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Variation of Ge Concentration in Some Coniferous Species Over Long Years

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Abstract: Increasing natural events and human activities in the last century led to the release of an excessive amount of inorganic and organic pollutants into the environment and natural ecosystems. One of the most important pollutants disrupting the balance between living organisms in the ecosystem is metals. Heavy metals, in particular, are transported to the top levels of the food chain and cause harm to the living organisms. Therefore, among the pollutants, heavy metals have a specific ecological importance. Heavy metals are carcinogenic and, due to their bioaccumulative, non-degradable, and refractory characteristics, they pose serious health risks to living systems and the environment. Pinus pinaster (Pp), Cupressus arizonica (Cpa), Picea orientalis (Po), Cedrus atlantica (Cda) and Pseudotsuga menziesii (Pm) species were examined in the present study. Changes in Ge concentrations in these species by directions and organs in the periods 1988-1992 and 2013-2017 were determined. As a result of the study, the lowest Ge concentration was found in the west in the Pb (872.8) and the highest one in the north in the Cpa (6367.5). The present study revealed that Ge accumulation in the plant species analyzed here is at a considerably high level. These results suggest that Ge pollution in the air is very high.

Keywords: Germanium, *Cedrus atlantica*, *Pinus pinaster*, Heavy Metals

Bazı İğne Yapraklı Türlerde Uzun Yıllar Boyunca Ge Konsantrasyonunun Değişimi

Özet: Son yüzyılda artan doğa olayları ve insan faaliyetleri, aşırı miktarda inorganik ve organik kirleticinin çevreye ve doğal ekosistemlere salınmasına neden olmuştur. Ekosistemde canlı organizmalar arasındaki dengeyi bozan en önemli kirleticilerden biri metallerdir. Özellikle ağır metaller besin zincirinin en üst basamaklarına taşınarak canlı organizmalara zarar vermektedir. Bu nedenle kirleticiler arasında ağır metallerin özel bir ekolojik önemi vardır. Ağır metaller kanserojendir ve biyoakümülatif, parçalanmayan ve dirençli özellikleri nedeniyle canlı sistemleri ve çevre için ciddi sağlık riskleri oluştururlar. Bu çalışmada *Pinus pinaster* (Pp), *Cupressus arizonica* (Cpa), *Picea orientalis* (Po), *Cedrus atlantica* (Cda) ve *Pseudotsuga menziesii* (Pm) türleri incelenmiştir. Bu türlerdeki Ge konsantrasyonlarının 1988-1992 ve 2013-2017 dönemlerinde yönlere ve organlara göre değişimleri belirlenmiştir. Çalışma sonucunda en düşük Ge konsantrasyonu batıda Pb'de (872,8) ve en yüksek Ge konsantrasyonu kuzeyde Cpa'da (6367,5) bulunmuştur. Mevcut çalışma burada analiz edilen bitki türlerinde Ge birikiminin oldukça yüksek seviyede olduğunu ortaya koymuştur. Bu sonuçlar havadaki Ge kirliliğinin çok yüksek olduğunu göstermektedir.

Anahtar Kelimeler: Germanyum, *Cedrus atlantica*, *Pinus pinaster*, Ağır Metaller

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1. Introduction

In the last century, environmental pollution caused by anthropogenic factors such as industrial activities, transportation, and mining operations became a global problem influencing all ecosystems (Isinkaralar et al., 2024; Bayraktar et al., 2024). Air pollution, in particular, became a problem that threatens people's health, comfort, peace, and happiness and causes approximately 7 million deaths and 4 million premature births worldwide annually (Isinkaralar et al.,2022; Key et al.,2022). It is estimated that approximately 99% of people live in polluted areas nowadays (WHO, 2024). Furthermore, it is also stated that air pollution is a major cause of global climate change (Çobanoğlu et al., 2023; Aricak et al., 2024; Erturk et al., 2024).

Heavy metals are considered the most threatening air pollution components from the aspect of human health since many of them can be toxic, carcinogenic, and lethal to humans even at low concentrations. Moreover, heavy metals can persist in the environment for a long time with no degradation and heavy metal concentrations in nature are in constant increase (Isinkaralar et al., 2023; Şevik et al., 2024; Gültekin et al., 2025). Due to their importance for human health, numerous studies were carried out on different heavy metals including Pb, Zn, Cr, Cu, Cd, and Al (Istanbullu et al.,2023; Ozturk Pulatoglu et al., 2025; Koç et al., 2025). Recently, because of the importance of the subject, heavy metals such as As (Yasar Ismail et al., 2024), Pd (Sevik et al., 2024), Sb (Canturk et al., 2024), Se (Şevik et al., 2024) and Bi (Isinkaralar et al., 2023)., which have not been extensively studied before, became the research subjects.

One of the elements that did not receive much attention in previous studies is Germanium (Ge). With an atomic weight of 72.59, an atomic number of 32, and a density of 5.32 (25°C) in its basic form, Ge is a metalloid, which has both metallic and non-metallic characteristics and is gray-white and brittle (Nordberg et al., 2005). Exposure to excessive amounts or prolonged exposure to Ge was reported to have toxicological effects on and damage to the kidneys, nervous system, and lungs. Acute Ge poisoning can cause depression, hypothermia, cyanosis of the skin, edema, and changes in the parenchymal cells of the liver, kidneys, or other organs (Li et al.,2017). Excessive exposure to Ge typically results in nephropathy, neuropathy, and hepatotoxicity, and can cause respiratory failure at lethal doses (Keith and Maples-Reynolds, 2022). Ge toxicity was also reported to cause weight loss, fatigue, gastrointestinal disorders (nausea, vomiting, and anorexia), anemia, muscle weakness, and renal failure, affecting skeletal and cardiac muscles, peripheral and central nervous systems, bone marrow, and the liver. Myopathy, neuropathy (severe axonal degeneration, sensory disturbance, and cerebellar ataxia), and vomiting were reported (Tao and Bolger, 1997). Therefore, monitoring the changes in Ge concentrations in the air and reducing their concentrations are particularly important because heavy metals pose even greater health risks when they are inhaled (Ghoma et al.,2023).

2. Materials and Methods

The materials used in the present study were obtained from the city center of Düzce province. Düzce province is located in the Western Black Sea region of Türkiye and, according to the 2021 World Air Pollution Report, it is one of the top 5 cities having the dirtiest air in Europe (Koc et al.,2024). Within the scope of this study, the log samples having approx. 10 cm thickness were taken at 50 cm height from the main stems of *Pinus pinaster* (Pp), *Cupressus arizonica* (Cpa), *Picea orientalis* (Po), *Cedrus atlantica* (Cda) and *Pseudotsuga menziesii* (Pm) species at the end of 2022 by labeling the north. The log samples were grouped into five-year intervals considering the annual ring widths and the specimens were taken from the outer bark, inner bark, and wood in each age range by using a steel drill. The present study was carried out in triplicate. The samples taken in the form of shavings were then placed in glass Petri dishes and left to dry for 15 days to have them air-dried. Then, they were dried at 45°C in a drying oven. 0.5 g of the samples were taken and added with 6 ml of 65% HNO3 and 2 ml of 30% H2O2. Then, they were placed in a microwave oven designed for these analyses. The solutions that became liquid were transferred to volumetric flasks and filled up to 50 ml by using ultra-pure water. The samples prepared were then analyzed by making use of an ICP-OES device and the results obtained were multiplied by the dilution factor to calculate the Ge concentrations. The method used in this study has been frequently used in recent studies carried out on this subject (Erdem et al., 2023a,b; Cobanoglu et al., 2023).

The data obtained were analyzed using the SPSS package program and the Duncan test was conducted for factors with significant differences with a minimum of 95% confidence level ($P<0.05$) in the Variance analysis. The data obtained were interpreted by simplifying and tabularizing. Thus, the changes in Ge concentration by species, direction, organ, and year range were separately determined and evaluated.

3. Results

The changes in Ge concentration by species and direction and the statistical analysis results are given in Table 1.

Table 1. Variation of Ge concentration on the basis of species and direction

Species	North	East	South	East	Mean
Pp	4851,4 ab	4385,1	3809,1	872,8 a	3937,8
Cpa	6367,5 c	4075,0	3528,1	4683,8 bc	4697,0
Po	4473,2 a	6131,2	3233,8	1544,5 a	4127,5
Cda	5686,7 bc	3424,0	3531,8	5240,9 c	4359,3
Pm	4441,0 a	3763,5	3199,3	3689,8 b	3791,8
F	5,0**	2,0 ns	0,4 ns	15,3***	1,7 ns

*Significant at 0.05 level; **significant at 0.01 level; ***significant at 0.001 level ns not significant

Given the results of the variance analysis, the changes in Ge concentration by species were not statistically significant in directions other than north and west. The highest value in the north was found in the Cpa and the lowest one in the Po and Pm. In the west, the lowest value was found in Pp and Po and the highest value in Cda. It is remarkable that, considering the Duncan test results, the values found in Cpa and Cda were in the last group in both directions. The change in Ge concentration by species and organ is given in Table 2.

Table 2. Variation of Ge concentration on the basis of species and organs

Species	DK	IK	Wood	Mean
Pp	3991,2 a	4039,8	3909,6	3909,6
Cpa	6849,7 b	7043,5	4157,1	4157,1
Po	4791,8 ab	4840,8	3907,3	3907,3
Cda	3825,2 a	5703,9	4229,6	4229,6
Pm	6764,9 b	5222,3	3192,3	3192,3
F	3,7*	1,5	2,1	2,1

*Significant at 0.05 level; **significant at 0.01 level; ***significant at 0.001 level ns not significant

As seen in table, it was revealed that the changes in Ge concentration by species were not statistically significant in all organs except for the outer bark. The highest value in the outer bark is observed in the Cpa and Pm species, while the lowest value is obtained in the Pp and Cda species. The change in Ge concentration by period and direction is given in Table 3.

Table 3. Change of Ge concentration by period and direction

Year	North	East	South	West	F	Mean
2018-2022	5359,2 B	2336,6 A	2369,7 Aab	2453,3 Aab	14,2***	3524,7
2013-2017	4051,8	3845,7	3775,3 bcd	2217,9 ab	1,1 ns	3778,1
2008-2012	4092,4 B	4041,9 B	3348,0 Babcd	1554,7 Aa	5,5**	3573,3
2003-2007	4008,0 B	3208,2 AB	2883,5 ABabcd	2160,6 Aab	3,1*	3224,7
1998-2002	4547,3	7169,5	2674,5 abc	2747,5 ab	2,4 ns	4556,0
1993-1997	4781,0 B	3940,6 B	4257,7 Bd	1491,5 Aa	8,2***	3978,8
1988-1992	4678,8	3738,1	4095,9 cd	5790,2 c	1,9 ns	4420,7
1983-1987	5071,7 C	3840,1 B	2273,7 Aa	3822,8 Bb	12,7***	3830,6
F	1,9 ns	2,0 ns	2,7*	5,1***		1,6 ns

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level ns not significant

Considering the results presented in table, it was found that the changes in Ge concentration by direction were statistically significant in all periods except for 1988-1992, 1998-2002, and 2013-2017. The change in Ge concentration by period was not statistically significant in directions except for the south and west. The highest value in the south was obtained in the period 1993-1997 and the lowest one in the period 1983-1987. The highest value in the west is determined in the period of 1988-1992. The change in Ge concentration by organ and direction is given in Table 4.

Table 4. Change of Ge concentration by organ and direction

Organ	North	East	South	West	F	Mean
DK	7841,8 Bb	6308,1 B	4255,6 Aa	2767,7 Aa	19,0***	5180,5 b
IK	7207,8 Bb	4132,4 A	4243,0 Aa	5096,9 ABb	3,6*	5285,3 b
OD	4573,8 Ba	4143,0 B	3209,1 Aa	2817,3 Aa	9,2***	3666,4 a
F	32,6***	1,5 ns	3,6*	7,3**		11,7***
Mean	5164,0 C	4308,8 B	3451,0 A	3263,3 A	14,5***	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level ns not significant

As seen in Table, the changes in Ge concentration by direction were statistically significant in all organs and the changes by organ were statistically significant in all directions except for the east. The highest value in the north was observed in the outer and inner barks, whereas the lowest one was found in the wood. The lowest value in the west was found in the outer bark and wood and the highest one in the inner bark. It was determined that the highest mean value was in the north and the lowest one in the south and west. The change in Ge concentration by organ and direction in Pp is given in Table 5.

Table 5. Change of Ge concentration in Pp by organ and direction

Organ	North	East	South	West	F Value	Mean
DK	7024,6 Bb	6614,4 Bb	1191,2 Aa	1134,6 Ab	135,3***	3991,2
IK	5035,6 Bab	4853,3 Ba	5142,5 Bb	1127,6 Ab	254,0***	4039,8
OD	4556,8 Ba	3999,7 Ba	4066,0 Bb	614,4 Aa	17,3***	3909,6
F Değeri	3,9*	12,1***	13,4***	72,4***		0,0 ns
Mean	4851,4 C	4385,1 BC	3809,1 B	872,8 A	26,5***	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level ns not significant

As indicated by the variance analysis results, the change in Ge concentration by direction in Pp was statistically significant in all organs and the changes by organ were statistically significant in all directions. The highest value in the outer bark was observed in the north and east and the lowest one in the south and west. The lowest values in the inner bark and wood were obtained in the west, whereas the highest value was observed in the north, south, and east. Examining the mean values, the highest mean value was obtained in the north and the lowest one in the west. The changes in Ge concentration by period and direction in Pp are given in Table 6.

Table 6. Variation of Ge concentration in Pp in woods by period and direction

Year	North	East	South	West	F Value	Mean
2018-2022	5335,9 Bbc	2366,0 Aa	LA	LA	94,0**	3850,9
2013-2017	1971,2 Aa	4936,4 Bd	LA	LA	891,4***	3453,8
2008-2012	2398,0 Aa	4931,0 Cd	3817,7 Bb	LA	38,6***	3715,5
2003-2007	4468,0 Bb	4692,1 Bd	4696,4 Bbc	545,6 A	47,4***	3600,5
1998-2002	5456,4 Cbc	3260,1 Ab	4508,5 Bbc	LA	9,2*	4408,3
1993-1997	5554,2 Cc	3962,0 Bc	5050,4 Bc	683,2 A	40,8***	3812,5
1988-1992	6032,9 Bc	LA	2257,1 Aa	LA	241,3***	4145,0
1983-1987	5237,8 bc	3850,4 bc	LA	LA	18,2*	4544,1

F Değeri	23,5***	19,3***	12,6**	327,9***		0,4 ns
Mean	4556,8 B	3999,7 B	4066,0 B	614,4 A	17,3***	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level ns not significant

Given the results presented in table, it was found that the changes in Ge concentration in all trees were statistically significant in terms of direction and the changes by period were statistically significant in all periods. The lowest value was obtained in the periods 2008-2012 and 2013-2017 for the north, in the period after 2018 for the east, and in the period 1988-1992 for the south. The lowest mean value was observed in the west, whereas the highest one was found in the north, south, and east. Moreover, the changes in Ge concentration were found to be lower than the detectable limits in the period of 1988-1992 for the east, in the periods 1983-1987, 2013-2017, and 2018-2022 for the south, and in all periods other than 1993-1997 and 2003-2007 for the west. The changes in Ge concentration by organ and direction in Cpa are shown in Table 7.

Table 7. Change of Ge concentration in Cpa by organ and direction

Organ	North	East	South	West	F Value	Mean
DK	8339,0 Cb	LA	7136,7 Bb	5073,3 Ab	32,7**	6849,7 b
IK	9376,1 Bc	LA	3408,5 Aa	8346,1 Bc	114,0***	7043,5 b
OD	5745,0 Ca	4075,0 B	3092,0 Ba	632,0 Aa	34,7***	4157,1 a
F Value	126,6***		14,0***	297,8***		17,4***
Mean	6367,5 B	4075,0 A	3528,1 A	4683,8 A	14,7***	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level ns not significant

As seen in table, the changes in Ge concentration in Cpa by direction were statistically significant in all organs and the changes by organ were statistically significant in all directions. For the north and west, the lowest concentration was found in the wood, followed by outer bark and inner bark, respectively. The highest concentration in the south was observed in the outer bark and the lowest ones in the inner bark and wood. Examining the mean values, the highest mean value was found in the north and the lowest ones in the east, south, and west. In the east, the change in Ge concentration was found to be lower than the detectable limits in the outer and inner barks. The changes in Ge concentration by period and direction in Cpa are presented in Table 8.

Table 8. Change of Ge concentration in Cpa in woods by period and direction

Year	North	East	South	West	F Value	Mean
2018-2022	6126,4 Cc	1947,8 Ba	993,4 Aa	LA	146,6***	3022,5 a
2013-2017	5540,4 Bab	4058,6 Acd	4264,5 Ae	LA	75,8***	4621,2 abc
2008-2012	5770,1 Aabc	5705,5 Ae	5262,2 Af	LA	3,7 ns	5579,2 c
2003-2007	5253,8 Ba	2847,4 Aab	2648,1 Acd	LA	11,6*	3583,1 ab
1998-2002	6061,8 Dbc	5069,2 Cde	2382,2 Bbc	632,0 A	585,4***	3536,3 ab
1993-1997	5663,5 Cabc	4829,9 Bde	4326,7 Ae	LA	25,6**	4940,0 bc
1988-1992	5562,2 Cabc	4967,0 Bde	2141,2 Ab	LA	920,9***	4223,5 abc
1983-1987	5981,8 Bbc	3175,0 Abc	2717,7 Ad	LA	45,7***	3958,1 ab
F Value	3,1*	17,0***	241,3***			2,6*
Mean	5745,0 C	4075,0 B	3092,0 B	632,0 A	34,7***	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level ns not significant

As shown in table, the changes in Ge concentration in Cpa by direction were statistically significant in all periods, except for the period 2008-2012, and so were the changes by periods in all directions. The highest value in the north was observed after the year 2018 and the highest values in the east and south were observed in the period 2008-2012. Besides that, the highest mean value was observed in the period 2008-2012 and the lowest one was observed after the year 2018. In addition, the lowest mean value by direction was obtained in the west and the highest one in the north. The changes in Ge concentration were lower than the detectable limits in all periods, except for the period 1998-2002 in the west. The changes in Ge concentration by organ and direction in Po are given in Table 9.

Table 9. Change of Ge concentration in Po by organ and direction

ORGAN	North	East	South	West	F Value	Mean
DK	8464,4 Cb	LA	3517,5 Ba	2393,6 Ab	616,9***	4791,8 a
IK	7003,8 Bb	3031,8 A	6714,1 Bb	2613,6 Ac	99,9***	4840,8 a
OD	3658,0 ABa	6647,7 B	2606,4 Aa	585,4 Aa	4,1*	3907,3 a
F Value	26,8***	0,5 ns	12,8***	710,5***		0,3 ns
Mean	4473,2 BC	6131,2 C	3233,8 AB	1544,5 A	3,8*	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level ns not significant

Given the variance analysis results presented in table, the changes in Ge concentration in Po by direction were found to be statistically significant in all organs and the changes by organ were statistically significant in all directions, except for the east. The highest value in the north was found in the outer and inner barks and the highest one in the south was obtained in the inner bark. In the west, the lowest concentration was found in the wood, followed by outer bark and inner bark, respectively. Considering the mean values, the lowest mean value was found in the west and the highest one in the east. Moreover, the change in Ge concentration was below the detectable limits in the outer bark in the east. The changes in Ge concentration by period and direction in Po are presented in Table 10.

Table 10. Variation of Ge concentration in woods in Po by period and direction

Year	North	East	South	West	F Value	Mean
2018-2022	5339,8 Bc	LA	5306,2 Be	571,0 A	145,0***	3739,0 ab
2013-2017	2320,7 a	LA	2251,9 b	LA	1,6 ns	2286,3 a
2008-2012	2737,3 Ba	4884,8 Ca	2550,6 Bcd	599,9 A	377,9***	2693,1 ab
2003-2007	2483,9 Aa	3844,0 Ba	2381,7 Abc	LA	254,0***	2903,2 ab
1998-2002	4285,8 Ab	16742,8 Aa	2588,6 Ad	LA	1,5 ns	7872,4 b
1993-1997	4871,5 bc	4926,7 a	LA	LA	0,0 ns	4899,1 ab
1988-1992	2178,9 a	6423,6 a	LA	LA	21199,0***	4301,3 ab
1983-1987	5046,0 Cc	3064,7 Ba	559,8 Aa	LA	79,6***	2890,1 ab
F Value	35,2***	1,3 ns	748,0***	0,2 ns		1,3 ns
Mean	3658,0 AB	6647,7 B	2606,4 A	585,4 A	4,1*	

Uppercase letters show horizontal direction, whereas lowercase letters indicate vertical directions
*Significant at 0.05 level, **significant at 0.01 level, ***significant at 0.001 level ns not significant

Given the results presented in table, it was determined that the changes in Ge concentration in Po woods by direction were statistically significant in all periods except for 1993-1997, 1998-2002, and 2013-2017. On the other hand, the changes by period were found to not be statistically significant in directions other than the north and south. The highest value in the north was found in the periods 1983-1987, 1993-1997, and after 2018, whereas the lowest value in the east was determined in the period 1983-1987. The lowest mean value was found in the south and west and the highest mean value in the east. In addition, the changes in Ge concentration were below the detectable limits in the periods 2013-2017 and 2018-2022 for the east, in the periods 1988-1992 and 1993-1997 for the south, and in all periods except for the periods 2008-2012 and 2018-2022 for the west. The changes in Ge concentration in Cda by organ and direction are shown in Table 11.

Table 11. Change of Ge concentration in Cda by organ and direction

Organ	North	East	South	West	F Value	Mean
DK	6888,2 Cb	4255,4 Ba	1786,4 Aa	2370,8 Aa	68,5***	3825,2 a
IK	7681,0 Cc	4512,2 Ba	3252,9 Aa	7369,5 Cc	326,0***	5703,9 b
OD	5287,2 Ba	3184,1 Aa	3821,0 Aa	5611,6 Bb	11,5***	4229,6 a
F Value	37,6***	1,8 ns	1,6 ns	159,3***		4,2*
Mean	5686,7 B	3424,0 A	3531,8 A	5240,9 B	15,4***	

Given the results achieved, the changes in Ge concentration by direction were found to be statistically significant in all organs. On the other hand, the changes in Ge concentration by organ were not statistically significant in directions except for the north and west. The lowest concentration was found in wood, followed by outer bark and inner bark, respectively, for the north, whereas the lowest concentration was found in the outer bark, followed by wood and inner bark, respectively, for the west. The highest values in the inner bark and wood were seen in the north and west, whereas the one in the outer bark was obtained in the north. Considering the mean values, the highest mean value was observed in the north and west and the lowest ones in the east and south. The changes in Ge concentration by period and direction in Cda are presented in Table 12.

Table 12. Variation of Ge concentration in Cda in woods by period and direction

Year	North	East	South	West	F Value	Mean
2018-2022	5049,4 Cab	2696,0B e	809,4 Aa	LA	154,9***	2851,6 a
2013-2017	5111,0 Bab	2542,1 Ad	6362,0 Cd	LA	59,0***	4671,7 b
2008-2012	4641,2 a	2356,7 c	LA	LA	166,1**	3498,9 ab
2003-2007	6116,4 Bc	2210,6 Ab	2415,8 Ab	LA	105,5***	3580,9 ab
1998-2002	5172,5 Bab	6090,4 Cg	2124,8 Ab	LA	558,1***	4462,6 ab
1993-1997	5512,5 Bb	2043,9 Aa	5975,5 Bd	LA	85,0***	4510,6 ab
1988-1992	5442,3 Cb	2262,8 Abc	4721,8 Bc	6007,2 C	66,3***	4608,5 b
1983-1987	5252,7B b	5270,2B f	4337,5 Ac	5216,0 B	31,1***	5019,1 b
F value	6,3**	1372,7***	53,1***	87,5**		2,0 ns
Mean	5686,7 B	3424,0 A	3531,8 A	5240,9 B	15,4***	

As seen in table, the changes in Ge concentration in Cda woods by direction were statistically significant in all periods and the changes by period were statistically significant in all directions. The highest concentration in the north was obtained in the period 2003-2007, whereas the highest one in the east was obtained in the period 1998-2002 and the highest one in the south in the periods 1993-1997 and 2013-2017. Considering the mean concentrations, the highest mean value was found in the north and west, while the lowest one was seen in the east and south. In addition, the changes in Ge concentration were determined to be lower than the detectable limits in the period of 2008-2012 in the south and in all periods except for 1983-1987 and 1988-1992 in the west. The changes in Ge concentration by organ and direction in Pm are given in Table 13.

Table 13. Variation of Ge concentration in Pm by organ and direction

Organ	North	East	South	West	F Value	Mean
DK	8492,8 Bb	8054,5 B	7646,2 Bb	2866,3 Aa	7,2*	6764,9 b
IK	6942,4 ab	LA	2696,9 a	6027,6 b	0,4 ns	5222,3 b
OD	3621,9 Aa	2690,8 A	2635,8 Aa	3500,5 A	2,2 ns	3192,3 a
F value	4,6*	21,2***	10,2**	7,0**		14,9***
Mean						

Given the results of variance analysis in table, the changes in Ge concentration in Pm by direction and organ were statistically significant in all organs and all directions, respectively. The highest value in the north was obtained in the outer and inner barks, whereas the highest value in the south was observed in the outer bark. In the outer bark, the highest values were seen in the north, south, and east, whereas the lowest one was found in the west. In the east, the changes in Ge concentration in the inner bark were below the detectable limits. The changes in Ge concentration in Pm by period and direction are given in Table 14.

Table 14. Variation of Ge concentration in woods in Pm by period and direction

Year	North	East	South	West	F Value	Mean
2018-2022	4944,4 cd	LA	LA	4335,7 d	4,0 ns	4640,0 c
2013-2017	5315,9 Bd	LA	2222,8 Ab	2217,9 Aa	118,3***	3252,2 ab
2008-2012	4915,6 Bcd	2331,7 Ab	1761,7 Aa	2509,6 Ab	18,1**	2879,6 a
2003-2007	1717,9 Aa	2447,1 Cb	2275,7 Bb	3775,5 Dc	391,1***	2554,0 a
1998-2002	1760,0 Aa	4685,2 Bc	1768,6 Aa	4863,0 Be	313,4***	3269,2 ab
1993-1997	2303,5 Ba	LA	1678,1 Aa	2299,8 Bab	12,8**	2093,8 a
1988-1992	4177,5 Bbc	1299,2 Aa	7263,7 Dc	5573,2 Cf	182,7***	4578,4 bc
1983-1987	3840,3 Cb	LA	1479,9 Aa	2429,6 Bab	66,1***	2583,3 a
F Value	36,4***	37,1***	233,4***	286,8***		4,0**
Mean	3621,9	2690,8	2635,8	3500,5	2,2 ns	

As seen in table, the changes in Ge concentration by period were statistically significant in all directions and so were the changes by direction in all levels other than the period 2018-2022. The highest value in the east was observed in the period 1998-2002, whereas the highest values in the south and west were found in the period 1988-1992. Besides that, the highest mean value was found after the year 2018. In addition, the changes in Ge concentration were below the detectable limits in the periods 1983-1987, 1993-1997, 2013-2017, and 2018-2022 for the east and in the period 2018-2022 for the south.

4. Discussion and Conclusion

As a result of the study, it was determined that Ge accumulates in all samples within detectable limits. This finding indicates that the species studied here have a high potential for accumulating Ge. One of the most important features sought in species that can be used in determining heavy metal pollution is their ability to accumulate heavy metals in their bodies (Key et al.,2023). Previous studies showed that each species has a different potential for accumulating heavy metals (Koç et al.,2024). The results achieved in the present study showed that the differences in the mean Ge concentration among species, especially in wood, were not statistically significant. Therefore, all of those species can be used for monitoring the changes in Ge concentration and reducing the Ge concentration.

At the end of the study, statistically significant differences were found between Ge concentrations in woods that formed in different directions during the same period. It can be stated that the transfer of Ge in the wood was limited. Similar results were also reported by different researchers. For instance, Zhang (2019) found that Zn and Pb concentrations in annual rings of *Cedrus deodora* changed to a certain extent, but Cu concentration did not change at all. Koc et al., (2024) reported that the transfer of the Cr element in *Pseudotsuga menziesii* was limited, but Sb, Ag, Se, Tl could be displaced in *Pinus nigra* (Şevik et al., 2024).

In the present study, the highest Ge concentrations were generally obtained in the north and east. Ankara-Istanbul highway, one of Turkey's busiest highways, passes through the northeast of the study area. Given these results, it can be stated that Ge concentrations increase significantly depending on traffic density. In previous studies on heavy metals, traffic density was specified as one of the most important heavy metal sources (Koç et al., 2025; Ozturk Pulatoglu et al., 2025).

In this study, the highest values were generally found in the outer bark. High heavy metal levels in the outer bark in polluted areas are related to the structure and contamination of the bark. Heavy metals in the air stick to particles, contaminate them, and settle on plant organs. Thereby, the concentration of heavy metals in these organs increases (Sulhan et al.,2022). Since the outer bark has a rough surface structure, particles can easily adhere to it and, as a result, heavy metal concentrations are high, especially in the bark on the side where the traffic is dense (Yayla et al.,2022). The results achieved in this study also support these findings and confirm that Ge concentrations in the air increase due to traffic.

Heavy metals are one of the most threatening pollutants for human and environmental health and, therefore, numerous studies were carried out on heavy metals in recent years (Cobanoglu et al.,2023; Kuzmina et al.,2023). However, those studies mainly focused on heavy metals such as Pb, Cr, Ni, Co, Cu, and Zn (Erdem et al., 2024). On the other hand, recent studies showed that other heavy metals that have been ignored to date can also be extremely dangerous for human and environmental health (Yasar Ismail et al., 2024).

One of the elements that have generally been neglected in previous studies is Germanium. Organic Ge is mainly found in industrial wastewater and soil contaminated with heavy metals. Organic Ge is one of the compounds of various coal-zinc-containing minerals and is the biggest human-made pollutant source in the environment, originating from coal combustion, oil refining, and different metal recycling processes. Organic Ge and its compounds are volatile at high temperatures, which results in a significant amount of organic Ge being released into the atmosphere. It can be seen that if land use for mining, agriculture, and human settlements is not properly planned, germanium compounds, including organic Ge, will cause significant harm to the environment and human health (Zheng et al.,2020). The results achieved in the present study show that Ge accumulation in the plants examined here can be quite high. These results can be considered as an indicator that Ge pollution in the air is at dangerous levels. Therefore, more and diversified studies on Ge are needed.

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6. Compliance with Ethical Standard

a) Author Contributions

1. Nurcan Yiğit.: Conceptualization, process, software, verification, formal analysis, research, materials, composing the first draft, composing the review, and editing.

b) Conflict of Interests

There is no conflict of interest, according to the authors.

c) Statement on the Welfare of Animals

Not relevant

d) Statement of Human Rights

There are no human subjects in this study.

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