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Statistical Variability Indices and Concentration Coefficient of Soil Microelements in Azerbaijan

Shalala Salimova[1], Kamala Nuriyeva[2], Matanat Aliyeva[1*],
Afag Rzayeva[1], and Anara Nasirova[2]

Abstract. *The aim of this study is to investigate the current state of essential, potentially toxic, and poorly understood microelement content in soils under vegetation in dry-steppe ecosystems. The objectives of the study included: determining regional characteristics of microelement content in soils and plants, identifying their relationships in the plant-soil system (hidden micronutrient deficiency), determining the intensity of biological uptake by plants from the soil, which characterizes their ecological activity, and assessing the removal of elements by aboveground phytomass and their involvement in biogenic migration. Soil and vegetation samples were collected from dry-steppe ecosystems. Soil samples were collected from the root layer (0–20/40 cm), prepared for laboratory analysis, and the microelement contents were determined. Statistical and correlation analyses were performed to evaluate the relationships between microelement contents in soils and vegetation. The results of the correlation analysis revealed a direct, significant relationship between the microelement content in soils and their accumulation in vegetation for Cd, Cr, Mn, Fe, Zn, Ba, and Pb. A moderate to strong positive correlation was found between the content of Cd, Cr, Mn, Fe, Zn, Ba, and Pb in vegetation and soil ($r = 0.51–0.82$). No correlation was found for the remaining trace elements: B, Zr ($r = -0.07–0.08$), Li, Al, Ti, Ni, Cu, and Mo ($r = 0.19–0.39$). The findings of this study are important for the development of agriculture in Azerbaijan, as the removal of heavy metals from soils and irrigation water is supported by national law and remains a priority for environmentalists and soil scientists.*

Keywords: *microelement deficiency, plant-soil system, eco-biological parameters, vegetation, heavy metals*

Introduction

Plants remain one of the main sources of biologically active substances. Experts predict that global demand for studying plant soils used to produce natural fertilizers will only grow. Microelements are an important component of plant mineral nutrition. Many of them are vital because, as components of biologically active substances, they perform a variety of catalytic and regulatory functions in metabolic processes – absorption, transport, oxidation-reduction, biosynthesis of organic compounds, and the transfer of genetic information (Akhundova et al., 2025; Bunyatova et al., 2025).

[1]Institute of Geography Public Legal Entity, Ministry of Science and Education of the Republic of Azerbaijan, PhD in Biology, Baku, Azerbaijan
[2]Institute of Geography Public Legal Entity, Ministry of Science and Education of the Republic of Azerbaijan, PhD in Agrarian Sciences, Baku, Azerbaijan
[*]Corresponding author. E-mail: aliyeva.matanat@internet.ru
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The modern classification of trace elements based on their importance to living organisms is presented as follows: a) vital – Fe, Mn, I, Cu, Zn, Co, Cr, Mo, Se; b) conditionally essential – Li, B, Ni, Cd, V, Si, F, Br, Ti; c) potentially toxic – Al, Cd, Pb, Hg, Ba, Ti, Bi. In addition, Fe and Si are classified as mesoelements. The number of biologically significant elements is expanding: elements significant for individual species now include As, Br, Sr, Cd, Sn, Ba, W. Each element has its own safe concentration range, within which normal soil function occurs under plants (Hasanova et al., 2026; Akhundova et al., 2025; Bunyatova et al., 2025).

Violations of this range lead to various pathological abnormalities in metabolic processes, leading to microelement deficiency in the case of a deficiency, and to toxic microelement deficiency in the case of an excess (Ramazanova et al., 2026). In recent decades, ecologists and agricultural chemists have focused primarily on studying heavy metal pollution of soils, natural waters, and plants caused by industrial emissions. Steppe ecosystems occupy significant areas of Azerbaijan, perform important biosphere functions, and are of high economic importance (Verdiyeva et al., 2025).

The content of microelements in soils under plants, as an important factor in the functioning of steppe ecosystems, has been poorly studied. Only data are available on the content of Mn, Zn, Cu, Co, and I in some steppe vegetation, and a study of lead in the "rock-soil-humic substances-plants" system in forest-steppe and steppe soils of the Republic of Azerbaijan (Hasanova & Mammadova, 2023). The region's deep inland location allows these ecosystems to exist in extremely arid conditions. The climate of Azerbaijan's dry steppe zones (primarily the Kura-Araz Lowland, Shirvan, Aran and Absheron) is a dry subtropical climate with hot summers and mild to cool winters. It is characterized by insufficient precipitation (130–300 mm per year), high evaporation, frequent winds, and average temperatures of 1–4 °C in January and 21–27 °C in July. The parent rocks are deluvial and deluvial-proluvial deposits, as well as sand and gravel deposits. The basis of the soil cover is typical Kastanozems soils with a thin humus horizon (Gahramanova et al., 2026; Hasanova Baba-zade et al., 2026; Ismayilov et al., 2025; Ismayilova et al., 2025a; Ismayilova et al., 2025b; Nasirova et al., 2026).

Materials and Methods

The method for determining microelements in soil under vegetation includes sampling from the root layer (0–20/40 cm), removing roots, drying, crushing and sifting (0.25–1 mm sieve). Variation and statistical parameters of element contents were studied in soils, plant ash, and their interaction coefficients in the vegetation-soil system. Average element contents in soils ranged from 3.0 mg/kg for Mo to 70–180 mg/kg for Al. These can be roughly divided into the following groups: slightly high contents (Fe and Al), which are classified as macroelements in soils (42–350–70–180 mg/kg); moderate contents (Zr, Mn, B, Ti) (318–5040 mg/kg); low contents (Li, Cu, Ni, Pb, Cr, Zn, Cd) (20–100 mg/kg); and very low contents (Mo, B, Co) (3.1–6.2 mg/kg). All data on microelement contents in chestnut soils are within the limits of normal variation according to the classification of G.N.Zaitsev (1990) (Shukurov et al., 2025; Shukurov et al., 2026; Mammadova et al., 2025a; Mammadzada et al., 2025; Mirzezadeh et al., 2025; Makki et al., 2025).

Results and Discussion

The content of Ba, Li, Mn, Pb, Ti, Al, B, Cd, and Fe in soils is within the lower limit of 9–21%, while Cr, Ni, Cu, Zn, Zr, and Mo are within the upper limit of 27–34%. The average content of Cd and Pb reaches their maximum permissible concentration (MPC) in soils (Table 1). The content of trace elements in the cuttings of steppe vegetation varied by 4 orders of magnitude: from 0.07 for B to 217 mg/kg for Fe (Aliyeva, 2025; Mammadzade, 2025).

According to the average content in vegetation, trace elements are conditionally divided into the following groups: high content – Fe, Al (217–266); average – Ba, Ti, Sr, Mn, Zn (22–67); low – B, Cu, Li, Cr, Mo, Cd, Zr (1.22–6.9) and very low – Ni, Pb (0.07–0.88) mg/kg. The series of these elements according to the degree of decrease in content in steppe vegetation is presented as follows: AI > Fe > Sr > Mn, Ba > Ti > Zn > Cu > B > Zr > Cr > Li > Mo > Cd > Pb > Ni. The results of the correlation analysis revealed a direct, significant relationship between the microelement content in soils and their accumulation in vegetation for Cd, Cr, Mn, Fe, Zn, Ba, and Pb. The pairwise correlation coefficients for these elements ranged from 0.56 for Zn to 0.81 for Pb. For the remaining microelements, no correlation was found in the vegetation-soil system. A comparative analysis of the content of all studied microelements in the phytomass of steppe communities, either within the norm or within the clarkes in the absence of a norm, showed that the phytocenoses of sample plots 3 in the Absheron Steppe and 15 in the Kura-Araz Steppe (12 elements out of 16), as well as sample plots 13 in the Aran Steppe (8 out of 13), and sample plot 16 in the Shirvan Steppe (10 out of 16) were best provided with them. The lowest microelement status of vegetation was observed in sample plots 11 of the Aran steppe (10 elements out of 15, normal – 1, elevated – 2). The most unfavorable microelement status of steppe phytocenoses was observed in sample plots 7 of the Lerik steppe (7 elements out of 15, content increased by 2.0–3.7 times, normal – 5) and sample plots 14 of the Aran steppe (5 out of 15, increased by 2.9–4.1 times, normal – 5).

Regarding the supply of steppe vegetation with individual microelements, a deficiency of B and Ni and a decrease in Zr compared to the clarke were found in all phytocenoses, Mn and Li were within the norm, the concentration of Fe in vegetation in all sample plots was above the norm from 2.2 to 6.5 times, Mo in 15 sample plots (by 2.3–10.8 times), Ba in 14 sample plots (1.7–4.1), Sr in 14 sample plots (1.7–3.8). Exceeding the maximum permissible level in vegetation was noted for Mo (> 3 mg/kg) in three sample plots, Fe (> 300 mg/kg) in two and Cr (> 5 mg/kg) in two sample plots. It should be noted that there are no standards in plants for such toxic microelements as B and Al. Based on the differences identified, it can be concluded that the steppe vegetation of Azerbaijan is provided with microelements in significantly different ranges – from a deficiency for some to exceeding the maximum level for others. Compared to clarke soils, chestnut soils in steppe ecosystems are characterized by normal contents of Li, B, Al, Ti, Cd, Cr, Co, Zn, and Zr; elevated contents of Pb (2.9 times), Mo (2.5 times), and Ba (1.9 times); and decreased contents of Mn (1.7 times), Ni (1.4 times), and Cu (1.2 times). This is determined by the predominance of granitoids, a group of acidic rocks, as bedrock. The average values and ranges of content for 16 microelements in steppe vegetation were determined. Elements were classified by content as high (Fe, Al – > 200 mg/kg), medium (Ba, Ti, Sr, Mn, Zn – 23–69), low (B, Cu, Li, Cr, Mo, Cd, Zr – 1.22–7.0), and very low (Be, Ni, Pb – 0.08–0.89 mg/kg).

Significant heterogeneity in microelement content in vegetation was revealed, due to both the biological characteristics of plants, the intensity of their absorption from the soil, and ecological and geochemical factors determining the bioavailability of elements (Mammadova et al., 2026a; Mammadova et al., 2025b; Mammadova et al., 2025; Mazhar et al., 2025).

The lowest coefficient of variation (15%) was observed for Li, and the highest for Cr (59%). According to the intensity of biological absorption from soil by vegetation, which characterizes the ecological activity of elements in the soil, Mo (10.5), Zn (5.2), B (3.6), and Cu (3.4) were classified as high; Li (1.6) and Mn (1.1) were classified as medium; Al, Ti, Cd, Cr, Fe, Co, Ni, Zr, Ba, and Pb (0.09–0.83) were classified as low. A moderate to strong positive correlation was found between the content of Cd, Cr, Mn, Fe, Zn, Ba, and Pb in vegetation and soil ($r = 0.51–0.82$). No correlation was found for the remaining trace elements: B, Zr ($r = -0.07–0.08$), Li, Al, Ti, Ni, Cu, and Mo ($r = 0.19–0.39$). A comparison of microelement levels in steppe vegetation with standard values (or clarkes) revealed that concentrations of Fe (3.7 times higher than normal), Mo (2.3 times higher than normal), Ba (2.8 times higher than normal), and Sr (1.3 times higher than normal; Mn (1.8 times higher than normal), and Zn (1.4 times lower than normal), Cu (1.4 times lower than normal, and B (3.4 times lower than normal).

Exceedances of the maximum permissible levels in vegetation were noted for Mo at three sample sites, and for Fe and Cr at two. These differences in content are the cause of unfavorable ratios in vegetation between Fe:Zn, Fe:Mn, Zn:Cu, and Cu:Mo. Due to the low biological productivity of steppe phytocenoses, the involvement of microelements in the biogenic migration of aboveground phytomass is 1–2 orders of magnitude less compared to the average capture of them by the annual growth of terrestrial vegetation (Madnee et al., 2025; Mammadova et al., 2026b; Mammadov et al., 2026).

Distribution of the concentration coefficient which calculated by dividing the total content of each microelement in treated soil by its content in untreated soil ($C_{amended}/C_{control}$) in the soil profile showed in Figure 1. The results of the analysis of total potentially hazardous trace elements concentrations in soil samples with additives and control samples are presented in Figure 2 to graphically display the change in concentration with depth.

The study of micronutrients in the soil under vegetation is critically important for fertility management, as their deficiency or excess directly inhibits enzymatic processes, disrupts photosynthesis, and reduces crop immunity. Accurate analysis helps prevent plant diseases and increase yields. A balanced level of trace elements protects the flora from adverse weather conditions (drought, frost), and also strengthens immunity to fungal and bacterial diseases (Nasirova, 2023a; Nasirova, 2023b; Nasirova et al., 2025; Nasirova & Verdiyeva, 2023).

Microelements are part of enzymes, vitamins, and hormones. They regulate the process of photosynthesis, nitrogen, and carbohydrate metabolism. Forbs form complex root systems that actively extract elements from deep soil horizons. Studying this process allows us to understand how minerals are redistributed and returned to the soil with sediments. In arid climates, due to the high alkalinity of the environment, many trace elements are converted into insoluble forms that are inaccessible to plants. On the contrary, some metals can accumulate to toxic concentrations, inhibiting biomass growth. Toxicological monitoring helps prevent contamination of agricultural products (Rzayeva, 2023; Rzayeva & Mamedzade, 2024; Sadigov et al., 2025; Sadigov et al., 2026; Samadov et al., 2026a; Samadov et al., 2026b; Verdiyeva et al., 2026; Togola et al., 2023).

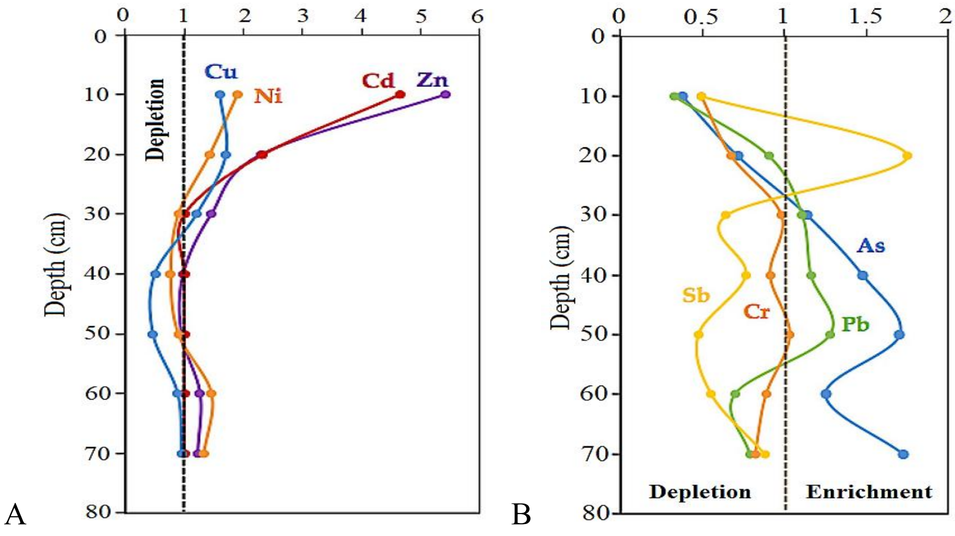

Figure 1
Distribution of the concentration coefficient

Note. Cd, Cu, Ni, and Zn (A); As, Cr, Sb, and Pb (B)

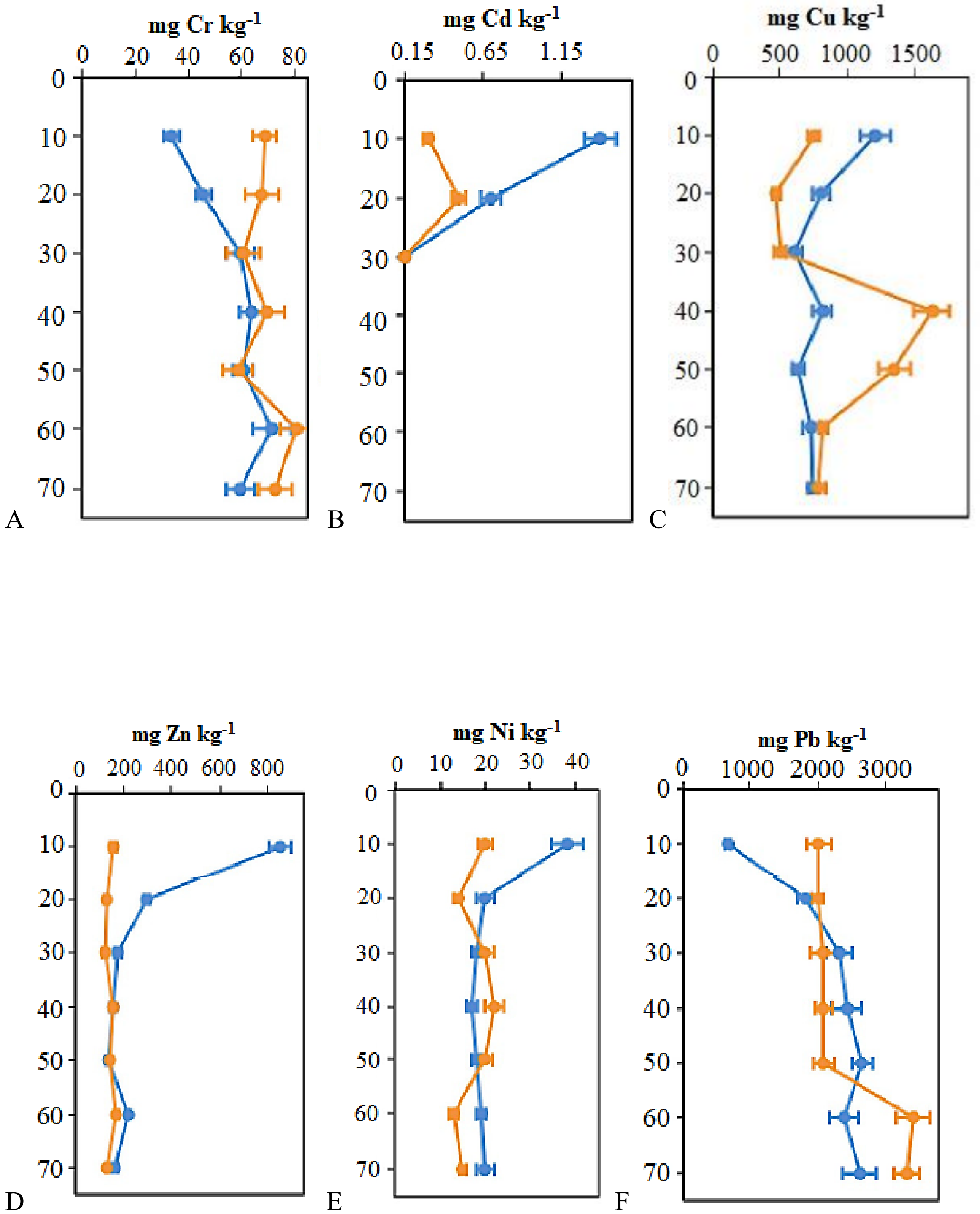

Figure 2

Distribution of microelements along soil sampling sites
(with amended soils – blue lines; and control soils – orange lines) of the soil profile

Table 1
Variational statistical indicators of the content (C) of some studied microelements in soils under vegetation, in vegetation ash and the correlation coefficient (r) in the soil-vegetation system of steppe phytocenoses

Microelements	C in soils, mg/kg		V* %	C in ash, mg/kg		V, %	r	Clarke in soils, mg/kg***	MPC in soils, mg/kg***
	M ± m	limits		M ± m	limits				
Li	22.3 ± 0.6	18–27	11	34.3 ± 1.14	28–43	15	0.19	25	–*****
B	16.4 ± 1.29	13–22	21	57.0 ± 9.5	27–97	44	-0.07	20	25
Al	74480 ± 320	53100–94980	17	6638 ± 1090	2500–15000	66	0.29	71000	–
Ti	5060 ± 148	3670–6080	13	557 ± 41	325-960	33	0.23	5000	–
Cr	62 ± 4.2	35–98	28	35.0 ± 2.6	17-53	31	0.72	70	100/90
Mn	786 ± 28	535–960 827 ± 45	15	827 ± 45	400–1125	22	0.60	1000	1500
Fe	45360 ± 261	30040–60110	22	3875 ± 164	1470–8000	46	0.70	40000	–
Co	10.9 ± 0.07	9–15	20	8.8 ± 0.29	6–10	10	0.05	8	50
Ni	29.1 ± 2.0	15–49	28	9.5 ± 0.88	4–16	38	0.21	50	100
Cu	25.0 ± 2.1	10–49	35	80.0 ± 8.4	33–175	42	0.39	30	100
Zn	81.0 ± 7.0	42–136	33	414 ± 46	200–800	45	0.57	90	300
Mo	3.0 ± 0.24	1.3–4.5	34	29.0 ± 1.8	13–42	28	0.38	1.2	5
Pb	35.0 ± 1.4	28–48	16	13.4 ± 1.1	9–25	33	0.82	12	100/32

Conclusion

The study helps identify heavy metal contamination and trace element concentrations in the soil. This allows for timely intervention to prevent toxins from entering groundwater or the food chain. It also helps assess fertility, optimize fertilizer application, increase yields, and ensure the quality of agricultural products. The analysis revealed deficiencies and excesses of certain trace elements that impact plant, animal, and human health, and helps monitor the level of heavy metal contamination in soils. Differences in content of microelements are the cause of unfavorable ratios in vegetation between Fe:Zn, Fe:Mn, Zn:Cu, and Cu:Mo. Exceedances of the maximum permissible levels in vegetation were noted for Mo at three sample sites, and for Fe and Cr at two. The lowest microelement status of vegetation was observed in sample plots 11 of the Aran steppe. The most unfavorable microelement status of steppe phytocenoses was observed in sample plots 7 of the Lerik steppe and sample plots 14 of the Aran steppe. Regarding the supply of steppe vegetation with individual microelements, a deficiency of B and Ni and a decrease in Zr compared to the clarke were found in all phytocenoses.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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