Along with the industrial revolution and technological advancements in the last century, people’s demands and needs have diversified and increased. To meet these demands (for example, phones, cars, all kinds of electronic devices *etc*.), underground mineral resources are extracted and used as raw materials in various industries (Cesur *et al.* 2021; Ghoma *et al.* 2022). Mine production and mining operations are rapidly increasing worldwide due to the increased amount of raw materials needed by the developing industry (Makineci *et al.* 2011; Alaquori *et al.* 2020; Gao *et al.* 2021).

Mining activities directly or indirectly affect soil, water, and air. During mining activities, various elements in underground mineral deposits are extracted to the surface and released into nature. Using these elements as raw materials in industrial activities and various chemicals employed during the mining process cause elements to mix with soil, water, and air, leading to significant environmental pollution (Makineci 2021; Kuzmina *et al.* 2023).

Environmental pollution has become a global problem today, and it is stated that it affects all living things and ecosystems worldwide and is responsible for global climate change (Tekin *et al.* 2022; Varol *et al.* 2022; Işınkaralar *et al.* 2023). According to the European Environment Agency data, air pollution is one of the biggest environmental concerns in Europe (Cobanoglu *et al.* 2023; Arıcak *et al.* 2024).

It is reported that heavy metals are the most harmful element among environmental pollution components (Isinkaralar *et al.* 2023) because they do not break down easily in nature and remain for a long time. Many heavy metals are harmful, carcinogenic, and even fatal to living things, even at low concentrations (Ghoma *et al.* 2022; Istanbullu *et al.* 2023). Especially, Ag, Al, As, Ba, Be, Cd, Co, Cr, Cu, Pb, Mn, Hg, Ni, Pd, Pu, Sb, Se, Sr, Tl, Th, U, V, and Zn are extremely harmful to human and environmental health. Thus, the ATSDR (Agency for Toxic Substances and Disease Registry) has included them in the substance priority list (Savas *et al.* 2021). These elements are defined as heavy metals, and it is stated that heavy metal concentrations in nature are constantly increasing due to anthropogenic effects, particularly mining activities, industry, and vehicles, and decreasing heavy metal pollution is among the priority research subjects (Sulhan *et al.* 2023; Koc *et al.* 2024).

This study aimed to identify variations in the concentrations of Sr, Tl, and V, which are the most harmful heavy metals to human and environmental health and are, therefore, on the substance priority list of ATSDR in soils and plant organs at mining sites. From a scientific point of view, it is impossible to know what the various metal concentrations would be at mining sites without plants. In addition, due to the nature of mining, it would be wrong to expect any uniformity or specific pattern in metal concentrations. Therefore, “control” testing is not possible in these areas. For this reason, determining the current situation in areas that have been mined and rehabilitated for a long time can provide important information about the development of the process in these areas. The study, which was conducted in areas where copper mining activities had been carried out for many years and had been completed and rehabilitation activities were carried out, determined variations in Sr, Tl, and V concentrations by soil depth and plant organs in the forest area and spoil areas where different species grow.

Logically, metal concentrations are expected to vary with soil depth. This variation is because elements in the upper layers can be leached deeper by precipitation. Biomass binds divalent metal ions, and such leaching can be influenced by plant-based substances in the soil, including humus. However, suppose there is no plant-based matter in a part of the soil. In that case, there will be no reason for divalent metals washed from the upper layers to be retained in the lower levels of the soil, and in this case, they are more likely to continue leaching until they reach groundwater (Singh *et al.* 2022; Jiang *et al.* 2022; Deepika and Haritash 2023). In studies conducted on this subject, it has been determined that elemental concentrations in soils in the same area vary depending on soil depth and plant species (Erdem *et al.* 2023a,b). Therefore, the hypotheses of the study were:

a) Sr, Tl, and V concentrations in soils vary depending on soil depth.

b) Sr, Tl, and V concentrations in soils vary depending on plant species.

c) Sr, Tl, and V concentrations in plant organs vary depending on plant species.

d) Sr, Tl, and V concentrations in plant organs vary depending on the plant organ.

EXPERIMENTAL

Materials and Methods

The study was conducted in the Küre district, Kastamonu, where copper mining had been conducted for decades, and where one of the largest copper mines in Türkiye is operated. Within the scope of the research, soil samples were taken from the topsoil (0 to 5 cm) and subsoil (30 to 35 cm) in the spoil area (the area where rehabilitation activities had not been carried out yet), the rehabilitation area where planting had been performed, and adult trees were at least 20 years old, and the forest area. Soil samples were taken from the rehabilitation and forest areas where *Pinus nigra* Arnold., (Pn), *Pinus sylvestris* L. (Ps), and *Robinia pseudoacacia* L. (Rp) species grow. Leaf, bark, wood, and root samples were also taken from trees in the same areas.

During sampling, samples were taken from 3 areas from each site (forest, rehabilitation area, and leach field) in 3 replicates. Thus, soil samples were taken from 9 areas: 3 forests, 3 rehabilitation areas, and 3 waste areas, from each of which 3 tree species grow (there are no trees in the waste area); thus, soil samples were taken from 21 areas. Since soil samples were taken from 2 depths, a total of 42 soil samples were taken. Since soil samples were analyzed in triplicate, a total of 126 soil samples were analyzed. Similarly, plant samples were taken from a total of 18 trees from the forest and rehabilitation area where 3 tree species grow. The branches taken from each tree were divided into wood, bark, and leaf samples, and root samples were also taken. Root samples were excavated from the closest possible point to the tree and taken as a whole from the section approximately 30 to 35 cm below the soil level Thus, a total of 72 plant samples were analyzed in triplicate, resulting in a total of 216 plant samples. The soils were sieved and dried, while the plants were first washed by scrubbing with water, and particulate matter was removed from their surfaces and then cleaned with pure water. After that, drying processes were carried out.

The collected samples were brought to the laboratory and stored in a dry environment by ventilating them for two weeks to ensure that they were air dried and were then crushed. The soil was sieved, and the plants were ground, and made homogeneous. Afterward, they were dried at 45 °C for two weeks. The dried samples were analyzed for Sr, Tl, and V elements with an inductively coupled plasma-optical emission spectroscope (ICP-OES) device (Spectro, Kleve, Germany), and the metal concentrations were determined. The above-mentioned method has often been employed in recent years for elemental analysis in soils (Cetin *et al.* 2022) and various organs of plants (Erdem *et al.* 2024). The obtained data were assessed with the package SPSS 22.0 (SPSS, IBM, v.20, Armonk, NY, USA), and variance of analysis and Duncan's test were applied to the data. The data were simplified, tabulated, and interpreted.

In the study, the bioconcentration factor (BCF) and the translocation factor (TF) were also calculated, and the following formulas were used in the calculations (Takarina and Pin 2017).

$$\mathrm{BCF} = \frac{\text{concentration in organ}}{\text{concentration in soil}} \tag{1}$$

$$\mathrm{TF} = \frac{\text{BCF of organ}}{\text{BCF of root soil}} \tag{2}$$

RESULTS

Table 1 presents the organ-based variations in Sr concentrations, one of the heavy metals evaluated in this study, in trees from different areas.

Table 1. Organ-based Variations in Sr (ppm) Concentrations in Trees from Different Areas

Area	Species	Root	Wood	Bark	Leaf	F	Average
Spoil	Pn	2.0 ^{aA}	2.8 ^{aB}	6.4 ^{aC}	3.3 ^{aB}	75.2***	3.6 ^{a}
	Ps	11.9 ^{bcC}	2.1 ^{aA}	7.2 ^{aBC}	2.9 ^{aAB}	7.6**	6.0 ^{a}
	Rp	21.8 ^{deA}	11.8 ^{cA}	55.4 ^{cB}	50.7 ^{bB}	14.2***	34.9 ^{c}
Forest	Pn	9.7 ^{bB}	2.3 ^{aA}	9.7 ^{aB}	4.3 ^{aA}	23.9***	6.5 ^{a}
	Ps	16.5 ^{cdC}	3.9 ^{aA}	10.7 ^{aB}	5.3 ^{aA}	45.5***	9.1 ^{a}
	Rp	23.4 ^{eB}	7.1 ^{bA}	32.4 ^{bC}	40.2 ^{bD}	103.6***	25.8 ^{b}
F-value		14.4***	21.9***	69.7***	32.1***		40.7***
Average		14.2 ^{B}	5.0 ^{A}	20.3 ^{B}	17.8 ^{B}	9.6***	

According to Duncan's test results, numbers followed by the same letters (A, B, or a, b) are not statistically different at $p>0.05$. Lowercase letters illustrate vertical directions, while capital letters indicate horizontal directions. ns=not significant; ***$P\leq0.001$.

The data from Table 1 revealed that variation in Sr concentrations in plants was statistically significant ($p < 0.05$) on an organ basis in all species and on a species basis in all organs. According to average values, the highest value among species was obtained in Rp in the spoil area. Likewise, when examined by organs according to average values, the lowest value was acquired in wood, whereas the highest was in roots, bark, and leaves. Table 2 shows variations in Sr concentrations in soils based on species and soil depth.

Table 2. Variation in Sr (ppm) Concentrations in Soils Based on Species and Soil Depth

Area	Species	Sub	Top	F	Average
Spoil	-	19.3 ^{ab}	17.3 ^{a}	1.5 ^{ns}	18.3 ^{ab}
Spoil	Pn	14.3 ^{a}	13.1 ^{a}	0.3 ^{ns}	13.7 ^{a}
	Ps	21.5 ^{ab}	27.3 ^{b}	1.2 ^{ns}	24.4 ^{c}
	Rp	25.5 ^{b}	20.2 ^{ab}	1.0 ^{ns}	22.8 ^{bc}
Forest	Pn	38.6 ^{c}	36.8 ^{c}	0.2 ^{ns}	37.7 ^{d}
	Ps	18.6 ^{ab}	16.2 ^{a}	0.3 ^{ns}	17.4 ^{ab}
	Rp	48.1 ^{d}	40.8 ^{c}	2.8 ^{ns}	44.4 ^{e}
F-value		18.1***	15.3***		32.3***
Average		26.59	24.56	0.7 ^{ns}	

According to Duncan's test results, numbers followed by the same letters (a, b, c, d) are not statistically different at $p>0.05$. Lowercase letters illustrate vertical directions. ns=not significant; ***$P\leq0.001$.

The analysis of variance determined that variation in Sr concentration in soils was not statistically significant based on soil depth in all species but was statistically significant on a species basis, both in the subsoil and topsoil and according to average values.

According to average values, the highest value was acquired in Rp in the forest area, while the lowest was obtained in Pn in the spoil area. Table 3 contains species- and organ-based variations in Tl concentration in plants.

Table 3. Species- and Organ-based Variations in Tl (ppm) Concentrations in Plants

Area	Species	Root	Wood	Bark	Leaf	F	Average
Spoil	Pn	2.3 ^{aA}	2.6 ^{bA}	4.1 ^{bB}	3.7 ^{dB}	24.1***	3.2 ^{ab}
	Ps	2.6 ^{aA}	2.1 ^{aA}	3.0 ^{aB}	3.0 ^{aB}	10.4***	2.8 ^{a}
	Rp	2.9 ^{aA}	2.4 ^{aB}	3.4 ^{aC}	3.3 ^{abcC}	9.8***	3.0 ^{a}
Forest	Pn	4.7 ^{bC}	2.4 ^{aA}	4.9 ^{cC}	3.5 ^{cdB}	10.4***	3.9 ^{c}
	Ps	2.6 ^{aA}	2.4 ^{aA}	3.3 ^{aB}	3.1 ^{abB}	44.4***	2.8 ^{a}
	Rp	4.3 ^{bC}	2.5 ^{aA}	3.4 ^{aB}	3.4 ^{bcdB}	212.4***	3.4 ^{b}
F-value		10.9***	7.2***	19.6***	4.3**		9.0***
Average		3.2 ^{B}	2.4 ^{A}	3.7 ^{C}	3.3 ^{B}	24.8***	

According to Duncan's test results, numbers followed by the same letters (A, B, or a, b) are not statistically different at $p>0.05$. Lowercase letters illustrate vertical directions, while capital letters indicate horizontal directions. ***$P\leq0.001$; **$P\leq0.01$.

Table 4. Variation in Tl (ppm) Concentration in Soils Based on Species and Soil Depth

Area	Species	Sub	Top	F	Average
Spoil	-	34.5 ^{c}	30.7 ^{bcd}	2.6 ^{ns}	32.6 ^{de}
Spoil	Pn	28.6 ^{b}	31.1 ^{cd}	2.5 ^{ns}	29.9 ^{cd}
	Ps	25.4 ^{ab}	26.4 ^{ab}	0.2 ^{ns}	25.9 ^{b}
	Rp	30.1 ^{bcB}	25.3 ^{aA}	9.8**	27.7 ^{bc}
Forest	Pn	34.0 ^{c}	34.7 ^{d}	0.1 ^{ns}	34.3 ^{e}
	Ps	20.5 ^{a}	23.1 ^{a}	0.4 ^{ns}	21.8 ^{a}
	Rp	34.6 ^{c}	29.7 ^{bc}	4.3 ^{ns}	32.2 ^{de}
F-value		8,8***	7.4***		13.6***
Average		29.74	28.76	0.7 ^{ns}	

According to Duncan's test results, numbers followed by the same letters (A, B, or a, b) are not statistically different at $p>0.05$. Lowercase letters illustrate vertical directions, while capital letters indicate horizontal directions. ns=not significant; ***$P\leq0.001$; **$P\leq0.01$.

The results revealed that variation in Tl concentration in soils was statistically significant ($p < 0.05$) based on soil depth in Rp in the spoil area and based on species in all soils. According to the average values, while the highest value among species was obtained in Pn in the forest area, the lowest value was obtained in Ps in the forest area. Table 5 shows species- and organ-based variations in V concentration in plants.

The analysis of variance showed that variation in V concentration in plants was statistically significant on an organ basis in all species and on a species basis in all organs. According to the average values, the highest value among species was acquired in Pn in the forest area, whereas the lowest value was obtained in Ps in the spoil area, Rp in the spoil area, and Ps in the forest area. When examined by organs according to the average values, the lowest value was in wood, and the highest was in roots. Table 6 contains variations in V concentrations in soils based on species and soil depth.

Table 5. Species- and Organ-based Variations in V (ppm) Concentrations in Plants

Area	Species	Root	Wood	Bark	Leaf	F	Average
Spoil	Pn	5.8^{aA}	5.1^{bA}	11.8^{bB}	10.0^{bB}	9.2***	8.2^{b}
	Ps	8.0^{aB}	4.8^{aA}	5.5^{aA}	5.1^{aA}	15.0***	5.8^{a}
	Rp	7.6^{aB}	4.8^{aA}	5.7^{aA}	5.8^{aA}	5.8**	6.0^{a}
Forest	Pn	20.1^{bB}	5.1^{bA}	15.8^{cB}	9.6^{bA}	10.0***	12.7^{c}
	Ps	6.1^{aC}	4.8^{aA}	5.8^{aBC}	5.4^{aB}	10.7***	5.5^{a}
	Rp	8.0^{bC}	5.1^{bA}	7.3^{aB}	7.1^{aB}	646.7***	8.8^{b}
F-value		12,6***	3.0*	25.0***	10.2***		14.4***
Average		10.5^{C}	5.0^{A}	8.6^{B}	7.2^{B}	14.7***	

According to Duncan's test results, numbers followed by the same letters (A, B, or a, b) are not statistically different at p>0.05. Lowercase letters illustrate vertical directions, while capital letters indicate horizontal directions. ***P≤0.001; **P≤0.01; *P≤0.05.

Table 6. Variation in V (ppm) Concentrations in Soils Based on Species and Soil Depth

Area	Species	Sub	Top	F	Average
Spoil	-	181.1^{b}	194.0^{cd}	3.3^{ns}	188.9^{b}
Spoil	Pn	180.8^{b}	206.9^{d}	3.7^{ns}	193.9^{b}
	Ps	144.2^{a}	146.8^{a}	0.0^{ns}	145.5^{a}
	Rp	190.3^{bB}	153.2^{abA}	37.5***	171.8^{b}
Forest	Pn	189.4^{b}	195.1^{cd}	0.6^{ns}	192.2^{b}
	Ps	143.6^{a}	146.5^{a}	0.0^{ns}	145.0^{a}
	Rp	184.3^{b}	175.8^{bc}	0.6^{ns}	180.0^{b}
F-value		3,1*	7.3***		7.6***
Average		173.05	174.09	0.0^{ns}	

According to Duncan's test results, numbers followed by the same letters (A, B, or a, b) are not statistically different at p>0.05. Lowercase letters illustrate vertical directions, while capital letters indicate horizontal directions. ns=not significant; ***P≤0.001; *P≤0.05.

According to the results, variation in V concentration in soils was statistically significant based on soil depth in Rp in the spoil area and based on species in all soils. According to average values, the lowest value among species was obtained in Ps in the spoil area and Ps in the forest area. BCF values for the elements subject to the study are calculated and given in Table 7.

When BCF values were examined, they were found to vary between 0.03 and 2.43. Only in Sr element Rp, BCF values in bark and leaves were above 1. Again, BCF values in roots and wood in Sr element Rp were above 0.5, while RCF values in all other organs were below 0.5. Translocation factor (TF) values of the elements subject to the study are given in Table 8.

Table 7. BCF Values for the Quantities Evaluated in the Study

Element	Species	Root	Wood	Bark	Leaf
Sr	Pn	0.15	0.20	0.47	0.24
	Ps	0.49	0.09	0.30	0.12
	Rp	0.96	0.52	2.43	2.22
Tl	Pn	0.08	0.09	0.14	0.12
	Ps	0.10	0.08	0.12	0.12
	Rp	0.10	0.11	0.15	0.14
V	Pn	0.03	0.03	0.06	0.05
	Ps	0.05	0.03	0.04	0.04
	Rp	0.04	0.03	0.03	0.03

Table 8. Translocation Factor Values for the Quantities Evaluated in the Study

Element	Species	Wood	Bark	Leaf
Sr	Pn	1.33	3.13	1.60
	Ps	0.18	0.61	0.24
	Rp	0.54	2.53	2.31
Tl	Pn	1.13	1.75	1.50
	Ps	0.80	1.20	1.20
	Rp	1.10	1.50	1.40
V	Pn	1.00	2.00	1.67
	Ps	0.60	0.80	0.80
	Rp	0.75	0.75	0.75

As a result of the calculations, it was determined that TF values ranged between 0.18 and 3.13. The highest TF values were determined in bark (3.13) in Pn, bark (2.53) and leaf (2.31) in Rp in Sr element. In addition, TF values of all organs of Pn and TF values of all organs of Rp in Tl were calculated above 1 in all elements subject to the study.

DISCUSSION

Some compounds of Sr, which are harmful to human health even in low amounts, can cause lung cancer and accumulate in the body throughout life, leading to serious problems that may even cause sudden death (Erdem 2023). Hence, monitoring the variation in Sr pollution and its reduction is an essential subject of study. This study found that Sr concentration in the wood of plants in the spoiled area varied between 2.1 ppm and 11.8 ppm. However, another study on the subject revealed that Sr concentration in the wood of different species ranged between 1.2 ppm and 5.3 ppm according to average values. It was emphasized that there was heavy traffic in the study area, which might have caused Sr pollution (Erdem 2023). However, the values obtained in this study are considerably higher.

The results from this study revealed that the concentration of Tl did not change statistically significantly based on soil depth. However, the lowest values on a species basis were obtained for Ps in both the spoil and forest areas. Tl concentrations in the spoil area are in the last group, which aligns with Duncan's test results. Therefore, it can be said that Tl pollution in the spoil area is at a high level, Pn does not take Tl from the soil (Pn and spoil soils are in the same groups according to Duncan's test), and Ps significantly reduces the Tl concentration in the soil. On a species basis, the highest values were obtained for Pn, whereas the lowest values were obtained for Ps. On an organ basis, the highest values were acquired in the bark, and the lowest values were obtained in the wood, according to average values.

Thallium is one of the elements neglected in studies on heavy metal pollution. However, Tl usually exhibits more acute and chronic toxicity than harmful elements, including As, Cd, Hg, and Pb (Cantürk 2023). In addition to being considered one of the most toxic metals, it is a more toxic heavy metal than elements with significant harmful effects on human health, *e.g.*, Hg, Cd, Pb, Cu, and Zn (Peter and Viraraghavan 2005; Blain 2022).

Thallium mixes with natural materials in three ways. The first is through natural pathways and the geochemistry of local rocks. The second source usually occurs due to mining activities and is of anthropogenic origin. The third occurs when coal is burned in cement factories (LaCoste *et al.* 2001). After the rapid, almost complete absorption of Tl from the gastrointestinal tract, soluble Tl compounds are widely distributed throughout the body, with the highest concentration initially accumulating in the kidneys. Vague illness, paresthesia, and, in some cases, hair loss are the main symptoms of chronic poisoning (Blain 2022). The negative impacts of Tl pollution emerge with chronic Tl poisoning with symptoms of fatigue, muscle and joint pain, visual impairment, and hair loss for humans (Xiao *et al.* 2012). A study found that the Tl concentration in the wood of plants growing in a region with high air pollution ranged between 3.3 ppm and 4.7 ppm on average (Cantürk 2023). The concentrations in wood found in this study ranged from 2.1 to 2.6 ppm. Hence, it can be stated that Tl pollution did not increase due to copper mining.

It was revealed that the concentration of V, another element evaluated within the scope of the study, did not change statistically significantly based on soil depth. However, the lowest values on a species basis were obtained for Ps in both the spoil and forest areas. On a species basis, the highest values were obtained for Pn in spoil and forest soils, whereas the lowest values were obtained for Ps. On an organ basis, the highest values were obtained in roots, and the lowest values were acquired in wood according to average values.

Vanadium, one of the most threatening elements for the environment and human health, is the fifth most abundant transition element in the earth's crust (Imtiaz *et al.* 2015). It enters the environment primarily through anthropogenic activities, including mining, industry, burning of fossil fuels, and fertilization (Altaf *et al.* 2021), and high V concentrations pose potential health risks to microbes, plants, animals, and humans (Chen *et al.* 2021; Hao *et al.* 2021). Vanadium has toxic impacts on the respiratory, digestive organs, kidneys, liver, skin, and immune system (Jayawarda *et al.* 2015; Hao *et al.* 2021), causing pulmonary lesions, renal failure, and neurological disorders (Frank *et al.* 1996) (Hao *et al.* 2021). Long-term exposure to V increases the risk of functional lesions in the spleen, bones, and nervous system (Yu and Yang 2019).

The heavy metals investigated in the study can be extremely harmful and even fatal to human and environmental health. Therefore, it is crucial to monitor the variation in these heavy metals in the environment and reduce their concentrations. Heavy metal pollution is a global problem that poses a primary threat to the health of humans and living things in recent years, and numerous studies have been conducted on this subject. Nevertheless, research focuses on more common heavy metals, *e.g.*, Pb, Cr, Ni, Co, Cd, and Mn (Aricak *et al.* 2019; Ucun Ozel *et al.* 2019; Key *et al.* 2022). Contrastingly, heavy metals, such as Ag, As, Ba, Be, Pd, Pu, Sb, Se, Sr, Tl, Th, U, and V, are extremely harmful at considerably lower concentrations, and it is stated that concentrations of these heavy metals in nature are constantly increasing due to anthropogenic impacts (Cantürk 2023; Cetin *et al.* 2023; Erdem 2023; Koç *et al.* 2024; Özel *et al.* 2024). Therefore, it is crucial to monitor variations in the concentrations of these heavy metals and reduce their concentrations.

Phytoremediation by plants is one of the most effective methods that can be utilized for reducing heavy metal pollution. Plants absorb and trap heavy metals in the environment, thus contributing significantly to reducing heavy metal pollution (Cesur *et al.* 2022; Yayla *et al.* 2022). Heavy metals can enter the plant body directly from the soil through the roots, air through the leaves, and trunk parts (Key *et al.* 2023). Nevertheless, the potential of plants to absorb and accumulate heavy metals depends on numerous factors, such as organ structure, weather conditions, and plant habitus, in addition to the heavy metal's structure and its interaction with the plant (Savas *et al.* 2022). The above-mentioned factors are also associated with other factors. For example, plant physiology is shaped under the influence of genetic structure (Hrivnak *et al.* 2023; Kurz *et al.* 2024) and environmental conditions (Ertugrul *et al.* 2019; Sevik *et al.* 2021). Hence, all factors influencing plant physiology also impact the entry and accumulation of heavy metals in plants. In contrast, plant physiology is shaped under the mutual interaction of numerous factors affecting each other, *e.g.*, genetic structure (Erturk *et al.* 2024), edaphic (Kravkaz Kuscu *et al.* 2018; Yigit *et al.* 2023), climatic (Gur *et al.* 2024; Isinkaralar *et al.* 2024), and stress factors (Ozel *et al.* 2021a,b; Koc and Nzouko 2022).

Heavy metals entering the plant are trapped in the organs, thus decreasing heavy metal pollution in the environment. Nevertheless, research reveals that different organs of plants have different potentials for heavy metal accumulation, and this difference varies significantly based on plant species and organs (Karacocuk *et al.* 2022; Key *et al.* 2022). In studies aimed at reducing heavy metal pollution, the amount of heavy metals that can accumulate in tall trees, particularly in wood, is of great importance because wood is the largest organ of trees in terms of mass (Koc *et al.* 2024). Therefore, in areas with high heavy metal pollution, it is necessary to select species that accumulate heavy metals the most, especially in wood, when determining the plant species that can be utilized to decrease pollution.

Translocation factor (TF) values of plant organs were calculated within the scope of the study. Trees with TF values greater than 1 for heavy metals are considered as strong accumulators (Takarina and Pin 2017). As a result of the study, the highest TF values were determined in bark in Pn, bark in Rp, and leaf in Sr element. In addition, TF values of all organs of Pn and all organs of Rp in Tl were calculated to be above 1 in all elements subject to the study. These results indicate that Pn and Rp are very suitable bioaccumulators for both Sr and Tl.

CONCLUSIONS

1. This study determined variations in the concentrations of Sr, Tl, and V elements in soils and plant organs at a copper mining site. It was found that the concentration of Sr did not change statistically significantly based on soil depth.
2. Based on species, the lowest Sr, Tl, and V values were obtained in *Pinus nigra* in the spoil area and *Pinus sylvestris* in the forest area, and the highest values were obtained in *Pinus nigra* in the forest area. Notably, the areas where the lowest values were obtained and spoil area were in the same group, as revealed by Duncan's test. In plants, the highest values were acquired in *Robinia pseudoacacia* in both the spoil and forest areas.
3. On an organ basis, the lowest Sr, Tl, and V values were found in wood. In wood, the highest values were again acquired in *Robinia pseudoacacia*. The highest values in *Robinia pseudoacacia* organs were obtained in leaves in spoiled and forest areas.
4. As a result of the study, *Pinus nigra* and *Robinia pseudoacacia* were found to be very suitable bioaccumulators for Sr and Tl. *Pinus nigra* and *Robinia pseudoacacia* can be used for phytoremediation in areas with high pollution of these elements.

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