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Soil Fertility Indicators of Forest Ecosystems in the Shaki District of the Southern Greater Caucasus Slope

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Abstract. *Forest ecosystems of the Sheki district on the southern slope of the Greater Caucasus play an important role in biodiversity conservation, regulation of water resources, and prevention of soil erosion. The fertility indicators of forest soils in the Sheki district, one of the main forested areas of the southern slope of the Greater Caucasus, were evaluated. During the study, soil samples were collected from different altitudinal zones of the area, and their physicochemical properties, including humus content, pH, total nitrogen, available phosphorus, exchangeable potassium, and soil texture, were analyzed. The results of the research showed that the forest soils of the region possess relatively high organic matter reserves and favorable physical properties. The observed variations in soil fertility indicators were mainly associated with altitude, vegetation cover, and relief conditions. The obtained findings contribute to a better understanding of the formation characteristics of soil fertility in mountain forest ecosystems and provide a scientific basis for sustainable forest management.*

Keywords: *forest soils, soil fertility, humus, nutrients, Greater Caucasus, Sheki district, Azerbaijan*

Introduction

The forest soils of the southern slope of the Greater Caucasus are an important component of mountain ecosystems, influencing forest productivity, biodiversity conservation, and soil fertility (Mammadov, 1998; Mammadov & Khalilov, 2002)**.** The diverse climatic conditions and rich forest vegetation of the southern slope of the Greater Caucasus have contributed to the development and enrichment of brown mountain-forest and dark brown mountain-forest soils in the region (Mammadov, 1998; FAO, 2022; Mammadov & Khalilov, 2002). In this respect, the Sheki district occupies a significant position due to its extensive forest resources and complex topography (Mammadov, 1998; FAO, 2022)**.**

Soil fertility is formed through the complex interaction of physical, chemical, and biological factors (FAO, 2019; Khar'kina, 2017; Kovda, 2011)**.** The assessment of fertility indicators enables the determination of soil quality and provides insight into the processes of forest soil formation within mountain forest ecosystems (FAO, 2022; Khar'kina, 2017; Soil Atlas of the Republic of Azerbaijan, 2007)**.** Therefore, the study of the fertility characteristics of forest soils in the Shaki district is of great importance from both scientific and practical perspectives (Huseynova, 2007; Mammadov & Khalilov, 2005).

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Methods

The study area covers the Shaki district located on the southern slope of the Greater Caucasus. The region is characterized by mountainous terrain, elevations ranging from approximately 500 m to over 2,500 m above sea level, and a moderately humid climate. The dominant vegetation consists of broad-leaved forests composed mainly of Oriental beech (Fagus orientalis), Georgian oak (Quercus iberica), Caucasian hornbeam (Carpinus caucasica), and other tree species. The predominant soil types in the study area are brown mountain-forest soils and dark brown mountain-forest soils. These soils provide favorable conditions for the development of forest ecosystems and are distinguished by their high biological activity (FAO, 2022; Mammadov & Khalilov, 2002). Studies conducted to assess the fertility indicators of soils in the Sheki district on the southern slope of the Greater Caucasus have revealed significant changes in the upper and lower boundaries of forest distribution. The lower forest boundary has been consistently exposed to anthropogenic impacts. In the past, the mountain-forest soils of the region were predominantly covered by low-growing oak forests and, to a lesser extent, hornbeam–oak forests (Baghaee et al., 2020; FAO, 2019; Khar'kina, 2017). The forests of the region play an important role in soil conservation and the protection of water resources. However, parts of these forests have been cleared by local populations and converted into agricultural lands. Owing to the favorable conditions for the completion of the growing season of agricultural crops in the plains and foothill zones of the Shaki district, cultivated areas have expanded onto former forest lands (Huseynova, 2007; Mammadov & Khalilov, 2002).

The gradual destruction of forests, which were once rich in vegetation, has led to the weakening of water resources and the intensification of soil erosion on sloping terrains. Consequently, a dual challenge has emerged: on the one hand, there is a growing need to ensure the conservation and sustainable development of forests, while, on the other hand, the demand for agricultural production and the cultivation of crops remains an important socioeconomic issue (Mammadova, 2022; Mammadov & Khalilov, 2005).

Results

Five representative soil profiles established within the forest ecosystems of the Sheki district were analyzed to evaluate the fertility status of mountain forest soils. The investigated soils included leached brown mountain-forest soils, carbonate brown mountain-forest soils, forest-derived brown soils, and steppe-affected brown mountain-forest soils distributed under different vegetation communities and elevation zones. The results demonstrated considerable variation in soil fertility indicators among the investigated profiles and soil horizons (Table 2). Humus content ranged from 0.85% to 4.48%. The highest humus concentration was recorded in the surface horizon (0–11 cm) of Profile 5 (4.48%), whereas the lowest value (0.85%) occurred in the 62–90 cm layer of Profile 1. In all soil profiles, humus content gradually decreased with increasing soil depth, reflecting the accumulation of organic matter mainly within the upper horizons.

Soil reaction varied from pH 7.5 to 8.4, indicating neutral to slightly alkaline conditions throughout the study area. The lowest pH value (7.5) was observed in the 12–27 cm horizon of Profile 3, while the highest value (8.4) occurred in the deeper horizons of Profile 1. Vertical changes in soil reaction were relatively small, although a slight increase in alkalinity with depth was observed in most profiles. Exchangeable calcium was the dominant basic cation in all investigated soils. Calcium concentrations ranged between 6.0 and 30.0 meq/100 g soil, with the highest value recorded in the surface layer of Profile 5 and the lowest in the 45–62 cm horizon of Profile 1. Exchangeable magnesium varied from 5.0 to 19.5 meq/100 g soil, following a distribution pattern similar to that of calcium. The highest magnesium content was also measured in Profile 5, whereas the minimum value occurred in the middle horizon of Profile 1. Exchangeable sodium content remained consistently low in all investigated soils, ranging between 0.4 and 1.7 meq/100 g soil. These values indicate the absence of sodium accumulation and confirm that salinity is not a limiting factor for forest soil fertility in the study area. The total amount of exchangeable bases varied considerably among soil profiles, ranging from 11.5 to 49.7 meq/100 g soil. The highest value was determined in the surface horizon of Profile 5, while the minimum value occurred in the 45–62 cm layer of Profile 1. Surface horizons generally contained greater amounts of exchangeable bases than subsurface layers. Comparison of the five soil profiles showed that Profiles 4 and 5 possessed the highest fertility indicators owing to their greater humus content and higher concentrations of exchangeable calcium and magnesium. In contrast, Profile 1 exhibited comparatively lower fertility values, particularly in the middle horizons, where both humus content and total exchangeable bases reached their minimum levels. The obtained results indicate that soil fertility in the forest ecosystems of the Sheki district is strongly influenced by soil depth and environmental conditions. Surface horizons consistently exhibited higher organic matter accumulation and greater nutrient reserves than deeper soil layers. Overall, the investigated mountain forest soils demonstrated favorable fertility characteristics suitable for sustaining natural forest vegetation.

Discussion

The main objective of the study was to analyze and assess the current condition of the soils within the high-mountain landscape–soil complexes of the Greater Caucasus and to identify the characteristics of their transformation under the influence of anthropogenic factors. Accordingly, comprehensive information was obtained on soil cover structure, vegetation cover, ecological conditions, relief, hydrographic features, climate, and other environmental characteristics of the study area (Huseynova, 2007; Kovda, 2011; Soil Atlas of the Republic of Azerbaijan, 2007).

Table 1
Coordinates of the soil profiles established in the Shaki District on the southern slope of the Greater Caucasus

Soil profiles	Latitude	Longitude	Elevation m²
Soil Profile 1: Bideiz Village	41°0.7'58.29"	47°19'25.89"	727
Profile 2. Bash Gunchut Village	41°9'54. 32"	47°19'15. 14"	871
Profile 3. 5 km north of Kish Village	41°15'33. 74"	47°12'18.50"	761
Profile 4. Bash Shabalyd Village	41° 18' 10.07"	47°6'18. 84"	732
Soil Profile 5: 10 km East of Shin Village	41° 22'18. 11"	47°4'42. 09"	1260

The natural conditions and other characteristics of the Shaki district indicate that the soil-forming processes in the region occur under highly complex conditions. The sharp variations in relief, along with corresponding changes in climate and vegetation zones, as well as the influence of parent materials and the hydrographic network, have contributed to the complexity of soil development in the area (Kovda, 2011; Mammadova, 2022; Mammadov & Khalilov, 2002). On steeper slopes, shallow soils are formed, while well-developed soils are found in areas with gentler slopes. In the plain areas, the diversity of alluvial deposits, together with the varying influences of climate, vegetation cover, surface and groundwater conditions, creates a complex system of soil formation (FAO, 2022; Mammadov, 1998).

1. Brown mountain forest soils
2. Forest-derived brown soils
3. Carbonate-rich brown mountain forest soils
4. Steppe-affected mountain brown soils

These soil types are distributed in the northern part of the district, in the high-mountain zone around the villages of Bash Layski, Oxud, Bash Gunchut, and Oraban. The total area covers 404.45 hectares (Huseynova, 2007). These areas are predominantly used under forest cover. The soils have developed under beech–hornbeam forests in the middle forest belt and represent a transitional stage toward brown forest soils. In the upper layer, a fresh forest litter is present, beneath which a 2–3 cm humus layer is formed, which is a characteristic feature of these soils (Huseynova, 2007; Mammadov & Khalilov, 2002). The relief of the area consists of sloping mountainsides and dissected slopes divided by valleys. The natural vegetation includes oak, hornbeam, hawthorn, alder, wild strawberry, raspberry, and other widely distributed plant species. The soil-forming parent materials consist of eluvial and eluvial–deluvial deposits. The soil cover is of medium depth to shallow (Huseynova, 2007; Soil Atlas of the Republic of Azerbaijan, 2007). In the areas where brown mountain-forest soils are distributed, both leached and weakly leached soils are present. In some places, forest litter has been washed away in patches, leaving individual roots exposed. The morphological characteristics of these soils can be clearly observed from the description of the soil profiles (Huseynova, 2007).

Profile 1. Located 10 km east of Bideiz village, which belongs to the forestry area of the Sheki district, in a low-mountain zone. The vegetation cover is very rich, including mixed stands of ash, yew, maple, hornbeam, wild grape, blackberry, willow, walnut, apple, and pear trees, as well as shrub species such as cornel, medlar, hawthorn, rosehip, and barberry (Huseynova, 2007). The profile depth is 97 cm.

The soil is a steppe-affected brown mountain-forest soil

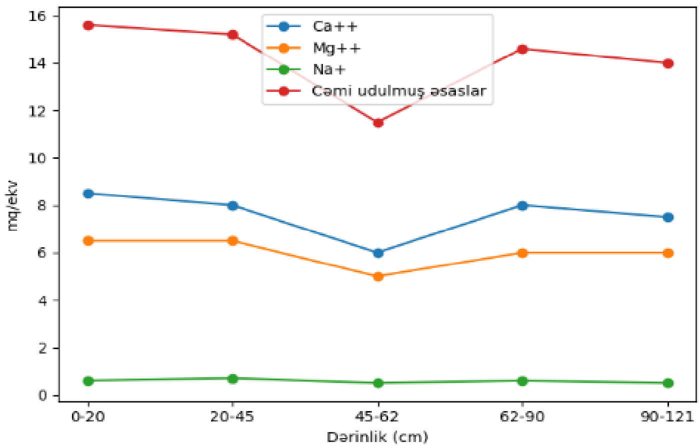
A second soil profile was established 7–8 km north of Bash Gunchut village. Hornbeam (Carpinus caucasica) dominates the vegetation in this area. Other plant species include walnut, ash, sea buckthorn, plum, rosehip, blackberry, cornel (dogwood), medlar, wild cherry, willow, and elm (Huseynova, 2007). The profile depth is 80 cm. The soil is classified as steppe-affected brown mountain-forest soil. A soil profile was established in the middle-mountain zone, 5 km northeast of Kish village. The soil-forming and parent materials consist of deposits that have undergone complete weathering of the original rock. The mesorelief is characterized by a middle-mountain landscape, while the microrelief is a west-facing slope. The vegetation cover includes hornbeam, sporadic oak, chestnut, maple, dogwood, rosehip, blackberry, goat willow, plum, wild cornel, occasional walnut, and herbaceous plants such as shepherd's purse, sorrel, red clover, sage, yellow clover, thistle, wormwood, yarrow, and others (Huseynova, 2007). The profile depth extends below 31 cm. The soil is classified as carbonate brown mountain-forest soil. A fourth soil profile was established in the natural forest area of the Shaki district, in the Bash Shabalyd village, located in the middle-mountain zone on a southeast-facing slope. The area has a slightly inclined relief, and the elevation ranges around 1100 m above sea level (Huseynova, 2007). The vegetation consists of hornbeam, oak, occasional beech, maple, plum, willow, and elm. The forest stand is well preserved, with only isolated signs of logging. Forest litter is present. The profile depth is 56 cm.

The soil is classified as leached brown mountain-forest soil

The fifth soil profile was established in a mountainous area 10 km east of Shin village, on the left bank slope of the Shin River in the middle-mountain zone. The profile depth is 36 cm. The land use type is natural forest. The vegetation cover includes hornbeam, oak, chestnut, maple, dogwood, rosehip, blackberry, walnut, hazelnut, and various herbaceous plants such as shepherd's purse, sorrel, red clover, sage, yellow clover, thistle, wormwood, yarrow, and others (Huseynova, 2007).

The soil is classified as carbonate brown mountain-forest soil

The natural conditions of the Shaki district, along with other characteristics, indicate that soil-forming processes in the region occur under highly complex conditions. The sharp variation in relief, together with corresponding changes in climate and vegetation zonation, as well as the influence of parent materials and the hydrographic network, has contributed to the complexity of soil development in the area. Shallow soils are mainly found on steep slopes, while well-developed soils are distributed in areas with gentler slopes (Kovda, 2011; Mammadova, 2022; Mammadov & Khalilov, 2002). In the southern slope of the Greater Caucasus, soil data for the mountainous and foothill zones of the Shaki district have been collected. These data are aimed at the efficient use of soil resources, refinement of land use classification, implementation of land reform activities, increasing productivity, and ensuring soil conservation. Within the landscape complexes of the area, soil fertility indicators of high- and low-mountain soils have been analyzed using GIS-based approaches, including the collection of large-scale geospatial data, processing of the collected information, spatial analysis, comparison, and systematization of the overall dataset (Huseynova, 2026; Soil Atlas of the Republic of Azerbaijan, 2007). One of the factors influencing soil fertility with increasing elevation above sea level is altitude. In high-mountain areas, greater accumulation of humus, better development of soil structure, and relatively higher levels of nutrient elements have been observed. These features are explained by lower temperatures in these regions and the slower rate of organic matter mineralization (Khar'kina, 2017; Kovda, 2011).



Fiqure 1

Variation of exchangeable base content with soil depth

The graph shows that the total amount of exchangeable bases is the lowest in the 45–62 cm layer. Calcium (Ca) and magnesium (Mg) constitute the main share and exhibit similar trends throughout the profile. Sodium (Na^+) remains relatively stable but at a very low level. Overall, the total exchangeable bases are higher in the upper and lower layers, while they decrease in the middle horizon. In the studied area, the humus content in forest soils ranged from 0.85% to 4.48% across the soil profiles. The highest humus content was recorded in the upper layer (0–11 cm) of the profile given in the table, reaching 4.48%, while the lowest value, 0.85%, was observed at a depth of 62–90 cm in Profile 1. In general, all soil profiles showed a decreasing trend of humus content with depth, which is associated with the accumulation of organic residues mainly in the surface horizons (Khar'kina, 2017; Kovda, 2011). The soil reaction (pH) varied between 7.5 and 8.4. These values indicate that the soils have a neutral to slightly alkaline reaction. The lowest pH value (7.5) was recorded in the 12–27 cm layer of the profile given in the table, while the highest value (8.4) was observed in the 45–62 cm and 90–121 cm layers of Profile 1 (FAO, 2022; Mammadov, 1998).

Table 2
Fertility indicators of forest soils in the Shaki district on the southern slope of the Greater Caucasus

Profile No.	Depth, см	Humus %	pH	Structural analysis of exchangeable bases in 100 g of soil, meq/100 g			
				Ca^{++}	Mg^{++}	Na^{+}	Total exchangeable bases
1	0-20	2.75	8.1	8.50	6.50	0.60	15.60
	20-45	2.28	8.3	8.00	6.50	0.70	15.20
	45-62	1.40	8.4	6.00	5.00	0.50	11.50
	62-90	0.85	8.3	8.00	6.00	0.60	14.60
	90-121		8.4	7.50	6.00	0.50	14.00
2	0-8	3.28	8.3	18.00	16.50	1.70	36.20
	8-21	2.36	8.1	15.00	13.50	1.30	29.80
	21-31	1.73	8.2	16.00	13.00	1.20	30.20
3	0-12	4.36	7.6	18.00	14.00	-	32.00
	12-27	3.04	7.5	10.00	8.50	-	18.50
	0-12	1.96	7.9	9.00	8.00	-	17.00
4	0-8	3.91	7.8	14.00	12.00	0.60	26.60
	8-19	3.03	7.9	10.00	6.00	0.40	16.40
	19-36	1.67	7.7	8.00	6.50	0.50	15.00
5	0-11	4.48	8.0	30.00	18.00	1.70	49.70
	11-28	3.17	8.2	26.50	19.50	1.60	47.60
	28-39	1.72	8.3	20.00	16.50	1.40	37.90

The fertility indicators of the forest soils of the Shaki district are presented in the table

Exchangeable bases are dominated by calcium (Ca^{2+}), whose content varied between 6.0 and 30.0 meq/100 g of soil. The highest value was recorded in the surface horizon of Profile 5 (30.0 meq/100 g), while the lowest value was observed in the 45–62 cm layer of Profile 1 (6.0 meq/100 g). The magnesium (Mg^{2+}) content ranged from 5.0 to 19.5 meq/100 g of soil. The highest value was found in the 11–28 cm layer of Profile 5 (19.5 meq/100 g), whereas the lowest value was recorded in the 45–62 cm layer of Profile 1 (5.0 meq/100 g). The sodium (Na^{+}) content remained generally low, ranging from 0.4 to 1.7 meq/100 g of soil. This indicates that there is no risk of soil salinization in the studied area (FAO, 2022). The total amount of exchangeable bases varied between 11.5 and 49.7 meq/100 g of soil. The highest value was observed in the surface horizon of Profile 5 (49.7 meq/100 g), while the lowest value was recorded in the 45–62 cm layer of Profile 1 (11.5 meq/100 g). The high cation exchange capacity indicates a strong ability of the soils to retain nutrient elements (Huseynova, 2007; Mammadov & Khalilov, 2005; Soil Atlas of the Republic of Azerbaijan, 2007). The results show that the studied forest soils are moderately to well supplied with humus, have neutral to slightly alkaline reactions, and are rich in calcium and magnesium. The generally high fertility indicators confirm favorable conditions for forest vegetation development in these soils. In particular, Profiles 4 and 5 can be considered more fertile due to their higher humus content and total exchangeable base values (Huseynova, 2007; Mammadov & Khalilov, 2002). The soil reaction is slightly alkaline in the upper horizons and becomes more alkaline with depth. The pH value ranges from 7.7 to 8.4 within the 0–100 cm soil profile (FAO, 2022; Mammadov, 1998). Typical brown mountain-forest soils have a high cation exchange capacity. In the surface horizons (0–20 cm), the total exchangeable bases range from 15.60 to 49.70 meq/100 g of soil, while in the deeper layers (0–50 cm), they range from 14.00 to 37.90 meq/100 g of soil (Huseynova, 2007; Soil Atlas of the Republic of Azerbaijan, 2007).

Conclusion

The results of this study demonstrate that the forest soils of the Shaki district on the southern slope of the Greater Caucasus possess generally favorable fertility characteristics and provide suitable conditions for the sustainable development of forest ecosystems. The analyzed soil profiles revealed relatively high humus content in the surface horizons, neutral to slightly alkaline soil reaction (pH 7.5–8.4), and high levels of exchangeable calcium and magnesium, indicating a strong nutrient-retention capacity. The study also confirmed that soil fertility indicators vary according to altitude, vegetation cover, relief conditions, and soil-forming parent materials. Humus content and the amount of exchangeable bases generally decrease with soil depth, reflecting the concentration of organic matter in the upper horizons. Among the investigated profiles, Profiles 4 and 5 exhibited the highest fertility due to their greater humus reserves and higher total exchangeable base content. At the same time, the research highlights the influence of anthropogenic activities, particularly deforestation and agricultural expansion, on the degradation of mountain forest ecosystems. These processes contribute to soil erosion, reduced water retention, and the gradual deterioration of soil quality. Overall, the obtained findings provide valuable scientific information on the fertility status of mountain forest soils in the Sheki district and can serve as a basis for sustainable forest management, soil conservation planning, and the rational use of natural resources. The application of modern monitoring methods, including GIS-based spatial analysis, together with effective forest protection measures, will contribute to maintaining soil fertility, preserving biodiversity, and ensuring the long-term ecological stability of the southern slope of the Greater Caucasus.

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