Using Trees to Monitor Airborne Cr Pollution: Effects of Compass Direction and Woody Species on Cr Uptake during Phytoremediation

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Among the heavy metals (HMs) whose concentrations in natural environments have risen considerably in the last era, chromium (Cr) is one of the most toxic. Because of the risks it poses to human and environmental health, it is of great importance to screen the variation in Cr contamination in the atmosphere and decrease the pollution. This study aimed to determine the proper tree species that can be used to monitor and reduce Cr contamination. For this aim, studies were conducted on *Tilia tomentosa*, *Robinia pseudoacacia*, *Cedrus atlantica*, *Pseudotsuga menziesii,* and *Fraxinus excelsior* species growing in Düzce, which is among the 5 most contaminated European towns according to the World Air Pollution report. Samples taken from these trees were examined, and changes in Cr concentration depending on species, organs, compass direction, and age range in the last 60 years were evaluated. Results indicated higher Cr pollution in recent years, consistent with higher traffic density, but that there was no consistent effect of compass direction. It was also determined that the tree species most appropriate for screening the variation in Cr contamination in the airborne were *Tilia tomentosa*, and the most appropriate species for decreasing pollution were *Robinia pseudoacacia* and *Cedrus atlantica*.

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INTRODUCTION

Global climate change, urbanization, and pollution, which are among the most critical and irreversible problems on a global scale today, have emerged because of the developments in industry and technology in the last century (Gur *et al.* 2024; Özel *et al.* 2024). In the last century, the workforce needed in the industrial field caused the population to migrate from rural to urban areas and gather in certain areas, which has led to various problems (Dogan *et al.* 2022; Cetin *et al.* 2023a). Excessive use of fossil fuels to produce the energy needed to meet the needs of industry and people has led to an increase in various gases in the atmosphere, disruption of atmospheric gas balance, and ultimately, global climate change (Tekin *et al.* 2022; Ozel *et al.* 2024). Mining activities and processing products to provide the raw materials needed for industrial activities have rapidly increased environmental pollution (Key *et al.* 2023; Kuzmina *et al.* 2023).

Urbanization and global climate change have become seemingly irreversible concerns in this era (Arıcak *et al.* 2024). Pollution has become a global problem that threatens all living things and ecosystems. Air pollution has reached such severe levels that it was reported that 99% of the worldwide population is subjected to low air quality; outdoor air pollution is estimated to have caused 6.7 million premature deaths annually (WHO 2022; Ghoma *et al.* 2023).

Among the categories of air pollutants, heavy metals (HMs) pose the most severe threat to human and environmental health. It is stated that HMs, some of which can be detrimental, poisonous, and lethal to people even in low amounts, can be dangerous at high concentrations, even those that are necessary as nutrients for living things (Ucun Ozel *et al.* 2019; Istanbullu *et al.* 2023). Among HMs, Cr is one of the most dangerous, and Cr contamination extremely disturbs ecosystems and environmental reserves, especially soil and water (Prasad *et al.* 2021).

Cr, a naturally occurring element in volcanic dust and rocky soils, is categorized as a carcinogen, according to the IARC (International Agency for Research on Cancer) (Sharma *et al.* 2020). Cr usually exists in two oxidative states, Cr(III) and Cr(VI). Cr(III) is harmful at high levels surpassing the limit, but Cr(VI) is 100 times more poisonous and 1000 times more mutagenic than Cr(III). Cr(VI) is a natural carcinogen, even in trace amounts. Cr(III) present in the soil is naturally oxidized to Cr(VI) during alkaline conditions or the presence of increased manganese contents (Benimeli *et al.* 2011; Suzuki *et al.* 2020). Due to its potential harm, it is included in the priority toxin catalog of ATSDR (Agency for Toxic Substances and Disease Registry) (Savas *et al.* 2021). Cr is released from numerous natural and anthropogenic activities (Hossini *et al.* 2022; Ullah *et al.* 2023). In the last 40 to 50 years, its contamination in aquatic and terrestrial biomes has become elevated due to several anthropogenic actions, which are influential environmental threats that utterly affect the environment and natural reserves, especially water and soil (Koç *et al.* 2024). Overexposure may lead to accumulation at higher levels in human and animal tissues, resulting in toxic and harmful health effects. Numerous studies have revealed that Cr is a noxious element that unfavorably affects plant metabolic behaviors (Prasad *et al.* 2021). Chronic exposure and bioaccumulation of Cr induces toxicity. It causes numerous pathophysiological defects such as allergic reactions, anemia, burns, and wounds, particularly in the stomach and small intestine, and damage to sperm and the male reproductive system (Hossini *et al.* 2022), lung cancer, stomach, liver, and kidney injury and epidermal irritation and sensitivity (Kimbrough *et al.* 1999).

Monitoring and reducing the levels of Cr pollution are priority research topics. Monitoring and reducing the change in airborne concentrations of Cr is vital, since the metal is extremely dangerous, particularly if absorbed into human tissue *via* inhalation (Yayla *et al.* 2022; Koc *et al.* 2024).

Trees exposed to air pollution for a long time can absorb pollutants with their roots, leaves, and bark, and transport them to the wood. Tree annual rings formed every year in wood can provide clues about the effects of atmospheric pollution. Many trials have been conducted to detect HM pollution in polluted areas and monitor the history of pollution using tree wood (Edusei 2021; Isinkaralar 2022; Cuciurean *et al.* 2024). Studies in recent years have shown the correlation between urban and industrial areas and the chemical content of tree rings, showing that tree annual rings can be used as biomonitors in monitoring HM concentrations (Chen *et al.* 2021; Savas *et al.* 2021; Key *et al.* 2023; Cobanoglu *et al.* 2023).

The region where the research was performed is the 5th most unclean city in Europe and has attracted the attention of many researchers due to its high pollution level. In the studies conducted in the region, the usability of *Cupressus arizonica*, *Pseudotsuga menziesii, Cedrus atlantica, Picea orientalis,* and *Pinus pinaster* species, which are widely grown in the region, were examined as potential biomonitors. In these studies, the highest values in wood were obtained on average in *Picea orientalis* with 1848 ppb for Cr (Koc *et al.* 2024) and 5323 ppb for Sr (Erdem 2023), in *Cupressus arizonica* with 11065 ppb for Pd (Sevik *et al.* 2024), 53000 ppb for Bi (Isinkaralar *et al.* 2023), 2105 ppb for Sn (Cetin *et al.* 2023b), and 4672 ppb for Tl (Canturk 2023).

For many years, plants have been used to screen the shifts in HM contamination in the airborne and phytoremediation studies aimed at diminishing pollution (Sulhan *et al.* 2023). However, different characteristics are required in both the species used as biomonitors and the plants used in phytoremediation studies. For plants to be used for both purposes, the plants must be able to absorb and accumulate HMs, but they must not die due to the effects of pollution. While the allocation of HM in wood should be limited in species that will be used as biomonitors (Canturk 2023; Key *et al.* 2023), in species that will be used to decrease pollution, it is desired that HM accumulate as much as possible, especially in wood, which is the main organ of the tree in terms of mass (Sevik *et al.* 2024; Koç *et al.* 2024). Therefore, choosing the proper trees for biomonitoring and phytoremediation analyses is essential. The current study aimed to define Cr concentration variation in the atmosphere over the last 60 years in Düzce, Türkiye, one of the uppermost air-polluted European towns, and to conclude the most appropriate tree species that can be used to lessen contamination. The main hypothesis of the research is that the accumulation of Cr in the organs of the studied species varies based on the direction of the compass.

EXPERIMENTAL

Düzce province, where the study samples were collected, has Europe's 5th highest pollution level, based on the World Air Pollution Report 2021 (Koc *et al.* 2024). The topography and meteorological parameters of Düzce province, located in the Western Black Sea province of Türkiye, play a part in the increased air pollution. The primary pollutants that cause air pollution in Düzce arise from industrial facilities, domestic fuel use, and vehicle traffic load (Key *et al.* 2023).

The log samples used in this study were obtained from the trunks of *Tilia tomentosa* (linden), *Robinia pseudoacacia* (acacia), *Cedrus atlantica* (cedar), *Pseudotsuga menziesii* (Douglas fir), and *Fraxinus excelsior* (ash) trees, which are widely used in landscaping in Düzce province. Log samples were taken at a thickness of 10 cm from a height of approximately 40 to 50 cm above the ground in late autumn of 2022. When taking log samples of these species, directions (North, South) were indicated on the logs. Samples taken from the trunk stumps were first sanded in the laboratory to smooth the upper surface so that the annual rings could be seen more clearly.

Annual rings were grouped according to their width and the tree's age. For this reason, trees that were approximately 60 years old were divided into 5-year age groups. Then, using a stainless-steel drill, samples from the wood (WD) of each age range, as well as outer bark (OB) and inner bark (IB), were taken and placed in glass Petri dishes. Samples were turned into sawdust without using any tools made of the metals examined in the research. After the samples were placed in glass containers without closing their lids, they were left room-dried in the laboratory for 15 days until they were completely dried, followed by drying for another week in an oven set at 45 °C. Then, 0.5 g of the dried samples were taken, and 6 mL 65% nitric acid (HNO_3) and 2 mL 30% hydrogen peroxide (H_2O_2) were added and positioned in the microwave oven. The microwave oven was set to reach 200 °C within 15 min and kept at 200 °C for 15 min. After the samples were burned, the obtained samples were transferred to volumetric bottles, and the final volume was completed at 50 mL with ultrapure water. Samples were analyzed using the ICP-OES (Inductively Coupled Plasma-Optic Emission Spectrometer; GBC Scientific Equipment Pty Ltd., Melbourne, Australia) instrument, and Cr concentrations were determined by multiplying the results by the corresponding dilution factor. This procedure has been commonly used in earlier studies (Isinkaralar *et al.* 2022; Erdem *et al.* 2023).

An analysis of variance (ANOVA) was used to analyze the data using the SPSS 22.0 package program. The Duncan test was also applied for factors indicating statistically significant differences at the minimum 95% confidence level ($p < 0.05$).

RESULTS AND DISCUSSION

The results regarding the detected Cr concentrations based on tree species and direction are illustrated in Fig. 1.

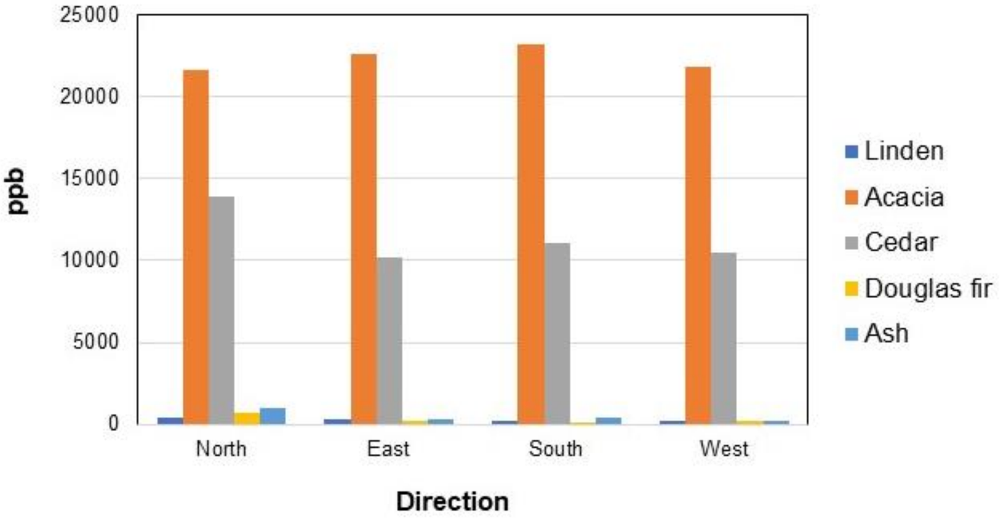

Fig. 1. Cr concentration variations based on tree species and direction

The ANOVA results indicate that the Cr concentration variation in all directions was statistically significant. The Cr concentration change based on direction was determined to be statistically significant in all species except linden. According to the mean concentrations, the uppermost value was found in acacia and the lowest in Douglas fir, ash, and linden. According to the average values, the highest (22400 ppb) was 92 times more than the lowest (242 ppb). The Cr concentration variation based on tree and age period is presented in Fig. 2.

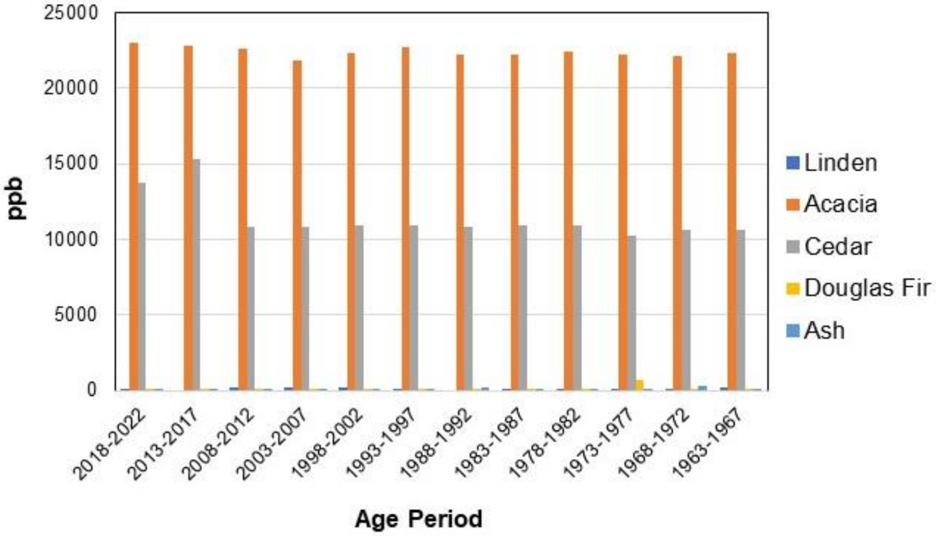

Fig. 2. Cr Concentration levels by tree species and period

Cr concentration differences were statistically noteworthy based on a species in all periods and a period basis in all species except acacia. While the uppermost value for linden was obtained in the 1988-1992 period, the highest value for cedar was obtained in the 2013-2017 and 2018-2022 periods. According to the mean concentrations, the uppermost value is in acacia, while the lowest was in linden, Douglas fir, and ash tree. Based on average concentrations, the value obtained in acacia wood was 200 times higher than in ash wood. The Cr concentration variation by organ and species is presented in Fig. 3.

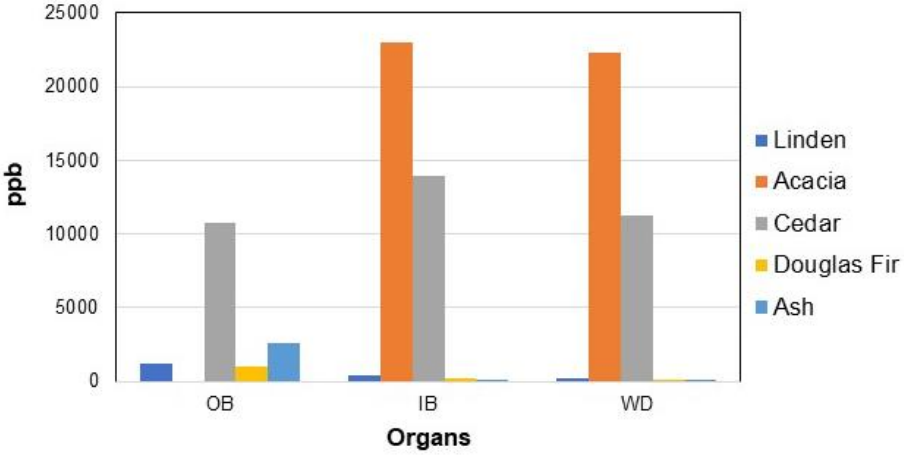

Fig. 3. Cr concentration variation by organ and tree species

Cr concentration level was statistically significant based on a species in all organs and an organ basis in all species except acacia. In linden, Douglas fir, and ash, the uppermost value was acquired in the outer bark, while in cedar, the maximum concentration was in the inner bark. According to the mean values based on species, the highest value is in acacia, while the lowest is in linden, Douglas fir, and ash. The Cr concentration variation in the linden tree based on organ, direction, and period is presented in Table 1.

Table 1. Cr Concentration Variation in Linden Tree Based on Organ, Direction, and Period

Age	North	East	South	West	F-value	Avrg
2018-2022	188 hC	BDL	110 dB	22 aA	652***	107 ab
2013-2017	811 jD	302 fC	30 abA	245 fB	4766***	347 cd
2008-2012	102 eB	206 dC	33 bA	293 gD	409***	159 ab
2003-2007	45 bcA	208 dC	76 cB	367 hD	1899***	174 ab
1998-2002	312 iB	14 aA	BDL	366 hC	490***	231 bc
1993-1997	55 cB	184 cD	15 aA	104 dC	428***	90 ab
1988-1992	162 gB	994 gD	367 gC	83 cA	3695***	402 d
1983-1987	78 dC	22 aA	BDL	64 bB	22**	55 a
1978-1982	BDL	114 bA	152 eC	135 eB	7*	134 ab
1973-1977	11 Aa	128 bD	77 cB	110 dC	272***	82 ab
1968-1972	33 Ba	171 cC	175 fC	104 dB	180***	121 ab
1963-1967	139 f	251 e	136 e	BDL	132***	176 ab
F-value	1988***	2332***	346***	512***		5***
WD	176	236	117	172	2.0 ns	177 a
OB	2867 bD	847 bC	567 bA	689 bB	29580***	1242 b
IB	265 aC	126 aA	882 cD	192 aB	4268***	366 a
F-value	230***	9**	113***	28***		57***

Based on Duncan's analysis results, numbers followed by the same letters are not statistically significant at $P > 0.05$. Capital letters indicate horizontal direction, while lower-case letters are vertical. Avg: Average; OB: Outer bark; IB: Inner bark; WD: Wood; BDL: Below detectable limit. Significant levels such as * = 0.05; ** = 0.01; *** = 0.001. These explanations are valid for all tables.

Cr concentration change in linden was statistically significant based on the direction in all organs except wood and on an organ basis in all directions. The uppermost value in the outer bark was observed in the north direction, while the lowermost value was obtained in the south. The uppermost value was achieved in the south direction in the inner bark, while the lowermost was in the east. The uppermost value was seen in the outer bark when considering the organs based on the means. While the value achieved in the outer bark in other directions was between 567 ppb and 847 ppb, it was seen at 2867 ppb in the north. This value was more than 16 times the value determined in the wood. The difference between the wood and the outer bark was less than 5 times in other directions.

According to the ANOVA results, Cr concentration differences in the linden tree were statistically significant based on direction in all periods and on a period basis in all routes. The maximum value in the north was achieved in the 2013-2017 period, the uppermost value in the south and east was in the 1988-1992 period, and the uppermost value in the west was in the 1998-2002 period. The 1978-1982 period in the north, the 2018-2022 period in the east, the 1983-1987 period in the north, and the 1963-1967 period in the west direction under the determinable limits. When the average values are examined according to the periods, the highest value was found in 1988-1992. The Cr concentration variation in the acacia tree based on plant organ, direction, and period is presented in Table 2.

Table 2. Cr Concentration Variation in Acacia Tree Based on Organ, Direction, and Period

Age	North	East	South	West	F-value	Avrg
2018-2022	BDL	23110	23400	22540 cde	1.5 ns	23020
2013-2017	BDL	22170	23220	22880 e	1.8 ns	22750
2008-2012	BDL	22330	23280	22200 bcde	2.4 ns	22600
2003-2007	18500	22500	23520	22620 de	1.4 ns	21790
1998-2002	22000 A	22200 AB	23180 B	21650 abcA	4.5*	22260
1993-1997	23080 B	22820 A	23370 A	21570 abA	4.3*	22710
1988-1992	22190	22010	23060	21540 ab	3.9 ns	22200
1983-1987	21770	22490	23030	21540 ab	3.5 ns	22210
1978-1982	21950 A	22500 A	23560 B	21750 abcdA	7.8**	22440
1973-1977	21670 AB	22470 BC	23140 C	21480 abA	8.4**	22190
1968-1972	21820 AB	22680 B	22900 B	20990 aA	6.2*	22100
1963-1967	21680 A	22780 B	23310 B	21280 abA	11.1**	22260
F-value	1.0 ns	0.7 ns	0.2 ns	4.1**		0.7 ns
WD	21630 A	22510 B	23250 C	21840 A	14.3***	22349
OB	21950 A	22710 aAB	23460 B	21760 A	5.7*	22470
IB	BDL	23960 bC	22950 B	22050 A	7.5*	23000
F-value	0.0 ns	8.4**	0.5 ns	0.1 ns		1.1 ns

Cr concentration in acacia was not statistically significant based on tree organs in all routes except the east. It was found to be statistically significant regarding direction in all organs. The uppermost value in the east direction was found in the inner bark. In the north direction, the inner bark remained under measurable limits. When looking at the directions according to the mean concentrations, the highest Cr concentrations were achieved in the south and the lowermost in the north and west.

Cr concentration in acacia was not statistically significant based on a period in all directions except the west. Cr concentration change was statistically meaningful based on the direction in 1963-1967, 1968-972, 1973-1977, 1978-1982, 1993-1997, and 1998-2002. The uppermost value in the western direction was achieved in the 2013-2017. In the northern direction, the periods 2008-2012, 2013-2017, and 2018-2022 remained under the determinable limits. Based on averages, the maximum Cr concentrations were achieved in the south, while the lowermost values were in the north and west. The Cr concentration difference in cedar tree based on tree organ, direction, and period is presented in Table 3.

Cr concentration variation in cedar tree was statistically significant based on organs in the north and south directions and a direction basis in all organs. While the uppermost value in the north was achieved in the inner bark, in the south, the uppermost value was acquired in the outer bark and wood. The highest Cr concentration was found in the north direction when looking at the directions according to the average values. Unlike other species, the cedar tree obtained the highest Cr concentration in the north route in the inner bark, more than twice that acquired in the outer bark.

Table 3. Cr Concentration Variation in Cedar Tree Based on Organ, Direction, and Period

Age	North	East	South	West	F-value	Avrg
2018-2022	23630 eB	10290 cdefA	10300 aA	10740 cA	970***	13740 b
2013-2017	23980 eB	BDL	10960 bA	11070 cA	2820***	15340 b
2008-2012	12390 dC	9070 aA	10990 bB	11010 cB	135***	10860 a
2003-2007	11600 cC	10060 bcA	10970 bB	10730 cB	53***	10840 a
1998-2002	11460 bcC	10100 bcdA	11080 bcB	10970 cB	25***	10900 a
1993-1997	11310 abcC	10030 bA	11150 bcdBC	10970 cB	52***	10870 a
1988-1992	11130 abcB	10230 bcdeA	11090 bcB	10830 cB	13**	10820 a
1983-1987	11130 abcC	10380 efgA	11210 cdeBC	10940 cB	23***	10920 a
1978-1982	11130 abcC	10320 defA	11410 efD	10850 cB	58***	10930 a
1973-1977	10780 aBC	10390 efgB	11270 cdeC	8470 aA	46***	10230 a
1968-1972	10990 abC	10510 fgB	11340 defC	9520 bA	29***	10590 a
1963-1967	10820 aB	10590 gB	11520 fC	9550 bA	123***	10620 a
F-value	875***	28***	25***	28***		3.8***
WD	13360 B	10180 A	11110 A	10470 A	12***	11300 a
OB	10810 aC	10630 B	11310 bB	10330 A	38***	10770 a
IB	24170 bC	10220 A	10660 aB	10710 B	3358***	13940 b
F-value	8.7**	1.8 ns	3.9*	0.1 ns		4.5*

Table 4. Cr Concentration Variation in Douglas Fir Tree by Organ, Direction, and Period

Age	North	East	South	West	F-value	Avrg.
2018-2022	BDL	48 cB	29 aA	167 eC	188***	81 a
2013-2017	BDL	28 abA	50 bB	81 cC	24**	53 a
2008-2012	BDL	220 gB	65 bA	BDL	162***	143 a
2003-2007	BDL	88 d	BDL	BDL	-	88 a
1998-2002	BDL	53 c	BDL	BDL	-	53 a
1993-1997	21 aA	114 eC	98 cB	BDL	322***	77 a
1988-1992	BDL	37 bc	BDL	16 a	3 ns	26 a
1983-1987	BDL	18 a	BDL	BDL	-	18 a
1978-1982	BDL	77 dA	BDL	155 dB	298***	116 a
1973-1977	1260 d	82 d	BDL	BDL	112550***	672 b
1968-1972	200 cC	122 eB	BDL	14 aA	1350***	112 a
1963-1967	50 bB	146 fA	14 aA	60 bC	637***	68 a
F-value	89630***	104***	25***	791***		6***
WD	383 B	86 A	533 A	82 A	7***	123 a
OB	1770 bD	1003 cC	51 aA	891 cB	4700***	1050 b
IB	BDL	201 bB	183 bA	341 bC	264***	241 a
F-value	19**	406***	361***	274***		65***

Cr concentration change in cedar was statistically significant in all routes based on period and in all periods based on direction. The highest value in the eastern and southern directions was obtained in 1963-1967. When one looks at the mean concentrations according to the periods, the maximum value was achieved in the 2013-2017 and 2018-2022 periods. Again, based on the directions, the uppermost average value is in the north. In the eastern direction, the 2013-2017 period remained under the determinable limits. The Cr concentration variation in Douglas fir tree by organ, direction, and period is presented in Table 4.

Cr concentration change in Douglas fir was statistically significant in all directions based on tree organs and in all organs based on route. It is possible to arrange wood < inner bark < outer bark for east and west directions. In the south direction, on the contrary, the ranking is outer bark < inner bark < wood. The uppermost value was achieved in the north according to the mean concentrations. In the north direction, the inner bark remained under measurable limits. The most notable result in Douglas fir was the significant difference between the values obtained in the outer bark. The value obtained in the north direction in the outer bark was more than 30 times the value obtained in the south direction.

According to the ANOVA results, Cr concentration variation in Douglas fir was determined to be statistically meaningful in all directions based on period. Cr concentration was at a statistically noteworthy level on a directional basis in all periods except the 1983-1987, 1998-2002, and 2003-2007 periods. While the uppermost value in the north was seen in the 1973-1977 period, the maximum value in the south was in 1993-1997. The uppermost value in the east was seen in the 2008-2012, while the highest value in the west was seen in the 2018-2022 period. According to the averages, the uppermost Cr was achieved in 1973-1977.

Table 5. Cr Concentration Variation in Ash Tree Based on Organ, Direction, and Period

Age	North	East	South	West	F-value	Avg.
2018-2022	BDL	56 bc	39 a	BDL	7 ns	47 a
2013-2017	42 bB	28 aA	BDL	BDL	13*	35 a
2008-2012	21 aA	124 eC	BDL	87 dB	285***	78 a
2003-2007	BDL	146 fC	36 aA	83 dB	145***	88 a
1998-2002	350 cC	89 dB	92 bB	22 aA	1706***	138 ab
1993-1997	BDL	65 cB	38 aA	BDL	30**	51 a
1988-1992	BDL	377 gC	151 dB	68 cA	1805***	199 bc
1983-1987	BDL	46 bA	188 eC	50 bB	287***	95 a
1978-1982	BDL	124 eC	114 cB	28 aA	205***	89 a
1973-1977	BDL	78 d	BDL	BDL	-	78 a
1968-1972	BDL	438 hB	BDL	109 eA	3720***	273 c
1963-1967	BDL	23 aA	BDL	85 dB	58**	54 a
F-value	1920***	1264***	170***	63***		4***
WD	138 a	133 a	94 a	67 a	2.4 ns	107 a
OB	4560 bD	2045 bB	2450 bC	1399 bA	1885.2***	2613 b
IB	12 aA	230 aB	BDL	BDL	1573.3***	120 a
F-value	1330***	330***	4791***	3798***		200***

Cr concentration change remained under the measurable limits in the north direction in periods other than 1963-1977 and 1993-1997, in the south in 1968-1992 and 1998-2007 periods, and in the west in 1973-1977, 1983-1987, and 1993-2012 periods. The

Cr concentrations change in the Ash tree based on organ, direction, and period is presented in Table 5.

Cr concentration changes in ash tree samples were statistically significant on a directional basis in the outer and inner bark and on an organ basis in all directions. The uppermost value in all directions was obtained in the outer bark. The highest value was achieved in the north according to the mean concentrations. The Cr concentration change in the inner bark in the south and west remained under measurable limits. It is seen that the concentrations achieved in the outer bark were much higher than the concentrations found in the wood in all directions. Even in the east, where this difference was the least, the value obtained in the outer bark was more than 15 times that in the wood. This difference exceeded 33 times in the north direction. Considering the results, it was defined that the Cr concentration variation in the ash tree was statistically significant on a directional basis in periods other than the 1973-1977 and 2018-2022 periods. The highest value was achieved in 1968-1972 according to mean values. In the northern direction, the Cr concentration change remained under measurable limits in all periods except 1998-2002, 2008-2012, and 2013-2017. The Cr concentration change remained under the measurable limits in the south in the 1963-1977 and 2008-2017 periods and in the west direction in the 1973-1977, 1993-1997, and 2013-2022 periods.

According to the current study, the highest values based on a species were obtained in acacia and cedar. When the values are examined, the average Cr concentration was 22400 ppb in acacia and 11460 ppb in cedar, while it varied between 240 ppb and 390 ppb in other species. The species' biology and interaction with HMs explain the large difference between species. Many studies have determined that HM concentrations vary significantly from species to species (Karacucuk *et al.* 2022; Yayla *et al.* 2022). The average Cr concentrations obtained in the studies were also quite different. While Savas *et al.* (2021) stated that the Cr concentration in *Cedrus atlantica* ranged between 923.3 ppb and 1588.4 ppb in the outer bark and 445.1 ppb and 765.8 ppb in the wood, Isinkaralar (2024) reported that the Cr concentration in *Ailanthus altissima* was 34480 ppb in the outer bark and 940 ppb in the wood. In the current study, there were significant differences between organs. For example, while the Cr concentration determined in the wood of linden was 180 ppb, this value was 370 ppb in the inner bark and 1240 ppb in the outer bark. Similarly, while the Cr concentration determined in the wood of linden was 110 ppb, this value was 120 ppb in the inner bark and 2610 ppb in the outer bark.

As can be seen, the Cr concentration variation on both species and organ basis was as high as 10-fold. Variation based on a species was mainly shaped by plant physiology and anatomy and the plant's interaction with HMs. Studies have determined that each plant's HM uptake and accumulation levels are different, and the change in HM concentration on a species basis can vary greatly (Koç *et al.* 2024; Öztürk Pulatoğlu *et al.* 2024). For this reason, it is frequently stated that bioaccumulator species should be determined separately for each HM (Sulhan *et al.* 2023; Sevik *et al.* 2024).

As a result, it was determined that the Cr concentrations in the outer bark were much higher than those in the wood and that the Cr concentration was generally in the order outer bark > inner bark > wood. Most studies obtained similar results (Key *et al.* 2022; Koc *et al.* 2024). This situation is primarily related to the structure of the outer bark and the contamination of particulate matter with HMs. After HMs are dispersed from their source, they adhere to particulate matter, which becomes a sink for HMs to collect. Afterward, contaminated particulate matter in the atmosphere sticks to the bark of trees, and the rougher the bark, the more particulate matter can adhere. Thus, HM concentrations in the outer bark can reach very high levels (Cesur *et al.* 2022). Afterward, these HMs can pass into the wood because HMs have three pathways to penetrate the plant tissue. These pathways are direct from the leaf through stomata, soil through the roots, and stem parts, namely the bark (Cobanoglu *et al.* 2023). If one accepts that all three routes are variable, then it can be expected that the higher the amount of HM accumulated in the outer bark, the higher the HM accumulation in the inner bark and the wood.

This study obtained the highest values for cedar, Douglas fir, and ash trees in the north direction. In fact, in these species, as a result of the Duncan test, the values obtained in other directions formed the first group, while those obtained in the north direction formed the second group. In studies with similar results, these findings were often interpreted as a direct result of heavy metal accumulation in roadside woods caused by traffic (Sulhan *et al.* 2023; Yayla *et al.* 2022; Canturk *et al.* 2024). However, the reality is far more complex. A multitude of studies have indicated that traffic and vehicles are indeed significant sources of heavy metals (Aricak *et al.* 2019; Kuzmina *et al.* 2023). Yet, when one delves into the subject, it is found that a highly intricate mechanism governs the entry of heavy metals into the plant body. According to Ejaz *et al.* (2023), heavy metals can translocate from the roots *via* the stem or enter the leaf through the stomata. Metals are usually transferred by active transport *via* the symplastic pathway inside cells after diffusion or penetration. Plant biochemical and metabolic activities play a pivotal role in the active transport of heavy metals inside plants (Shahid *et al.* 2017). The current understanding of the mechanism of Cr absorption and transport by plants in the soil is still in its infancy. Sulfate transporters have been identified as crucial for the movement of Cr in roots, as several recent studies have shown (Xu *et al.* 2023). The simultaneous occurrence of the two absorption pathways near urban and industrial locations makes it extremely challenging to discern whether the metal concentration within internal plant tissues is taken up by root cells from the soil or leaf surfaces from the atmosphere (Shahid *et al.* 2017).

The main hypothesis of the research is that the distribution of Cr accumulation in the organs of the studied species relies on the direction of the compass. It could have concluded that, despite the study’s findings highlighting variations in the directions, there was no consistent pattern in the data about compass directions. The distribution and accumulation of Cr in plants differed among species and was impacted by plants’ morphological and genetic traits. Furthermore, the absorption and enrichment of heavy metals in plants would be influenced by several variables, including the concentration of heavy metals in the soil, bioavailability, and the physical and chemical characteristics of the soil (Xu *et al.* 2023).

This situation indicates that the entry of metals into tree rings varies depending on other factors, as the data do not support the hypothesis. For instance, it is commonly known that water moves upward from a tree’s roots *via* the xylem of the previous year. An alternative route could be *via* ray cells that pass through the phloem tissue and reach specific areas of the xylem. Since a leaf oriented away from the wind is nevertheless predicted to be impacted by the wind, the second mechanism contradicts the first theory. The lower xylem on that side of a tree cannot be penetrated by any mechanism if metal falls on its trunk (Shahid *et al.* 2017; Wani *et al.* 2018). Moreover, studies have shown that the translocation of Cr in the plant body is more limited than other metals such as As, Hg, and Cd, and it mainly accumulates in plant roots (Xu *et al.* 2023). It was concluded that there is no empirical evidence to support the mechanism that would have been expected to have contributed to a consistent directionality. These findings led to the study's hypothesis being rejected.

In general, when the results were evaluated, the values obtained in the outer bark were much higher than the values obtained in the wood. The values, especially in the outer bark, were very high in the north direction. Indeed, in previous studies conducted in the region, it was determined that the HM concentrations in the soil were generally below the detectable limits; however, especially in the north direction where traffic is heavy, HM concentrations were determined to be at quite high levels both in the outer bark in this direction and it was emphasized that this accumulation was due to the HM load in the air (Cetin *et al.* 2023b; Erdem 2023; Koc *et al.* 2024). It is plausible that the direction of prevailing wind could contribute to a directional dependency of metal accumulation in outer bark.

Within the scope of the research, the aim was to define suitable species to reduce HM pollution in the air. Studies conducted in the region showed that there were large differences between the concentrations of heavy metals such as Cr (Koc *et al.* 2024), Pd (Sevik *et al.* 2024), Sn (Cetin *et al.* 2023b), and Tl (Canturk *et al.* 2023) in wood annual rings formed in different periods. It was stated that these differences were due to the alteration in HM pollution in the air during the process.

In addition, studies have shown that heavy metals are carried in the air by adhering to particulate matter in the air, but after a while, they mix into the soil and water under the influence of gravity and precipitation (Qiao *et al.* 2023; Han *et al.* 2024).

After particulate matter leaves its source, it can be carried away by adhering to particulate matter in the air and then mixed into the soil and water with gravity and precipitation. After this stage, the root can absorb into the plant body, enter the air via the leaves, and accumulate directly in the stem parts (Key *et al.* 2023). The transport of elements within the wood part of plants is largely related to the cell structure and, especially, the cell wall. In addition to being an apoplastic mechanical barrier, the cell wall–plasma membrane (CWPM) interface is a flexible structure that is involved in stress sensing, perception, and signaling for the metal/metalloid stress. The CWPs in crop plants have been widely identified and described in response to different abiotic stressors. Salt-overly sensitive kinases (SOS), phospholipases, transcription factors, C-repeat binding factor, mitogen-activated protein kinases and phosphatases, dehydration-sensitive element-binding proteins, and abscisic acid-responsive binding factors are the main (CWPM) under different stress conditions. Given that it collects significant amounts of HMs, the CWPM interface is thought to be the possible location of HM tolerance (Wani *et al.* 2018). The wood part does not have direct contact with soil or air, and heavy metals must be transported and accumulated within the plant structure. Therefore, wood is generally the organ with the lowest concentration of heavy metals (Şevik *et al.* 2024). This may be due to different ion exchange capacities of xylem in different tree species. The amount of metal ions adsorbed onto biomaterials is governed by the ion exchange capacity (IEC) (Hubbe *et al.* 2011). For one mole of metal sorbed, there is one mole of Ca displaced (Crist *et al.* 2003). In other words, each adsorbed metal ion is predicted to displace several other ions, such as sodium or hydrogen, corresponding to the valence of the metal species (Hubbe 2013). Most cellulosic materials can bind with positively charged ions (Hubbe *et al.* 2022). A complex and multipurpose system, the plant cell wall is a component of the apoplast. The plant cell wall regulates the periplasmic medium's composition and the passage of ions and metabolites across the plasma membrane because it contains ion-exchange groups (Meychik *et al.* 2017).

In the current study, there was no statistically significant difference between the periods in acacia, one of the species with the highest Cr concentrations. At the same time, the values obtained in cedar showed a notable increase in the last two periods (2013-2022 period). Similar results were obtained in different studies. Isinkaralar (2024) states that there was a significant increase in Cr concentration recently; for example, the Cr concentration in the eastern direction, which ranged between 439.4 ppb and 787.3 ppb between 1987 and 2016, increased to an average level of 1711.4 ppb after 2017. Cesur *et al.* (2021), who obtained similar results, stated that increased HM concentrations in recent years are due to increased vehicle numbers and traffic density.

The study's main objectives include determining suitable biomonitors that can be used to monitor Cr pollution and accumulator species that can be used to diminish Cr contamination. The most important feature sought in screening the variation in HM pollution is that the HM does not move or transfer within the wood tissue (Key *et al.* 2022). Studies have determined that some elements can be transferred in different types of wood, while the transfer of some elements is limited. For example, it has been determined that the transfer of Mn, Cr, and Ni in *Cedrus atlantica* (Koç 2021; Savas *et al.* 2021), Ni, Cd, Ni, Zn, and Fe in *Cupressus arizonica*, (Cesur *et al.* 2021; 2022;), Cd, Zn, Cr, Al, Pb, and Fe in *Corylus colurna* (Key *et al.* 2022; Key and Kulaç 2022), and Pd in *Pinus pinaster*, *Pseudotsuga menziesii*, and *Picea orientalis* woods is limited. On the other hand, it was determined that Co could be transferred in the wood of *Cedrus atlantica* (Koc 2021), Pb and Zn in *Cedrus deodora* (Zhang 2019), Bi, Li, and Cr in *Cupressus arizonica* (Zhang 2019; Cesur *et al.* 2021; 2022; Cobanoglu *et al.* 2023). As a result of the study, it was determined that there were large differences between the Cr concentrations in wood formed in different directions in the same year. This shows that the transfer of Cr in the wood of the species subject to the study is limited. The cell wall physically plugs heavy metal entrances into the plant cell. Interestingly, it is still unclear how heavy metals are contained within the cell wall (Ejaz *et al.* 2023).

This study determined that this feature was found only in linden among the tree species subject to the research. In the linden tree, there was a significant difference between Cr concentrations obtained in successive periods in the same direction and neighboring directions in the same period. This result shows that the displacement of Cr within the wood tissue is limited, and therefore, the linden tree is a good biomonitor for monitoring Cr pollution.

As a result, the uppermost Cr concentrations, especially in wood, were achieved in acacia and cedar trees. Therefore, these trees can be recommended as suitable accumulator species that can be used to decrease Cr contamination. However, when the alteration in Cr concentration in these species was examined, there were no significant differences between neighboring tissues. Therefore, these species are unsuitable biomonitors that can be used to monitor changes in Cr pollution.

CONCLUSIONS

1. It was concluded that only the linden tree, among the trees subject to the study, was a proper biomonitor for monitoring the change in Cr contamination in the air. The linden tree can be used to screen the Cr pollution variation during the process.

2. The acacia and cedar species were found to accumulate Cr intensively in their wood and bark. These species can be used to decrease Cr contamination.
3. Cr pollution has recently increased in the study area, and it has been concluded that this pollution is caused by traffic. Intensive planting of species that accumulate Cr between highways and agricultural or residential areas can ensure that traffic-related Cr pollution affects agricultural and residential areas less.
4. Although the element concentration in the north direction (where the traffic exists) was high in some species in the study, the study results are inadequate to demonstrate that the Cr concentration changes significantly depending on the direction. Many factors control the entry of heavy metals into the plant body and their transport between plant organs. For this reason, it is recommended that these factors be examined separately in future studies and their effects determined.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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