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Determining the plants to be used in monitoring the change in thallium concentrations in the air

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SILVICULTURE

ABSTRACT

Background: Thallium (Tl), which is one of the most toxic and destructive heavy metals for human and environmental health, has a higher level of chronic and acute toxicity in comparison to many harmful elements (such as Pb, Hg, Cd, and As) in comparison to many harmful elements and is classified as one of 13 primary metal contaminants by the US EPA (United States Environmental Protection Agency) and in ATSDR's primary pollutant list. Thus, monitoring the Tl pollution in the air and reducing the pollution are among the primary research subjects. The existing study aims to determine the species that are suitable for monitoring and reducing the Tl pollution in Düzce province, Türkiye, which is the fifth-most polluted province in Europe in terms of air pollution. This study analyzed the changes in Tl concentration in the samples (wood, outer and inner bark) taken from species grown in Düzce by species, organ, direction, and age groups in the last 40 years.

Results: As an outcome, the uppermost Tl concentrations were found in the outer barks, and it is thought to be caused by air pollution. The outcomes achieved in the existing study revealed that the suitable species to be used in watching the Tl pollution in the air are *Cupressus arizonica* and *Picea orientalis*, whereas those to be used in reducing the Tl pollution are *Pinus pinaster, Cedrus atlantica*, *Cupressus arizonica*, and *Pseudotsuga menziesii*.

Conclusions: *Cupressus arizonica* is a species that can be effectively used in both monitoring and decreasing Tl pollution.

Keywords: Biomonitor; Cupresus arizonica; Düzce; Heavy metal; Thallium.

HIGHLIGHTS

Thallium is one of the most toxic and destructive heavy metals for human and environmental health.
Plants are used to monitor and reduce metal element concentrations from the environment by using their organs.
The suitable species to be used in observing the thallium pollution in the air are *Cupressus arizonica* and *Picea orientalis*.
Cupressus arizonica is a species that can be effectively used in both monitoring and decreasing thallium pollution.

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INTRODUCTION

Global urbanization, population, and automobile density have risen promptly in urban regions, and there have been mutually and multidimensional triggering processes such as land degradation, socio-spatial issues, environmental contamination, and global warming in the long span (Koç, 2022; Isinkaralar, 2023). Air pollution is a global problem threatening the lives of millions of individuals worldwide and increasing due to anthropogenic factors such as industrial actions, vehicles, and mining activities in the last century (Ghoma et al., 2022; Isinkaralar et al., 2022a). This problem reached such a level that it causes the death of 7 million people yearly worldwide and approx. 90% of the global population resides in polluted areas (Cetin et al., 2022a). Moreover, it was emphasized that air pollution is also a source of much more important problems such as global climate change (Tekin et al., 2022).

Chromium (Cr), cadmium (Cd), manganese (Mn), zinc (Zn), copper (Cu), aluminum (Al), lead (Pb), nickel (Ni), and iron (Fe) are trace metal elements with distinct chemical forms that can cause destructive consequences when present in elevated concentrations (Isinkaralar, 2022). Poisonous elements lead to severe contamination in numerous big metropolises and can persistently accumulate via different pathways (Istanbullu et al., 2023). Most of the metals are amongst the leading and most harmful air pollution factors for human health since they can be lethal even at low concentrations, their concentrations in nature increase constantly, and they can remain undecayed in nature (Sulhan et al., 2022). One most dangerous and harmful ones among heavy metals for human health are included in the priority list of hazardous pollutants by ATSDR due to their potential effects (Savas et al., 2022). Among the elements included in this list due to their negative effects on human health, the elements such as Hg (mercury), Pb (lead), Cd (cadmium), and Cr (chromium) are widely discussed and examined in many studies. Frequently ignored in previous studies although it is listed in ATSDR's priority list of hazardous pollutants, thallium (Tl) is an element that is not necessary for humans, and it has no biological use for the human body. In addition to being accepted as one of the most toxic metals for humans, thallium is a heavy metal that is more toxic than the elements having remarkable ethyls, which are harmful to human health, such as mercury, lead, cadmium, copper, and zinc (Peter; Viraraghavan, 2005; Blain, 2022).

Thallium is dispersed into nature via three pathways. The first one of them is the natural processes and the geochemistry of local rocks, whereas the second one occurs generally as a result of mining activities, and it is anthropogenic in its nature. The third one originates from the combustion of coal in cement facilities. It is also thought that the pollution is more likely to be the result of the raw materials used in cement production rather than the coal combustion in those facilities (LaCoste et al., 2001). Moreover, Kazantzis (2000) also stated that industrial sources cause atmospheric emissions and deposition and that mine discharge facilities, coal-burning power plants, brick factories, and cement factories cause high levels of Tl nearby those facilities (Peter; Viraraghavan, 2005).

After thallium is rapidly and almost completely absorbed from the gastrointestinal system, soluble Tl compounds are extensively distributed in the body, and they first accumulate in the kidneys at the highest concentration. The main symptoms of chronic poisoning are uncertain illness, paresthesia, and, in some cases, hair loss (Blain, 2022). Chou; Lo (2019) revealed that treatment of the HEK293 cell line by using 5, 10, and 20 mg/L Tl^{+} for 24 hours resulted in reduced ribosome synthesis, leading to reduced protein synthesis, obstruction of cell cycle development and apoptosis, and disruption of ribosome biogenesis (Campanella et al., 2019). The negative environmental effects of Tl pollution are manifested by symptoms of chronic Tl poisoning, including visual impairment, joint and muscle pain, weakness, and hair loss (Xiao et al., 2012).

Thallium has more chronic toxicity and acute than other detrimental elements such as Pb, Hg, Cd, and As (arsenic) in general. Severe Tl poisoning might lead to mental disorders, ascending paralysis, and gastrointestinal dysfunction, whereas chronic poisoning might cause polyneuritis. The fatal dose of Tl for an adult person is only 8-10 mg kg^{-1}; therefore, this element is categorized as one of the 13 primary metal contaminants by the US EPA (United States Environmental Protection Agency) (Duri et al., 2020).

Since it is harmful to human health, it is very critical to monitor and diminish the Tl contamination in the air. However, no suitable method that can be used for this purpose was presented in previous studies. It is emphasized that the most effective procedure to be used in order to monitor and decrease the heavy metal contamination in the air is the use of trees (Kuzmina et al., 2023). The usability of tree species used in numerous studies in observing toxic substances and heavy metals in urban regions has been experimented with, and optimistic outcomes have been received (Isinkaralar et al., 2023). Previous studies reported that annual tree rings could be effectively used to watch the metal pollution in the air (Yayla et al., 2022; Key et al., 2022). However, it is underlined that the trees to be used in watching and diminishing heavy metal contamination should be individually specified for separately heavy metal (Karacocuk et al., 2022).

Düzce is located in the Western Black Sea district of Türkiye and has the 5th-most polluted air in Europe (average PM2.5 = 44.4 $\mu g/m^3$) as reported in the World Air Pollution Report 2021 (IQAir, 2021) due to numerous cement and brick factories, quarries, mining actions, and burning coal. Therefore, the current study aimed to define the most suitable tree species to be used to watch the change of Tl pollution in the air over the years and to reduce it.

MATERIAL AND METHODS

Description of the study area

This study was carried out in Düzce province, Western Black Sea of Türkiye, which was roughly 650 m away from the highway (40° 49′ 36.97″ N - 31° 10′ 31.40″ E)

(Figure 1). In the present study, each direction was marked on the stems of *Pinus pinaster* Aiton. (S1*), Cupressus arizonica* Greene (S2), *Picea orientalis* L. (S3), *Cedrus atlantica* (Endl.) Maanetti ex Carriere (S4), and *Pseudotsuga menziesii* (Mirb.) Franco (S5) and cut down the trees at the end of 2022. These tree species were chosen because they are preferred in urban green afforestation in Düzce, and they adapt to the climate of this region and show optimum growth. Then, 10 cm-thick log samples were taken about 50 cm above the ground surface.

Sample Preparation

The log samples were examined to determine their ages which were found to be about 40 years old. Specimens were taken from each tree's wood, outer bark, and inner bark for using a drill. In addition, based on the tree's annual ring widths, specimens were taken every five-year growth (grouped) of the wood. Specimens were air-dried first for about 2 weeks and oven dried for a week at 45 °C. After, 6 ml 65% nitric acid and 2 ml 30% hydrogen peroxide were added to specimens and placed in the microwave for 15 minutes (200 °C). Then, the solution was moved into the flask, and added distilled water up to 50 ml. Then, they were placed into the ICP-OES device for Tl analysis. This procedure is usually used in the latest studies examining for leaves (Turkyilmaz et al., 2020; Ateya et al., 2023; Ghoma et al., 2023), tree rings (Sevik et al., 2020; Çobanoğlu et al., 2022; Yayla et al., 2022) and soil (Cetin et al., 2022b; Istanbullu et al., 2023).

Figure 1: Study location.

Statistical Analysis

The data obtained were analyzed using the SPSS 21.0 package program. Conducted variance analysis on the data, the parameters found to have significant differences at the minimum confidence level of 95% (P≤0.05) were subjected to Duncan's test. The outcomes were simplified and tabularized for interpretation. Thus, the alteration of Tl concentration (ppb) by tree species, direction, organ, and age group was determined and discussed separately.

RESULTS

The alterations of Tl concentration by species and direction were analyzed and mean values, F-values taken from the Anova (Variance analysis), and letters indicating the groups obtained from Duncan's test are shown in Table 1. Considering the Anova results, it can be noticed that the change in Tl concentration was statistically meaningful in all directions. The uppermost values were found in S2 and S4 in the north and in S1 and S2 in the east, whereas the smallest Tl concentrations were found in S1 and S3 in the south and in S3 in the west. Considering the mean values, the lowest mean concentration was found in S3.

The differences in Tl concentration by species and organs are shown in Table 2. As seen in Table 2, it can be noticed that the alteration of Tl concentration by species was not statistically meaningful in all the organs other than the wood. Comparing the woods, the lowest value was found in S3 species. Comparing the results by organs, the lowest mean value was found in the wood, whereas the uppermost Tl values were noticed in the outer and inner barks.

The change in Tl concentration by directions and age periods is presented in Table 3. Regarding the results shown in Table 3, it can be noticed that the alteration in Tl concentration level by direction was statistically meaningful in all periods. The change by period was not statistically significant in directions other than the east and south. The highest Tl values in the east were observed in the period 1998-2002, whereas those in the south were seen in the period 1993-1997.

The alterations in Tl concentration level by organs and directions are shown in Table 4. Given the values shown in Table 4, it can be noticed that the alterations in Tl concentration by direction were statistically meaningful, whereas the changes by organs were statistically significant in directions other than the east. The maximum Tl values in the north and south were found in the outer bark, whereas the uppermost Tl level in the west was seen in the inner bark. Regarding the mean Tl values, the lowest Tl value was found in the west and the peak ones in the north and east.

The alterations in Tl concentration by organ and direction in S1 are shown in Table 5. The alterations in Tl concentration by organs in S1 were statistically significant in directions other than the west, whereas the alterations by direction were statistically meaningful in all organs. Considering the mean values, it was noticed that the lowest mean values among organs were obtained in the wood, whereas the smallest values among directions were noticed in the south and west directions. The uppermost Tl value in the north was noticed in the outer bark, whereas the ones in the south and east were found in the inner bark.

Table 1: Alteration of thallium concentrations (ppb) by species and direction.

Species	North	East	South	West	Mean
Pinus pinaster	5554.5 a	6443.5 c	3185.3 a	2525.6 b	4427.2 b
Cupressus arizonica	6536.8 b	6550.9 c	4253.3 b	2381.8 ab	4845.4 b
Picea orientalis	4604.7 a	5068.5 b	3432.0 a	1743.6 a	3602.2 a
Cedrus atlantica	6537.7 b	3646.3 a	4368.3 b	2906.3 b	4364.7 b
Pseudotsuga menziesii	5083.0 a	5550.7 bc	3636.3 ab	5021.3 b	4718.8 b
F-value	6.8***	10.9***	3.8**	27.5***	5.7***

According to statistical analysis, values followed by the different letters (a, b) means they are different at P≤0.05. * = P≤0.05; ** = P≤0.01; *** = P≤0.001.

Table 2: Change of thallium concentrations (ppb) by species and organ.

Species	Outer bark	Inner bark	Wood
Pinus pinaster	5714.0 ab	5960.0 a	4074.8 b
Cupressus arizonica	6013.7 ab	5517.8 a	4672.9 b
Picea orientalis	5158.5 ab	4451.7 a	3333.3 a
Cedrus atlantica	4327.8 a	5444.2 a	4234.3 b
Pseudotsuga menziesii	6883.6 b	4101.7 a	4475.7 b
F-value	1.9 ns	1.6 ns	5.7***
Mean	5623.2 B	5126.8 B	4160.7 A

According to statistical analysis, values followed by the different letters means they are different at P≤0.05. Lowercase letters (a, b) show vertical directions, while uppercase letters (A, B) show horizontal directions. *** = P≤0.001; ns= not significant.

Table 3: Change in thallium concentration (ppb) in wood by period and direction.

Age intervals	North	East	South	West	F-value
2018-2022	5790.1 B	4099.7 Aa	3946.3 Acd	2919.0 A	8.0***
2013-2017	5021.9 B	4920.6 Bab	3874.5 Bbcd	2289.1 A	8.7***
2008-2012	4894.0 B	6235.5 Cbc	2983.2 Aabc	2214.2 A	18.1***
2003-2007	4424.3 C	4093.0 BCa	2913.1 ABab	2510.8 A	3.8*
1998-2002	5470.2 B	7066.6 Cc	2731.4 Aa	2560.9 A	40.1***
1993-1997	5292.5 BC	5682.0 Cabc	4317.4 Bd	2419.2 A	10.7***
1988-1992	5377.1 B	4703.0 ABab	2689.2 Aabcd	3609.7 A	2.8*
1983-1987	5800.7 B	5694.5 Babc	3422.4 Aabcd	3065.9 A	10.9***
F-value	1.0 ns	3.7**	3.1**	1.2 ns	

According to statistical analysis, values followed by the different letters means they are different at P≤0.05. Lowercase letters (a, b) show vertical directions, while uppercase letters (A, B) show horizontal directions. * = P≤0.05; ** = P≤0.01; *** = P≤0.001; ns= not significant.

Table 4: Change in thallium concentration (ppb) by organ and direction.

Organ	North	East	South	West	F-value
Outer bark	8058.4 Cc	6046.1 B	5469.4 Bc	3088.2 Aa	25.9***
Inner bark	6504.4 Bb	5114.2 AB	4403.4 Ab	4480.1 Ab	4.0*
Wood	5258.8 Ca	5384.0 C	3484.7 Ba	2698.6 Aa	66.9***
F-value	18.9***	0.4 ns	16.0***	8.0***	
Mean	5663.3 C	5413.4 C	3575.0 B	2915.7 A	74.3***

According to statistical analysis, values followed by the different letters means they are different at P≤0.05. Lowercase letters (a, b) show vertical directions, while uppercase letters (A, B) show horizontal directions. * = P≤0.05; *** = P≤0.001; ns= not significant.

Table 5: Change in thallium concentration (ppb) by organ and direction in *Pinus pinaster.*

Organ	North	East	South	West	F-value
Outer bark	7914.0 Cb	8666.8 Db	3586.7 Ba	2688.5 A	3429.2***
Inner bark	7190.1 Cab	8576.8 Db	5315.9 Bb	2757.2 A	1076.8***
Wood	5055.1 Ba	5899.0 Ca	2868.8 Aa	2476.3 A	33.2***
F-value	4.5*	6.2**	16.0***	1.9 ns	
Mean	5554.5 B	6443.5 C	3185.3 A	2525.6 A	45.5***

According to statistical analysis, values followed by the different letters means they are different at P≤0.05. Lowercase letters (a, b) show vertical directions, while uppercase letters (A, B) show horizontal directions. * = P≤0.05; ** = P≤0.01; *** = P≤0.001; ns= not significant.

The changes in Tl concentration by periods and direction in the wood of S1 are shown in Figure 2. The alterations in Tl concentration by period and direction in the wood of S1 were statistically meaningful in all directions and periods (P≤0.001). Given the mean Tl values, the directions were divided into three groups; the highest mean levels were noticed in the east and north, whereas the lowest ones were found in the south and west (Figure 2). The highest Tl level in the north and east were noticed in the period 1988-1992 and 2003-2007, respectively. Tl concentration in the east showed a decreasing trend from 2008-2012. The lowest values were mostly seen in the south and west direction.

The alterations in Tl concentration levels by organ and direction in S2 are shown in Table 6. Given the levels shown in Table 6, it can be noticed that the alterations in Tl concentration levels in S2 by organ and direction were statistically meaningful in all directions and organs, respectively. The changes in Tl concentration levels in the inner and outer barks were below the detectable limits in the east. The uppermost Tl level in the north was noticed in the inner bark, and the smallest one in the wood. In the south, the lowest values were noticed in the inner bark and wood and the highest one in the outer bark. In the west, the uppermost values were noticed in the outer and inner barks and the smallest ones in the wood.

The alterations in Tl concentration level in S2 wood by period and direction are shown in Figure 3. The outcomes determined that the alterations in Tl concentrations by periods and direction in the woods of S2 were statistically meaningful (P≤0.001) in all directions and periods. Regarding the mean Tl levels, the uppermost mean levels by directions were noticed in the north and east direction and the smallest one in the west side (Figure 3).

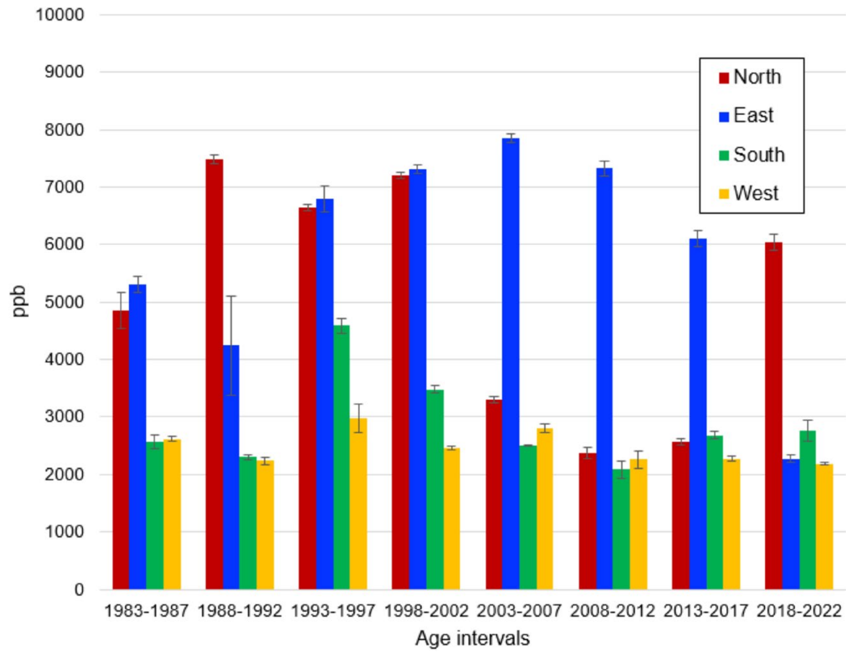

Figure 2: Change in thallium concentration by periods and directions in *Pinus pinaster* wood.

Table 6: Changes in thallium concentration (ppb) by organ and direction in *Cupressus arizonica*.

Organ	North	East	South	West	F-value
Outer bark	6755.3 Bab	UL	6858.5 Bb	4427.2 Ab	315.4***
Inner bark	8344.2 Cb	UL	3859.4 Aa	4349.9 Bb	13984.1***
Wood	6283.6 Ca	6550.9 C	3976.9 Ba	1880.1 Aa	67.7***
F-value	4.3*	-	5.9**	106.3***	
Mean	6536.8 C	6550.9 C	4253.3 B	2381.8 A	57.7***

According to statistical analysis, values followed by the different letters means they are different at P≤0.05. Lowercase letters (a, b) show vertical directions, while uppercase letters (A, B) show horizontal directions. * = P≤0.05; ** = P≤0.01; *** = P≤0.001; UL= Undetectable limit.

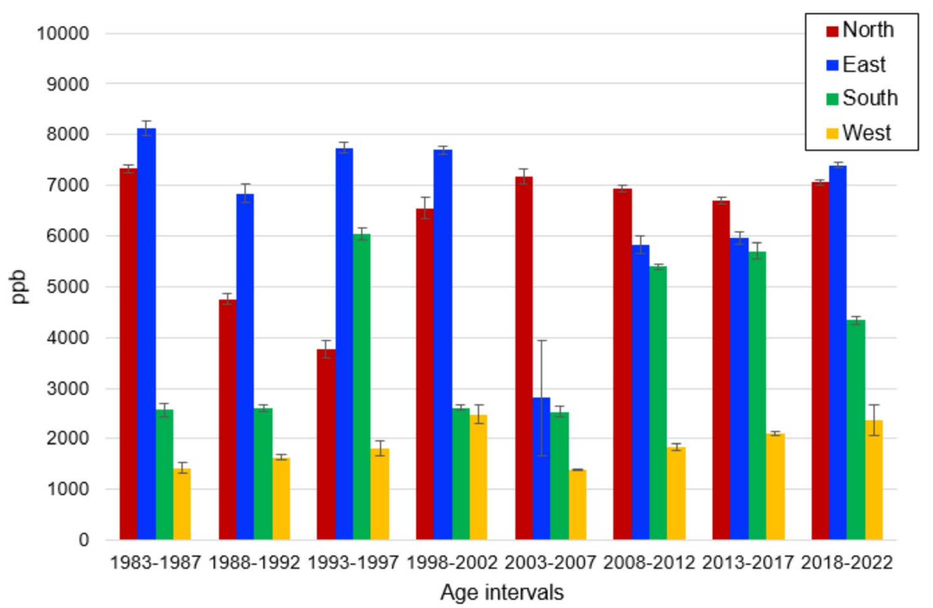

Figure 3: Change in thallium concentration level (ppb) in woods of *Cupressus arizonica* by period and direction.

The alterations in Tl concentration levels in S3 by organ and direction are shown in Table 7. Considering the Anova results, it can be noticed that the alterations in Tl concentration levels in S3 by organs and directions were meaningful in all directions and organs (P≤0.05), respectively. Considering the mean Tl concentration levels, the uppermost value was noticed in the outer bark and the smallest one in the woody section. Examining the directions, the uppermost values were noticed in the north and east direction and the lowest value in the west side. In the east, the alterations in Tl concentration levels were found to be lower than the detectable limits in the outer bark.

The changes in Tl concentrations in the woods of S3 by periods and directions are shown in Figure 4. The changes in Tl levels in the woods of S3 by periods and directions were meaningful (P≤0.001) in all directions and periods. The highest Tl level was mainly obtained in the east and north direction until 2013 (Figure 4). The highest Tl level in the east was obtained from 1988 to 2013. In the east, Tl concentrations were found to be lower than the detectable limits in the periods 2013-2017 and 2018-2022. The highest Tl level in the north was found in the periods 1993-1997 and 2018-2022. The lowest Tl values were in the west throughout 1983-2002.

The alterations in Tl concentration level by organ and direction in S4 are shown in Table 8. Considering the results shown in Table 8, it can be stated that the alterations in Tl levels in S4 by direction were statistically meaningful in all organs. The changes in Tl concentration level by tree organs were also noticed to be insignificant in directions (P>0.05) other than the west and north. Considering the mean values, the lowest value by direction was seen in the west and the highest value was seen in the north. In the north, the smallest value was noticed in the wood, whereas the uppermost values were found in the outer and inner barks. In the west, the highest value was determined in the inner bark and the smallest ones in the wood and outer bark.

The changes in Tl concentration in S4 wood by periods and directions are shown in Figure 5. The alterations in Tl concentration level by direction and period in S4 wood were statistically meaningful (P≤0.001) in all periods and directions. The peak Tl values were found in the north during 2003-2007 (Figure 5). Comparing the directions, the smallest value was found in the west and the uppermost in the north, especially after 1993. Tl values did not fluctuate much in the south and west, especially after 2003.

Table 7: Alteration in thallium concentration (ppb) in Picea orientalis by organ and direction.

Organ	North	East	South	West	F-value
Outer bark	8168.6 Cb	UL	4410.6 Bb	2896.4 Ac	801.3***
Inner bark	6917.2 Db	2975.9 B	5815.4 Cc	2098.5 Ab	450.0***
Wood	3870.2 Ca	5417.2 D	3011.7 Ba	1555.2 Aa	39.0***
F-value	19.0***	6.2*	14.0***	24.7***	
Mean	4604.7 C	5068.5 C	3432.0 B	1743.6 A	27.6***

According to statistical analysis, values followed by the different letters means they are different at P≤0.05. Lowercase letters (a, b) show vertical directions, while uppercase letters (A, B) show horizontal directions. * = P≤0.05; *** = P≤0.001; UL= Undetectable limit.

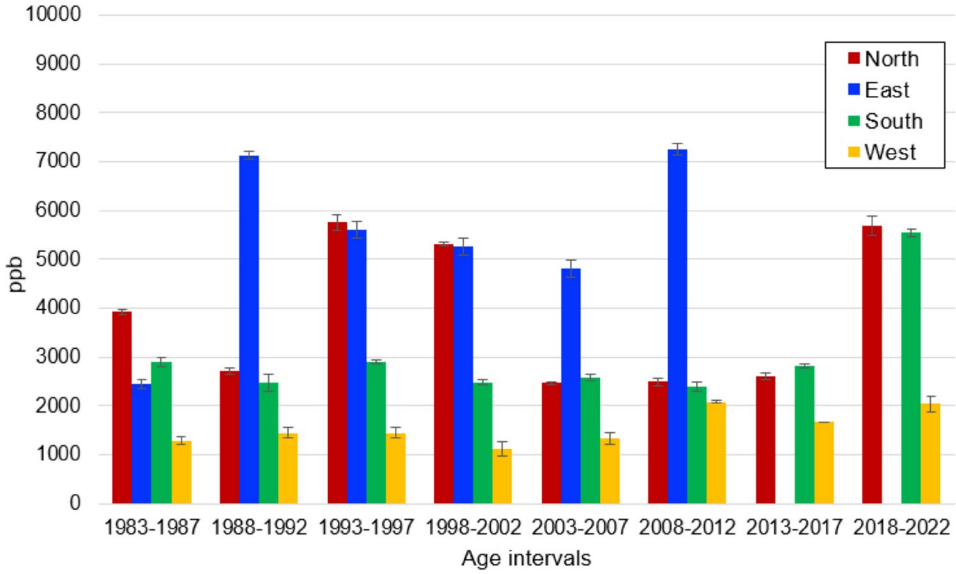

Figure 4: Changes in thallium concentration in the woods of *Picea orientalis* by period and direction.

Table 8: Change in thallium concentration (ppb) by organ and direction in *Cedrus atlantica*.

Organ	North	East	South	West	F-value
Outer bark	7444.1 Db	3403.7 B	4028.3 C	2435.2 Aa	2767.6***
Inner bark	7200.5 Bb	3790.0 A	3792.9 A	6993.3 Bb	625.6***
Wood	6341.6 Ca	3658.6 B	4482.7 B	2454.3 Aa	24.8***
F-value	7.8**	0.0 ns	0.5 ns	6.9**	
Mean	6537.7 C	3646.3 AB	4368.3 B	2906.3 A	28.5***

According to statistical analysis, values followed by the different letters means they are different at P≤0.05. Lowercase letters (a, b) show vertical directions, while uppercase letters (A, B) show horizontal directions. ** = P≤0.05; *** = P≤0.001; UL= Undetectable limit; ns = not significant.

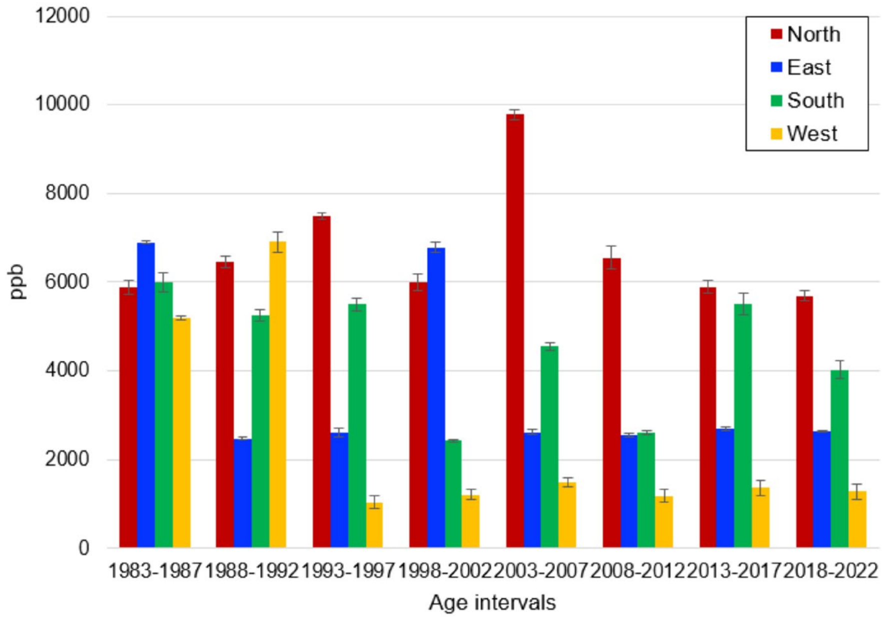

Figure 5: Change in thallium concentration levels (ppb) in *Cedrus atlantica* wood by period and direction.

The alterations in Tl concentration level by organ and direction in S5 are shown in Table 9. Given the results presented here, it can be noticed that the alterations in Tl concentrations in S5 by direction and organ were statistically meaningful in all organs and directions (other than east), respectively. In general, the smallest values were noticed in the wood and inner bark. The uppermost Tl values in the north and south were found in the outer bark and the smallest ones were noticed in the inner bark and wood. In the west, the smallest Tl concentration levels were found in the outer bark and the uppermost ones were detected in the inner bark and wood. Tl concentration was found to be lower than the detectable limits in the inner bark in the east.

The changes in Tl concentration in woods of S5 by period and direction are shown in Figure 6. The alterations in Tl concentration by periods and directions were meaningful in all directions and periods (P≤0.001). While the uppermost values in the north were noticed in the period 1983-1987 and 2013-2017, the ones in the east were found in the periods 1998-2002 and 2008-2012 (Figure 6). The smallest value in the south was found in the periods 2003-2007 and 2008-2012, whereas the minimum value in the west was found in the period 2008-2012. The changes in Tl concentration in the east were found to be lower than the detectable limits in the periods 1983-1987, 1993-1997, 2013-2017, and 2018-2022.

DISCUSSION

In the present study, Tl concentration was found to be higher than the detectable limits in almost all the samples. It suggests that all those species have a high potential to accumulate Tl. The plants to be used as biomonitors in determining the metal contamination should have certain characteristics. The leading one among those characteristics is to accumulate the element in various organs and the negative effect of that element on the species' life (Sevik et al., 2019; Çobanoğlu et al., 2022). It was determined that all the species examined here had a high potential to accumulate Tl. In the observation before taking the samples, it was found that all the trees were healthy. It suggests that the species examined here have the potential to be used in monitoring the Tl pollution. However, in order to use annual rings in observing the alteration of heavy metal contamination over the course of time, the relocation of the element within the wood should be limited. In former studies, it was notified that *Cedrus deodora* is suitable for monitoring Cu (copper) pollution (Zhang, 2019), *Cedrus atlantica* is suitable for Ni (nickel), Cr, and Mn (manganese) pollution (Koç, 2021; Savas et al., 2021), *Cupressus arizonica* is suitable for Cd, Ni, Fe (iron), and Zn (zinc) pollution (Cesur et al., 2021; 2022; Cobanoglu et al., 2023), and *Corylus colurna* is proper for Cd, Ni, Zn, Pb, Zn, and Cr pollution (Key et al., 2022; Key; Kulaç, 2022), and that the transfer of those elements in those species was limited.

On the other hand, in the same studies, it was reported that Pb and Zn could be transferred in *Cedrus deodora* wood (Zhang, 2019), Co in *Cedrus atlantica* wood (Koç, 2021), and Bi (bismuth), Li (lithium), and Cr in *Cupressus arizonica* wood (Zhang, 2019; Cesur et al., 2021; 2022; Cobanoglu et al., 2023). In the present study, however, it was reported that there were statistically significant variances between Tl concentration levels found in the woods in consequent periods in similar or different directions. This difference was found to be more profound in S2 and S3. Thus, it suggests that Tl has limited transfer in the woods of those species and that the proper tree species to be used in observing Tl pollution were S2 and S3.

The element transfer in the tree wood is mainly related to the cell wall and structure. The CWPM (cell wall–plasma membrane) interface defines an adaptable system involved in stress signaling, perception, and sensing for the metalloid/metal strain and an apoplastic mechanical barrier. The CWPs have been considerably recognized and distinguished among various plants under abiotic stresses. Under different strain conditions, it is claimed that the CWPM accumulated large fractions of metals due to being the possible area of heavy metal tolerance (Wani et al., 2018).

In this study, the uppermost Tl concentration levels in the woods were noticed in species other than S3. Pavlíčková et al. (2006) stated that the intake of Tl by plants varied between the species and plant organs differed in terms of Tl intake and accumulation. Similar outcomes were also narrated in many previous studies carried out on heavy metals and it was emphasized that heavy metal accumulation significantly varied by species (Erdem et al., 2023) and organs in the same species (Karacocuk et al., 2021). This is because many factors play an effective role in the intake and accumulation of heavy metals in plants. Intake of heavy metals into the plant tissue is affected by several factors, including plant species, organ structure, surface area, interactions between heavy metals and

Table 9: Changes in thallium concentration (ppb) by organ and direction in *Pseudotsuga menziesii*.

Organ	North	East	South	West	F-value
Outer bark	10010.1 Db	6067.8 B	8462.7 Cb	2994.0 Aa	577.9***
Inner bark	2870.1 a	UL	3233.4 a	6201.6 b	3628.7***
Wood	4743.7 Ba	5421.4 B	3083.4 Aa	5127.2 Bb	7.9***
F-value	13.5***	0.1 ns	38.8***	10.7***	
Mean	10010.1 Db	6067.8 B	8462.7 Cb	2994.0 Aa	577.9***

According to statistical analysis, values followed by the different letters means they are different at P≤0.05. Lowercase letters (a, b) show vertical directions, while uppercase letters (A, B) show horizontal directions. *** = P≤0.001; UL= Undetectable limit; ns = not significant.

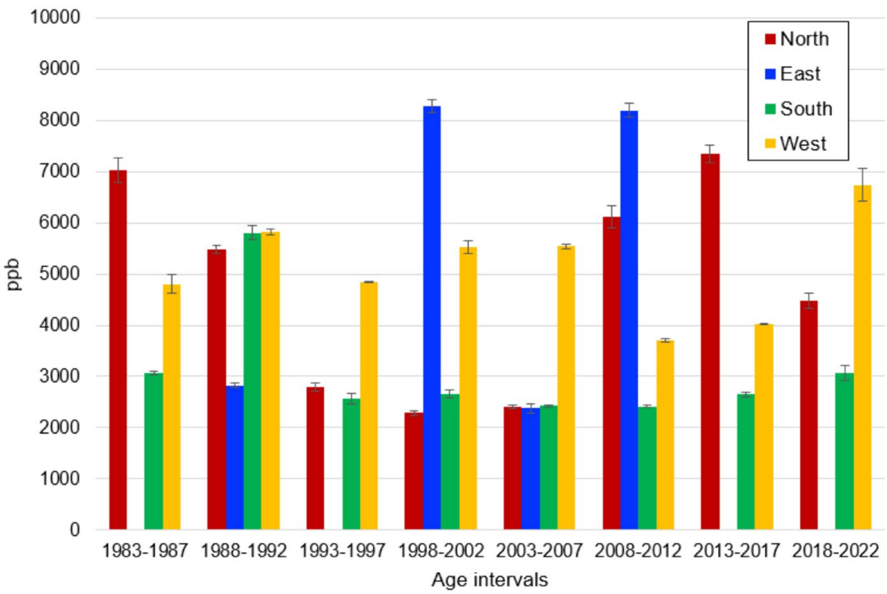

Figure 6: Change in thallium concentration (ppb) in woods of *Pseudotsuga menziesii* by period and direction.

plants, and weather conditions (Turkyilmaz et al., 2020). In addition, plant habitus and development also affect heavy metal intake and accumulation (Cobanoglu et al., 2023). Thus, all the factors influencing the plant habitus also affect the intake and accumulation of those heavy metals in those plants. Plant habitus is affected by the interaction between several factors affecting each other such as genetic structure (Kurz et al., 2023), edaphic (Kravkaz Kuscu et al., 2018), and climatic (Canturk; Kulaç, 2021; Varol et al., 2022; Dogan et al 2022) factors, and stress factors (Koç; Nzouko, 2022a,b; Koç; Nzouko, 2023). Therefore, many of these factors directly and indirectly affect each other's heavy metal accumulation potentials and the knowledge of this complex mechanism is still limited (Shahid et al., 2021; Isinkaralar et al., 2022b).

In the current study, the uppermost Tl concentration levels were found usually in the south and east. Ankara-Istanbul highway, which is one of the busiest highways in Türkiye, passes through the northeast side of the study area and this might suggest that thallium concentration increased as a result of the traffic. Besides that, previous studies showed that the concentration of Tl increased particularly due to anthropogenic sources such as industrial actions and coal combustion (Duri et al., 2020; Gasperi et al., 2022). The fact that the settlement and industrial areas are located on the north and east of the study area also supports this finding. In the existing study, the highest Tl concentrations were generally found in the outer barks. Plants receive Tl through roots and leaves. The ratio between the Tl content of soil and the concentration in plant species remains moderately constant under uniform conditions (Peter; Viraraghavan, 2005). It was reported that the too-high Tl concentrations in plants were not obtained from the soil pollution conveyed by the wind because Tl concentrations in plant samples were much higher in comparison to the Tl concentrations in soil (Anderson et al., 1999). It shows that Tl concentration in plant organs increased due to the air. As known, after being removed from their sources, heavy metals can be conveyed over long distances by wind, depending on the weather situations (Turkyilmaz et al., 2019; Aricak et al., 2019). Those heavy metals might cause high heavy metal concentration levels in the outer bark by accumulating in the cracks on the outer barks of trees that have rough outer bark structures. In many reports, the uppermost heavy meal concentration levels were found in the bark (Karacocuk et al., 2022).

CONCLUSION

The present study aims to determine the species that can be used in watching the changes in and reducing the Tl concentration in the air in Düzce province over time. As an outcome, it was noticed that the transfer of Tl in the wood of S2 and S3, which were examined in the existing study, was quite limited. Therefore, it can be said that these two species can be easily used for observing the changes in Tl pollution in the air. As an outcome of the present study, it was determined that the Tl accumulation potential in the woods of species other than S3 was very high. Wood is the largest organ of a tree in terms of mass and, therefore, species that can accumulate high amounts of Tl in their wood can be effectively used in reducing the Tl contamination in the air. Given the study results, S1, S2, S4, and S5 species are suitable for reducing Tl pollution in the air.

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