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ORIGINAL PAPER

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Tissue-specific barium accumulation in five conifer species: a 40-year dendrochemical assessment from a polluted urban environment

Hakan Sevik · İsmail Koç · Bert Cregg · Pascal Nzokou

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Abstract Heavy metal pollution is one of the most crucial issues threatening human and environmental wellness today. Barium (Ba), a widely used heavy metal, is one of the most hazardous for the environment and human wellness as all of its compounds are toxic. Therefore, monitoring and reducing Ba pollution is one of the priority study topics. This research aims to identify the most proper plant species for monitoring and mitigating both Ba sources as pollutants and Ba pollution. We examined 40-year-old *Cedrus atlantica*, *Pseudotsuga menziesii*, *Pinus pinaster*, *Picea orientalis*, and *Cupressus arizonica* trees grown in Düzce, which is among the five most unclean towns in Europe. Ba concentration was determined in annual tree rings and compared based on tree species, tree tissue, direction, and tree age. The most elevated Ba concentrations were generally obtained in the outer bark and the west direction in all tree species. Results revealed that agricultural activities led to a significant rise in Ba pollution and that all species had limited Ba allocation in their wood. As a result, the change in Ba pollution could be monitored using all of these species. It is concluded that the most proper tree species for sinking Ba pollution is *P. orientalis*, which accumulated the most Ba in wood.

Keywords Annual tree ring · Biomonitor · Düzce · Heavy metal · *Picea orientalis*

H. Sevik
Department of Environmental Engineering, Kastamonu University, Kastamonu 37150, Turkey
e-mail: hsevik@kastamonu.edu.tr

İ. Koç (✉)
Department of Forest Engineering, Düzce University, Düzce 81620, Turkey
e-mail: ismailkoc@duzce.edu.tr

B. Cregg
Department of Horticulture and Department of Forestry, Michigan State University, East Lansing, MI 48824, USA
e-mail: cregg@msu.edu

P. Nzokou
Department of Forestry, Michigan State University, East Lansing, MI 48824, USA
e-mail: nzokoupa@msu.edu

Introduction

The world population has reached around 8 billion in the last century and has condensed in urban zones since the industrial revolution (Cetin et al., 2019; Kilicoglu et al., 2020). Air pollution has become one of the biggest concerns in the world due to anthropogenic factors, especially industrial manufacturing and mining and vehicle emissions. More than 90% of the world's population resides in provinces with poor air quality and that about 1 in 8 human casualties are caused by air contamination (Cetin et al., 2021; Elsunousi et al., 2021). In addition, air pollution can cause permanent damage to ecosystems, affects the composition of the atmosphere, and contributes to global climate change (Ghoma et al., 2022; Tekin et al., 2022).

Heavy metals, have particular significance among air pollutants because they bioaccumulate in organisms. Moreover, some can be carcinogenic, poisonous, and deadly, even at low amounts. In addition, due to anthropogenic factors, their ability to stay in nature for an extended period without deterioration and the continuous increase in their concentrations in air, water, and soil make heavy metals more dangerous (Chen et al., 2022; Sevik et al., 2020; Ucun Ozel et al., 2019). Heavy metals in the atmosphere are particularly hazardous as they enter the human body via the respiratory system (Savas et al., 2021). Therefore, studies to observe and lower the concentrations of heavy metals, especially in the air, are crucial (Sevik et al., 2024). In addition, plant species have different metal accumulation potentials in different organs, which may be at different levels in distinctive sections of tree species grown in similar environmental conditions (Pulatoglu et al., 2025; Yayla et al., 2022). For this reason, it is necessary to determine proper tree species in phytoremediation and dendrochemistry studies.

Barium (Ba) is an essential element in producing many goods in the industry (Chałupnik et al., 2019). Ba element, its isotopes, compounds, and alloys are used in the manufacture of zinc (Zn), lead (Pb), and silver (Ag), rubber, rat poison, medicine, brake pad, machine oil, ink, radio vacuum tube, paint, and lamps, glue, candle, photographic paper, detergents, optical glass, battery and batteries, petroleum industry, drilling applications, textile and plastic products, oil paint production, paper coatings, production of special glasses, fireworks, and ceramic glazes (Cetin & Jawed, 2024). Ba does not have recognized biological roles in humans. However, Ba as a heavy metal is one of the most hazardous, and all Ba compounds are lethal. Ingestion of Ba salts can lead to fatal consequences such as hypokalemic paralysis, resulting in respiratory and cardiac arrest (Çobanoğlu et al., 2022; Peana et al., 2021). Moreover, heavy metals taken into the body through the respiratory tract are much more harmful than other types of exposure (Ghoma et al., 2022). Therefore, observing and lessening the Ba concentration variation in the atmosphere is crucial. In various studies carried out to date, annual tree rings can serve as a biomonitor of the variation of metal element contamination in the airborne from past to present (Key et al., 2022; Koç, 2021). Moreover, trees can function as a phytoremediation tool in reducing pollution (Liu et al., 2022; Rahman et al., 2022). Heavy metals can enter the plant body in three ways: through roots from the soil, through leaves from the air, and by direct adsorption from the stem parts (Cesur et al., 2021; Chen et al., 2022; Urošević et al., 2024). However, studies show that the accumulation potential of each heavy metal in different tissues of different plants is at different ratios (Erdem et al., 2023; Koç, 2025). Therefore, the main research topic has been which species can be used to monitor and reduce the concentration of heavy metals. Numerous studies have been conducted on heavy metal elements, such as Cr, Ni, Cd, Pb, and Cu (Key et al., 2022; Sulhan et al., 2022).

However, Ba has mostly been ignored in research conducted so far, and it has remained restricted in monitoring the variation of Ba concentration in the atmosphere. The current research aims to define the most appropriate tree species within five species (most preferred landscape tree species and show optimum development in the region) that can be used to determine the change of Ba concentration in the airborne from the past to the present (last 40 years) and to decrease contamination in Düzce, Türkiye.

Düzce is one of the most unclean cities in Europe in terms of air pollution due to diverse industrial manufacturing, such as cement, parquet, paint, plastic, and glass factories and quarries. Studies conducted in the region indicate that airborne metal element pollution has reached critical levels (Isinkaralar et al., 2024; Sevik et al., 2023) that the maximum PM2.5 and PM10.0 were measured at approximately 244.8 and 386.3 μg/m^3 in Düzce (Ministry of Environment, Urbanization and Climate Change 2023). Therefore, it was aimed to determine the type of Ba, which is one of the hazardous heavy metal elements in terms of individual and environmental wellness, that can be used as a biomonitor in determining the change in the level of pollution in the airborne and then the type that can be used for phytoremediation in order to reduce this contamination.

Materials and method

The research was conducted in Düzce, a city situated in the western Black Sea area of Türkiye

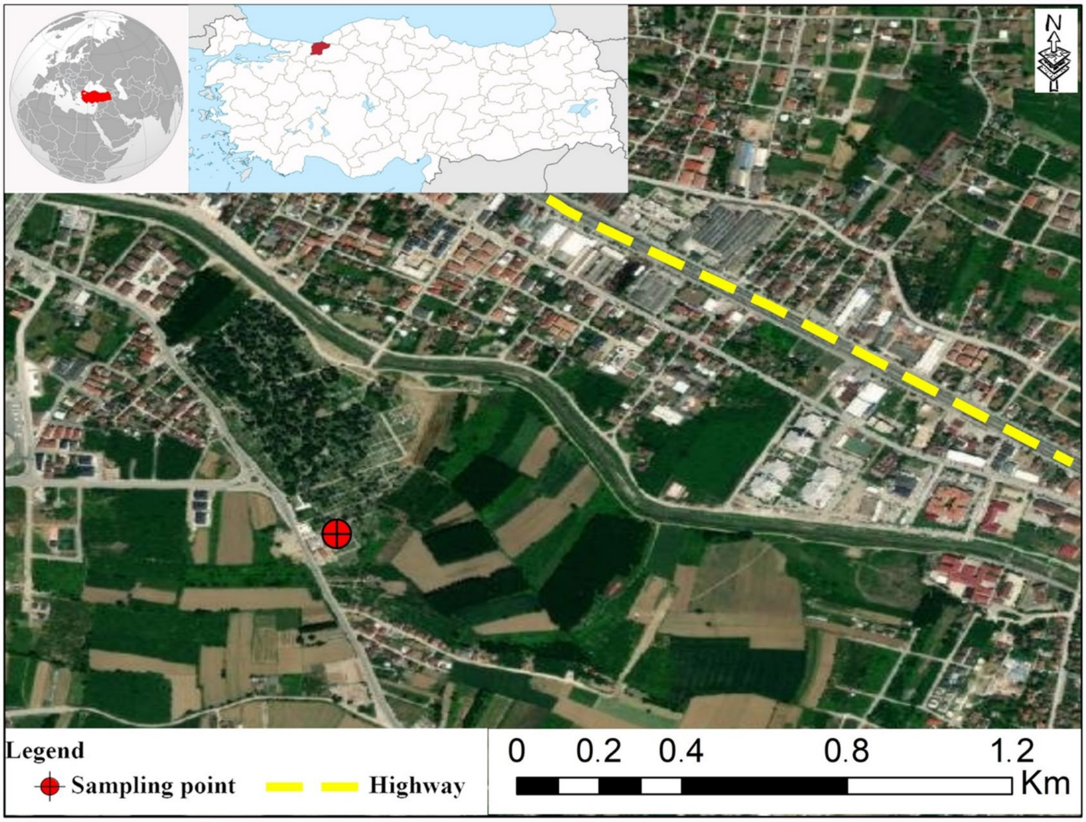

Fig. 1 Sampling location and its surroundings

(Fig. 1). As said by the World Air Pollution Report (IQAir, 2021), Düzce ranks among the top five most unclean cities in Europe, with an average PM2.5 concentration of 44.4 µg/m^3. Düzce is a region where industry is developing, and people make their living from agricultural activities (hazelnut, corn, paddy, and wheat cultivation). The prevailing average wind direction in the study area is northeast. Düzce province is where the human population reaches approximately 400 thousand, and there is a relatively high level of air pollution, thus threatening human health (Mayda & Karkaç, 2021). For the research, 5five evergreen trees (*Cupressus arizonica*, *Pseudotsuga menziesii*, *Pinus pinaster*, *Cedrus atlantica*, and *Picea orientalis)* were selected because they are landscape trees and show optimum development in this region. They were cut in late fall 2022, right after marking directions on their stems. Log samples (10 cm thickness) were taken roughly 50 cm from the ground level.

The trees selected for the study are about 40 years old and 15 m tall. While choosing these trees, attention was paid to the fact that the trees were mature, located close to each other (they should be equally affected by pollution factors), not touching each other, having a gap of at least 5 m between them, being tall, close to each other in height and age, and most importantly, being healthy. The main features sought in trees that can be used in observing and reducing metal pollution are that they can accumulate heavy metals in their body, but they do not die due to the effect of heavy metals, and their health is not affected (Pulatoglu et al., 2025; Sulhan et al., 2022).

When the log samples were obtained, the thickness of the wood (WD), inner bark (IB), and outer bark (OB) were measured, and each tree species tissue ratio is given below (Table 1). Inner bark is a tissue of living cells on the cambium's outer side in the tree trunk. Its primary function is transporting organic matter (sugars) from photosynthesis in the leaves

Table 1 The proportions of tissues (%) by plant species

Plant parts	*C. arizonica*	*P. pinaster*	*P. orientalis*	*C. atlantica*	*P. menziesii*
Outer bark	1.3	6.5	2.3	3.6	5.9
Inner bark	1.1	2.2	1.2	3.3	4.8
Wood	97.6	91.3	96.5	93.1	89.3

down the trunk toward the roots. It also serves as a nutrient storage and serves some defensive functions (Evert, 2006). The outer bark is outside the phloem and consists mainly of dead cells. Its main component is the secondary protective tissue called periderm. The periderm consists of three layers: phellem, phellogen, and phelloderm. This structure protects the tree trunk from external influences, pathogens, and water loss (Plomion et al., 2001). Studies on the subject frequently distinguish between inner and outer bark, and it is observed that significant differences in heavy metal accumulation in these organs are often observed (Key et al., 2023; Kulac et al., 2025). A planer was used in the lab to smooth the log samples and enhance the visibility of the annual rings. It was determined that the log samples of the tree species were 40 years old.

Regarding the annual ring widths, they were grouped as 5 years (a total of 8 age groups), and specimens were taken from the WD, IB, and OB of all age clusters with three replications using a steel drill. Five tree species × four directions × five log samples × ten (8 age group + outer bark + inner bark) × three repetitions = 3000 samples were used for analysis in this research.

The specimens (sawdust or chips) were placed in glass petri plates for 14 days to become air-dry. Later, they were oven-dried at 45 ± 2 °C for a week. 6 ml of HNO_3 (65%) and 2 ml of H_2O_2 (30%) were added to dried specimens (0.5 g), and the samples were placed in the microwave oven to burn. Then, samples were transferred into flasks and filled with ultrapure water to 50 ml. The liquid extract was placed inside the Inductively Coupled Plasma-Optic Emission Spectrometer (ICP-OES) (GBC Scientific Equipment Pty Ltd., Melbourne, Australia) for Ba element analysis. The actual concentration were computed by multiplying the obtained Ba concentrations by the dilution ratio. Çobanoğlu et al. (2022), Canturk et al. (2024), Koç (2025), and Pulatoglu et al. (2025), and are some of the recent research that have employed this approach.

The statistical program SPSS 22.0 was used to examine the measured Ba concentrations. The normality and equality of variances were assessed on Ba concentration values using the necessary Kolmogorov-Smirnow and Levene tests, respectively. The actual Ba concentration values were then subjected to an analysis of variance (ANOVA), and the Duncan test was applied to the components that showed significant differences with at least a 95% confidence interval ($p < 0.05$). This analysis allowed for determining and evaluating variations in Ba concentrations based on tree species, organs, aspect, and temporal span.

Results

Ba concentration in annul rings of the sampled trees varied by species and period (Fig. 2). Tissue Ba decreased until around 2005 and then increased in *P. menziesii* and especially *P. orientalis*, while other species followed a relatively horizontal course. In particular, the values obtained in *P. orientalis* differ significantly from other species.

Ba concentration of annual rings also varied depending on the aspect of the sample (Fig. 3). In general, Ba concentrations were highest on the west side of the trees. The highest Ba concentration in all aspects were obtained in *P. orientalis*.

The alteration of Ba concentration by tree organ and aspect is given in Fig. 4. As can be seen in the figure, the variation of Ba concentration, in general, is listed as outer bark > inner bark > wood. Notably, the values obtained in *P. orientalis*, especially in wood and inner bark, are much higher than those obtained in other species.

The difference of Ba concentration by tissue and species is given in Fig. 5. When the figure is examined, it is seen that the highest values in all organs are obtained in *P. orientalis*. Notably, the values obtained in *P. orientalis*, especially in wood and inner bark, are much higher than those obtained in other species.

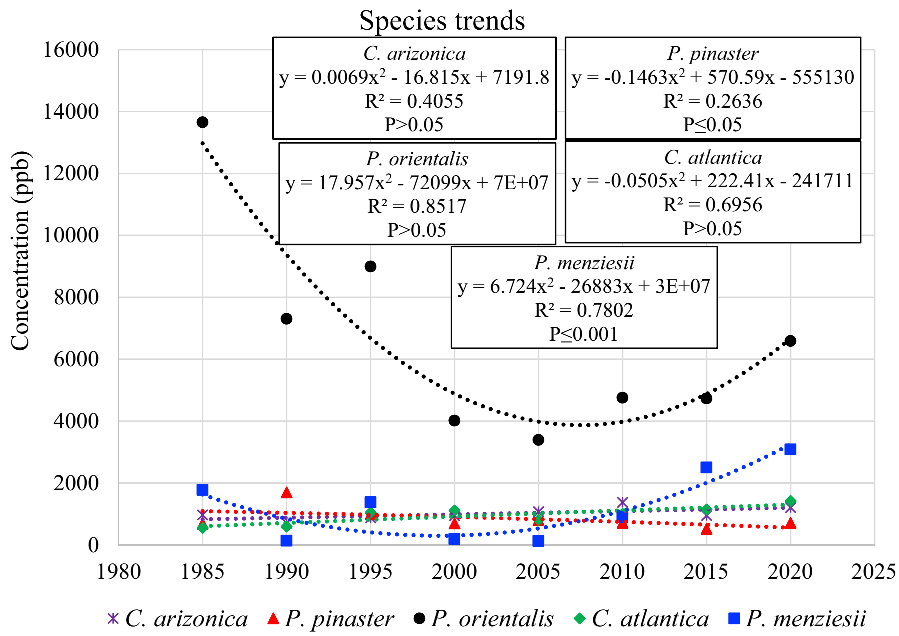

Fig. 2 Ba concentration (ppb) of annual growth rings of five conifers from Düzce city, Türkiye, sampled in 5-year increments from 1985 to 2020

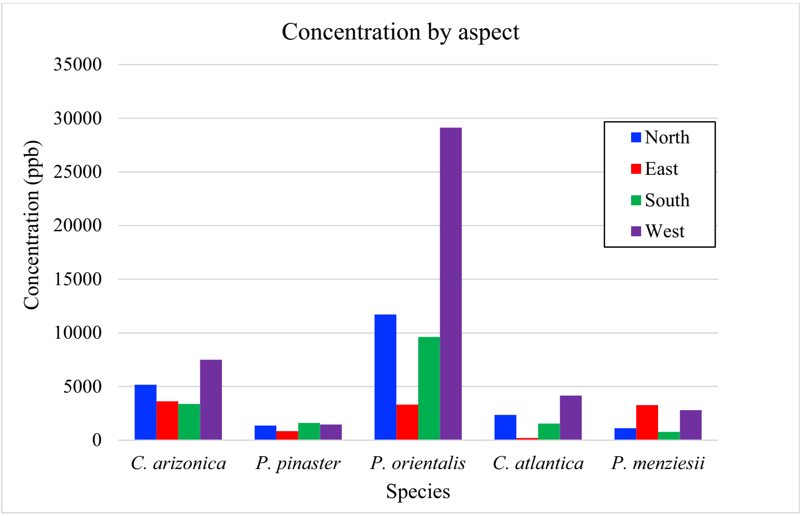

Fig. 3 Compass-directional variation of Ba concentration (ppb) in annual growth rings of five evergreen trees from Düzce city, Türkiye, between 1985 and 2020

The variation of Ba concentrations in wood by period and aspect is given in Fig. 6. When the variation of Ba concentrations in wood is examined, the highest values are obtained in the west orientation, and the Ba concentrations found in the west aspect generally follow a horizontal course. On the other hand, from the past, when there was an inverted bell curve in general, between the years 2000–2010, the Ba concentration decreased, and then there was a continuous upward trend.

Ba concentration was affected ($P < 0.0001$) by species, tissue, aspect, and their interactions (Table 2). The variation of Ba element concentration in five evergreen trees by tissue and aspect is presented below (Table 3). As a result, Ba concentrations in *C. arizonica* were generally listed as WD < IB < OB. The mean values show no significant difference between the directions ($P > 0.05$).

The highest Ba concentrations in *P. pinaster* were found in the OB, while WD and IB were generally

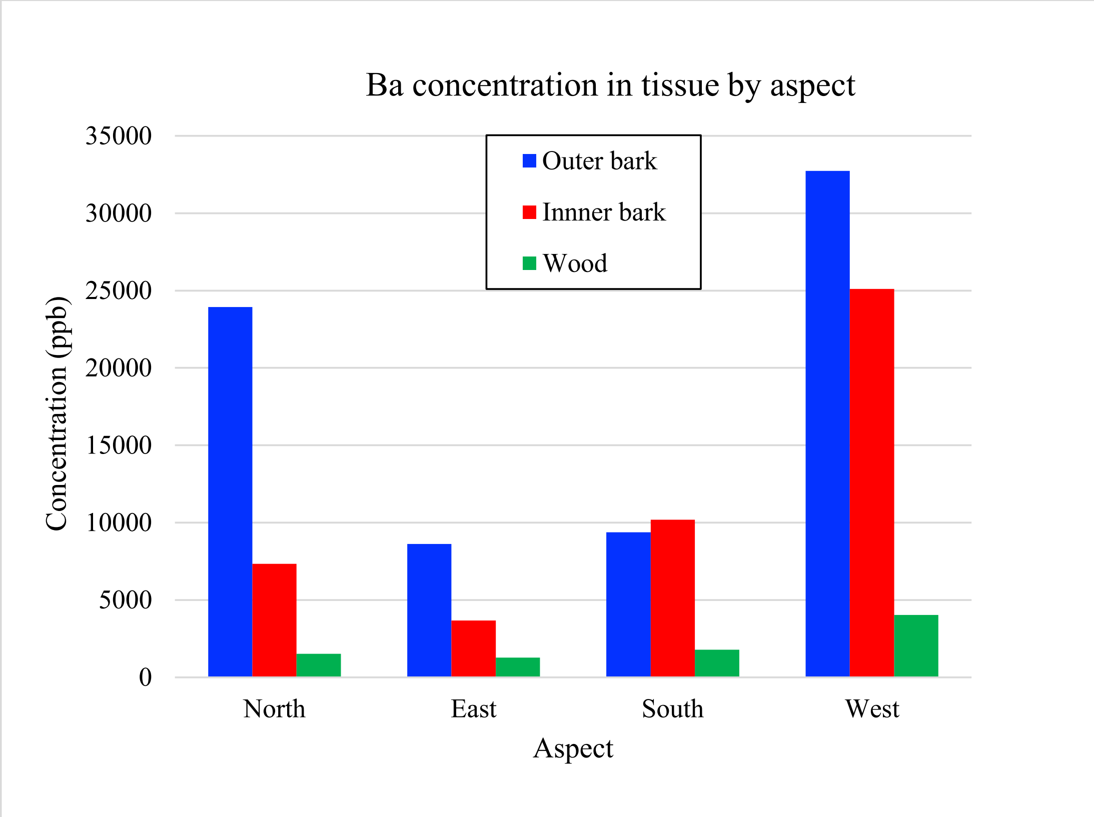

Fig. 4 Variation of Ba concentration by tissue and aspect of five conifer species from Düzce city, Türkiye

in the same groups as a result of the Duncan test. According to the average values, there is no difference between the directions ($P > 0.05$). The lowest Ba concentrations in *P. orientalis* were found in WD, while the IB and OB were in the highest group due to the same Duncan test. The uppermost Ba concentrations were received in the west direction, while the rest of the directions were clustered in the same group.

Based on the average values, the lowest Ba concentrations in *C. atlantica* were obtained in the IB and WD, while the highest were found in the OB. Regarding direction, the lowest concentrations were received in the east and south, and the uppermost Ba amounts were received in the west.

Based on the averages, the lowest Ba concentrations in *P. menziesii* were obtained in WD, while the highest were generally obtained in the OB. In terms of direction, the lowest amounts were found in the north and south, and the uppermost Ba concentrations were received in the east.

Discussion

High atmospheric concentrations of Ba in Düzce provided a unique opportunity to characterize tree uptake and distribution of Ba. This study evaluated Ba concentration variation in plant type, organ, direction, and wood in some trees growing in the Düzce city center. As a result, it was found that the variation of Ba amounts based on plant species was significant in all directions. It has been noticed in numerous research that the accumulation concentrations of heavy metals in various species are at distinct levels (Sevik et al., 2019a, 2019b; Turkyilmaz et al., 2019), and it is emphasized that the most critical parameter affecting the accumulation of heavy metal element is tree species (Koç et al., 2025a). Similar outcomes were found in studies on Ba. For instance, in a study conducted on five different species grown in Pakistan, they compared the changes in Ba concentration and reported that Ba concentration was 1162

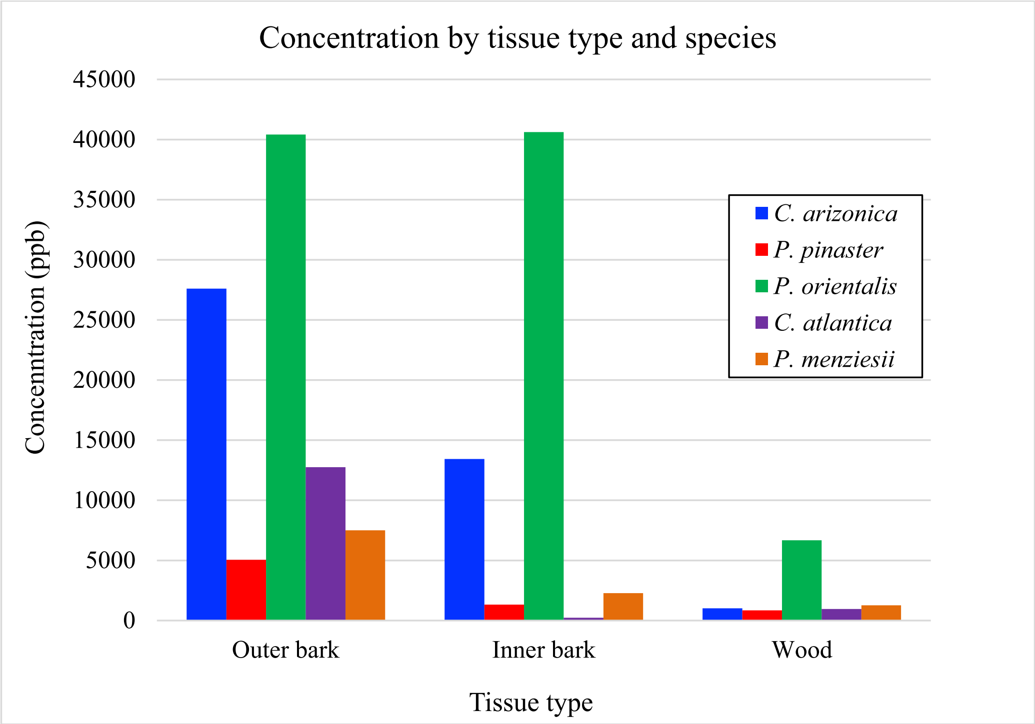

Fig. 5 Ba concentration (ppb) in tissues of five evergreen trees from Düzce city, Türkiye during 1985–2020

and 3982 ppb in Conocarpus erectus and Azadirechta indica in the heavily trafficked area, respectively (Cetin & Jawed, 2024).

This study found the highest Ba concentrations in OB of five species while the lowest Ba values in wood parts. This situation is related to how heavy metals enter the plant structure. The wood part has no connection with the outer environment. Therefore, unlike organs like bark and leaves, they do not directly absorb heavy metals from the outer environment. Similarly, they have no connection with the soil like the roots (Isinkaralar et al., 2025; Kulac et al., 2025). Wood is a tissue that mainly consists of lignified tracheids and vascular elements and does not show metabolic activity after its death. The absence of intracellular protoplasm and the lack of metal-binding proteins/peptides (e.g., metallothionein, phytochelatin) limit its metal retention capacity (Vangronsveld et al., 2009). On the other hand, lignin–cellulose-rich cell walls make a limited contribution to metal adsorption due to their low ion exchange capacity (Rosselli et al., 2003). Heavy metal ions absorbed by the roots participate in apoplastic flow with the xylem sap. However, charge-uncharge cycles occurring at the xylem–phloem interface direct a relatively large portion of the metals into the phloem. Metals transported in the phloem as sugar–amino acid complexes are re-deposited in photosynthetically active leaves and young tissues (Barceló & Poschenrieder, 2003).

The transport of elements within the woody part of plants is primarily related to cell structure, particularly the cell wall (apoplastic pathway). The extent to which metal ions are adsorbed to the sapwood remains available in these tissues likely depends on the xylem's ion-exchange capacity, which varies significantly by tree species (Crist et al., 2003; Hubbe et al., 2022). Therefore, each tree has a different potential to accumulate diverse heavy metals in the woody part (Isinkaralar et al., 2025; Kulac et al., 2025). Studies have shown that metal element concentrations in distinct organs of the same plant can alter considerably besides the plant species (Pulatoglu et al., 2025; Sevik et al., 2019a, 2019b). Heavy metal concentrations in diverse organs of plants grown in similar environments alter depending on characteristics such as the plant organ's structure, tree

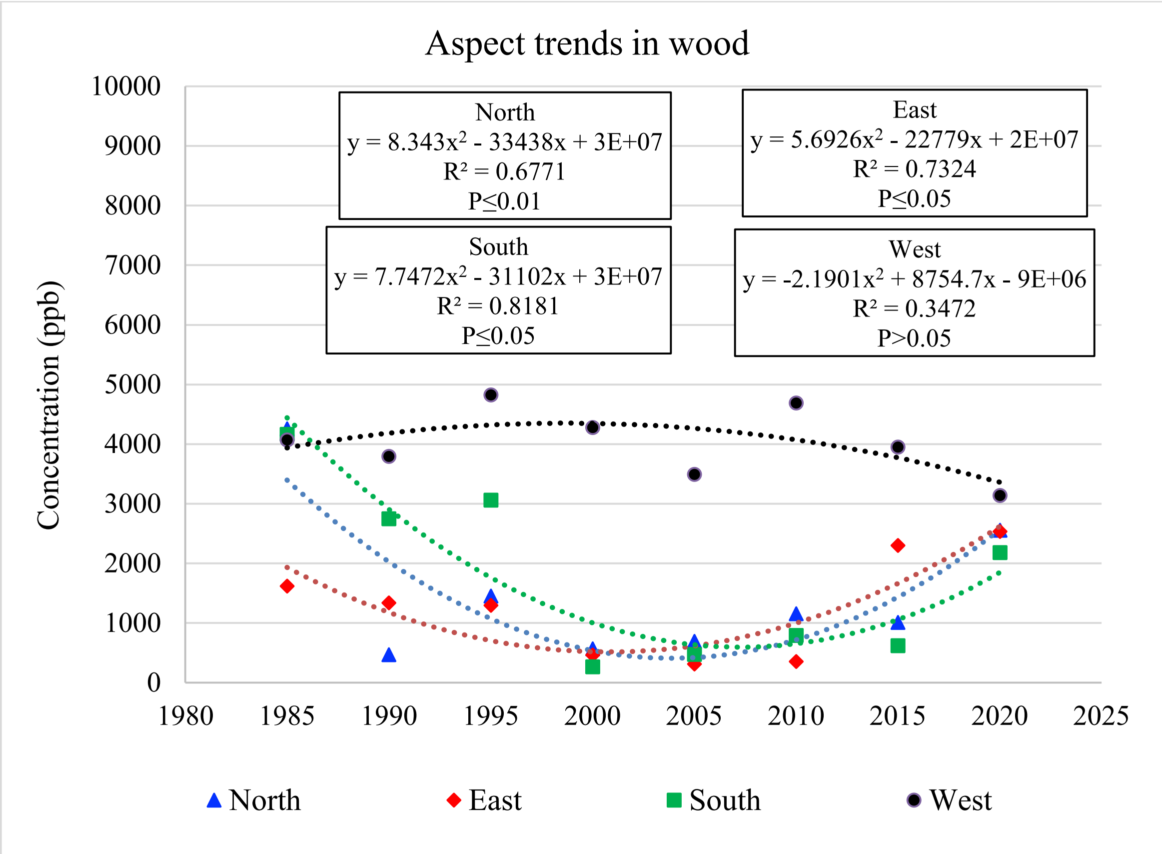

Fig. 6 Ba concentrations of wood by aspect, sampled in 5-year increments from 1985 to 2020

Table 2 Summary of analysis of variance for Ba element concentration for three tissues of five evergreen tree species under four aspect

Source of variation	df	P-value
Species (S)	4	0.0001
Tissue (T)	2	0.0001
Aspect (A)	3	0.0001
S×T	8	0.0001
S×A	12	0.0001
T×A	6	0.0001
S×T×A	24	0.0001

morphology, surface texture, surface area, and dimension (Isinkaralar et al., 2022a, 2022b). In addition, studies have indicated that heavy metal element concentrations in various species, especially in the OB, are high (Cobanoglu et al., 2023; Koç, 2021). This situation is mainly due to the structure of the OB and its interaction with heavy metals and contaminated particles. First, particulate matter in the airborne is contaminated with heavy metals, and because the OB surface is rough and cracked, these particles can stick to the bark surface (Yayla et al., 2022). In studies on Ba, it has been stated that the highest concentrations are generally obtained in the barks (Ozel et al., 2021).

Ba concentrations in the OB and IB were higher than WD in this study. This situation is related to entring metal elements into the tree tissue. Metal elements enter the tree tissue mainly from roots, stem parts, and leaves (Cesur et al., 2021; Chen et al., 2022). Ba is found in soil primarily as barite ($BaSO_4$) and witherite ($BaCO_3$), and these phases have low solubility. However, acidic pH, exudates released by roots, or potassium ammonium fertilizers can increase bioavailability by releasing Ba^{2+} adsorbed on clay surfaces into solution. Because

Table 3 Ba concentration of bark and wood tissue of five conifers from Düzce city, Türkiye, sampled by aspect

Plant parts	North	East	South	West
Cupresus arizonica				
Outer bark	27,492.9 Bc	23,844.7 Ac	29,457.9 Cb	29,621.3 Cb
Inner bark	14,840.4 Cb	8879.8 Bb	258.0 Aa	29,768.4 Db
Wood	1166.7 Ba	437.3 Aa	515.8 Aa	1949.5 Ca
Pinus pinaster				
Outer bark	7795.8 Db	865.2 A	7656.4 Cb	3890.9 Bc
Inner bark	687.8 Ba	366.2 A	1308.0 Ca	2921.0 Db
Wood	642.5 a	903.1	887.8 a	979.4 a
Picea orientalis				
Outer bark	66,073.5 Cc	17,031.7 Bb	1804.7 Aa	76,759.5 Db
Inner bark	20,318.3 Bb	639.2 Aa	49,116.1 Cb	92,423.2 Dc
Wood	3845.7 ABa	1949.2 Aa	5665.2 Ba	15,262.3 Ca
Cedrus atlantica				
Outer bark	16,911.3 Cb	321.1 A	6432.4 Bb	27,336.0 Dc
Inner bark	640.4 Ca	61.8 A	88.7 Aa	132.5 Ba
Wood	753.9 Ba	210.6 A	1127.0 Ca	1765.9 Db
Pseudotsuga menziesii				
Outer bark	1411.2 B	1069.6 Aa	1492.4 B	26,028.2 Cb
Inner bark	160.7 A	8439.6 Db	215.6 B	315.5 Ca
Wood	1202.2 A	2895.8 Ba	751.0 A	205.9 Aa

Based on Duncan's test results, values sharing the same letters (a, b, c or A, B, C) do not exhibit statistically significant differences at $P > 0.05$. Lowercase letters (a, b) denote comparisons in the vertical direction, whereas uppercase letters (A, B) represent comparisons in the horizontal direction

Ba^{2+} ions in solution have the same diameter and charge as Ca^{2+} (~135 pm), they primarily enter cortical cells through calcium-permeable ion channels. Ba^{2+} moves with Ca^{2+} in the xylem sap; upward transport accelerates as transpiration rates increase. Many studies have shown that Ba has a low redistribution ability in the phloem, and therefore leaves and bark serve as "final reservoirs" (Nan et al., 2018; Peana et al., 2021; Pyle et al., 2017). It is estimated that Ba in the IB enters through the body parts; and thus, the Ba concentrations in the IB, which are not in contact with the atmosphere, are higher. Another way heavy metals can enter into the plant body is through leaves. The fact that the species subject to the research were evergreen and dense-leaved species may have caused them to hold heavy metals and particulate matter contaminated in the air much more, and thus, more heavy metals entered the plant body.

The highest Ba values were obtained in the west direction in this study. The western aspect of the study area is a region with primarily agricultural lands. Previous studies reveal that Ba concentration increases due to traffic, and Ba is also included in the composition of drugs and rat poison (Cetin & Jawed, 2024). Therefore, the high Ba concentrations in the western direction, where the agricultural areas are located, indicate the excessive use of pesticides and poisons with high Ba content in the region's agricultural areas.

Monitoring the heavy metal contamination change in the air is one of the priority study subjects regarding human and environmental wellness, and several studies are being conducted on this subject (Jokanović et al., 2024; Koç et al., 2025b; Kuzmina et al., 2023). However, there needs to be more information about the transfer of heavy metals in wood between organs (Işinkaralar, 2022). Some studies reveal that the movement of metal elements in wood may vary according to the plant species. It was stated that the transfer of Ni, Cd, and Zn elements in cedar WD (Cobanoglu et al., 2023) and Ni, Co, and Mn elements in the WD of *Corylus colurna* (Key et al., 2022) were limited. While it was determined that Pb and Zn concentrations were displaced to a certain amount in the annual tree rings of *Cedrus deodora*, they found that the Cu concentration did not vary at all (Zhang, 2019). They remarked that the transfer of Fe, Ni, and Cd concentrations was restricted in *C. arizonica* woods. However, the transfer of Li, Bi, and Cr concentrations was at a higher level (Cesur et al., 2021, 2022).

Therefore, the suitability of tree species for detecting each heavy metal element pollution should be decided independently. In all tree species used in this research, Ba concentrations were quite different in woods formed in different orientations in the same year and in the same direction in consecutive years. These results show that all tree species used in the study can be used to track Ba concentration shifts in the airborne.

As a result, the highest concentrations were obtained in two species (*P. orientalis* and *C. arizonica*), and especially the Ba concentration in the wood of *P. orientalis* was 5 times higher than the values in the wood of other tree species. The fact that these results differ so much is critical, especially in phytoremediation studies. Plants play an important role in improving environmental health by accumulating heavy metal elements from soil, water, and air in their tissues (Kuzmina et al., 2023; Turkyilmaz et al., 2020). Among the organs of woody plant species, the wood section constitutes the largest part in terms of mass, which makes it the primary location for storing higher amounts of heavy metals. In our study, *C. arizonica* had the highest wood tissue among the tree species, followed by *P. orientalis*, and the lowest wood tissue was detected in *P. menziesii*. As a result, tree species that can accumulate metal elements in their woody tissues are of particular essence in terms of efforts to enhance environmental health.

In this study, the average Ba concentrations in wood were found to be low in other species (between 853.2 and 1263.7 ppb) while highest in *P. orientalis* wood (6680.6 ppb). In a study, the Ba concentration in *Ailanthus altissima* wood was found to be 2936.9 ppb, and it was stated that Ba concentration may be higher in the wood parts of the branches of shrub species (Işınkaralar, 2022). In another study, Ba concentrations in *Cotoneaster franchetii* and *Euonymus japonica* species woods were found to be below the detectable limits (Cobanoglu et al., 2022). In contrast, Ba concentrations in woods of *Pyracantha coccinea* and *Platycladus orientalis* were found to be 15.74 and 11.91 ppm, respectively. Ba concentrations in the wood of tall trees (between 2.62 and 5.54 ppm in *Tilia tomentosa*, 1.13–4.48 ppm in *Catalpa bignoides*, and 1.32–2.13 ppm in *Ligustrum vulgare*) vary depending on traffic density (Hmeer, 2020). It was determined that Ba concentration values in the wood of *C. atlantica* grown in an area with heavy traffic varied between 588.8 and 3194.6 ppb depending on the direction (Savas et al., 2021). Another study evaluating branches without separating the wood stated that Ba concentration in branches increased up to 3370.1 ppm in different species and traffic densities (Cetin & Jawed, 2024). Therefore, *P. orientalis*, which we used in our study, is the most suitable species to be used as a phytoremediation tool in reducing Ba pollution.

The high accumulation of Ba in *P. orientalis*, particularly in its woody tissues, raises questions about the underlying physiological mechanisms enabling this species to tolerate and compartmentalize Ba without severe metabolic disruption. Plants employ sophisticated detoxification strategies to mitigate heavy metal toxicity, including vacuolar sequestration via transporter proteins, which restrict metals from interfering with cellular processes (Singh & Kalamdhad, 2011; Nikalje & Suprasanna, 2018; Ghuge et al., 2023). This compartmentalization likely explains why *P. orientalis* can accumulate elevated Ba concentrations in its wood without apparent physiological damage, making it a resilient candidate for phytoremediation. The species' ability to immobilize Ba in non-living tissues (e.g., heartwood) or cell walls—where metabolic activity is minimal—further reduces its ecological risks while enhancing its utility in long-term pollution mitigation. These adaptive mechanisms underscore the environmental significance of *P. orientalis* in contaminated regions, as it not only monitors but also stabilizes Ba in biologically inert forms, reducing bioavailability and trophic transfer.

Conclusion

The 40-year dendrochemical analysis of five conifer species in Düzce revealed that *P. orientalis* accumulated significantly higher Ba concentrations in its wood (~6680 ppb) compared to other species (~853–1263 ppb), demonstrating its exceptional potential for Ba phytoremediation. The consistent pattern of highest Ba accumulation in outer bark tissues across all species, particularly in west-south-facing aspects adjacent to agricultural areas, strongly suggests fertilizer and pesticide applications as a primary pollution source. Notably, the temporal analysis showed a marked increase in wood Ba concentrations post-2005, overlapping with regional agricultural intensification. These tangible findings position *P. orientalis* as an effective biomonitor for tracking atmospheric Ba pollution and a practical phytoremediation solution for contaminated areas. The species' apparent tolerance mechanisms, evidenced by its ability to accumulate high Ba levels without visible physiological stress, affirm further investigation into its cellular detoxification processes. These results provide actionable insights for environmental management in polluted regions, recommending *P. orientalis* plantings in high-exposure zones while highlighting the need for stricter regulation of Ba-containing agricultural products.

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