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Fertility Indicators of Forest Soils in the South-Eastern Part of the Greater Caucasus

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Abstract. *This article examines the relationships between forest biogeocenoses and environmental factors on the southeastern slope of the Greater Caucasus, with particular emphasis on the role of soil as a key component in maintaining ecosystem stability and productivity. The study identifies the main ecological parameters influencing the fertility of forest soils and evaluates their significance in the functioning and development of forest ecosystems Based on field investigations and the analysis of soil profiles established under different forest formations, actual and optimal environmental indicators were determined for the construction of ecological fertility models. Special attention is paid to the soil block of the ecological model, which includes the soil profile and the physicochemical properties of soils as major sub-blocks. Diagnostic characteristics of soil horizons, including their thickness, structure, color, degree of compaction, and transition features, were used as indicators reflecting ongoing ecological processes such as soil evolution, degradation, erosion, and the effects of climatic changes. The study presents ecological characteristics of brown mountain-forest and brown forest soils formed under mesophilic beech–hornbeam–oak and xerophilous oak–hornbeam vegetation communities in different altitudinal zones of the region. The proposed soil block of the fertility model provides a scientific basis for the development of ecological passports of forest soils and can be used for monitoring the ecological condition of forest biogeocenoses, assessing the degree of their stability or degradation, and supporting the planning of conservation and restoration measures in mountain forest ecosystems of Azerbaijan.*

Keywords: *ecological fertility model, forest soils, soil profile, ecological passport, forest biogeocenosis, brown mountain-forest soils, beech, hornbeam, oak, Greater Caucasus*

Introduction

When developing ecological fertility models for agricultural crops and forage lands, the factors determining soil fertility and plant productivity are systematized, and zonal models of high soil fertility are created. Advanced farms, zonal experimental stations, and soils of small experimental stations may serve as ecological and agroecological fertility models. Taking the high-fertility model of a particular farm as a standard and applying appropriate agrotechnical and reclamation measures, it is possible, within 15–20 years, to improve and manage the fertility of soils throughout the region (Ismayilova, 2007). As noted above, unlike agroecosystems, forest biogeocenoses possess their own regulatory and management systems. Models intended for monitoring, protection, and restoration of forests reflect either the normal development of forest biogeocenoses (high level) or their degradation (medium and low levels). This approach has also been adopted in our studies.

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When implementing ecological fertility models for agricultural crops and forage lands, fertility models are developed in the form of standards or fertility passports to enhance their practical significance and facilitate monitoring (Ismayilova, 2018).

Methods

The research was carried out on the southeastern slope of the Greater Caucasus within forest ecosystems differing in altitudinal position, vegetation composition, and ecological conditions. The study area included territories of the Basgal, Topchu, Galynja, and Talystan forest districts, where representative soil profiles were established under mesophilic beech–hornbeam–oak and xerophilous oak–hornbeam forest communities. These forest ecosystems occupy both middle-mountain and low-mountain zones and differ in slope exposure, vegetation cover, and edaphic conditions.

The methodological approach was based on the concept of ecological fertility modeling of forest soils, according to which the fertility status of forest ecosystems is assessed through a system of interconnected ecological indicators reflecting the functioning and sustainability of forest biogeocenoses (Mammadova & Ismayilova, 2023). In accordance with this concept, ecological passports of forest soils were developed using information obtained from the main blocks and sub-blocks of the fertility model.

Field investigations included route surveys and detailed soil studies conducted at representative sites selected according to differences in relief, vegetation type, and forest productivity. Soil pits were excavated in typical forest stands, and their locations were chosen to represent the prevailing ecological conditions of the region (Ismayilova, 2025). The forest characteristics of each site, including forest site quality class (bonitet), stand density, average age of stands, crown closure, percentage of live ground cover, slope inclination, and slope exposure, were recorded during field observations.

Morphological descriptions of soil profiles were performed according to conventional pedological methods. The thickness of genetic horizons, their color, structure, consistency, compactness, boundary characteristics, and the presence of mottles or other diagnostic features were determined directly in the field. Particular attention was paid to the characteristics of forest litter and to the sequence and differentiation of soil horizons, as these properties serve as important indicators of the intensity and direction of soil-forming processes occurring within forest biogeocenoses (Mammadova & Ismayilova, 2023).

The soil block of the ecological fertility model was divided into two principal sub-blocks: (1) soil profile characteristics and (2) soil composition and physicochemical properties. The soil profile sub-block included diagnostic morphological features reflecting soil genesis, ecological conditions, and the degree of ecosystem stability. These indicators were used to assess processes such as erosion, degradation, humus accumulation, profile differentiation, and the possible impacts of climatic changes on forest soils (Ismayilova, 2018).

The study utilized data obtained from a series of representative soil profiles. Profiles No. 1, 2, 3, 5, 6, and 7 were examined in the forests of Basgal, Topchu, and Galynja under mesophilic beech–hornbeam–oak vegetation to characterize brown mountain-forest soils of the middle-mountain zone. Profiles No. 3, 4, 5, 8, 9, 12, 13, and 15 were established in the Talystan forestry area under xerophilous oak–hornbeam communities to evaluate the ecological characteristics of brown forest soils formed in the low-mountain zone.

The collected information was subjected to comparative ecological analysis aimed at identifying similarities and differences among the studied forest soil types. Based on the obtained results, actual ecological parameters characterizing the current state of forest ecosystems were determined and compared with optimal conditions associated with stable and productive forest biogeocenoses (Mammadova & Ismayilova, 2023). The identified indicators formed the basis for the development of soil blocks and sub-blocks within the ecological fertility model and for the preparation of ecological passports intended for monitoring, conservation, and restoration of forest ecosystems in the southeastern part of the Greater Caucasus.

Table 1
Soil composition and physico-chemical properties

Indicators	Beech-Hornbeam-Oak Mountain Forest Soils of the Mid-Mountain Zone under Mesophytic Forests			Oak-Hornbeam Mountain Forest Soils of the Low-Mountain Zone under Xerophytic Forests		
	Leached Brown Mountain-Forest Soils	Carbonate Brown Mountain-Forest Soils	Leached Meadow-Brown Mountain Soils	Leached Brown Mountain-Forest Soils	Typical Brown Mountain Forest Soils	Carbonate Brown Mountain-Forest Soils
Humus content (0–20 cm), %	6.4–9.1	3.8–7.3	7.0–8.2	2.9–6.5	3.8–4.8	1.9–5.4
Humus reserves, t/ha						
0–20 cm	143–170	99–110	150–162	50–97	67–89	49–69
0–50 cm	140–180	180–205	170–200	107–191	111–217	100–151
0–100 cm	190–230	250–280	310–330	187–297	217–401	197–235
			3.0–7.0	3.3–7.1	4.0–6.7	3.5–7.5
Nitrogen (0–20 cm), %	0.28–0.32	0.11–0.38	0.37–0.43	0.15–0.25	0.22–0.23	0.12–0.31
Phosphorus (0–20 cm), %	0.20–0.22	0.23–0.24	0.23–0.30	0.25–0.27	0.27–0.35	0.29–0.41
Potassium (0–20 cm), %	2.1–2.2	2.1–2.2	2.3–2.4	2.3–2.5	2.4–2.6	2.5–2.7
CEC, meq/100 g	20.4–34.7	23.4–29.1	20.1–23.3	29.0–35.0	21.9–40.1	17.6–27.8
pH	6.5	6.5–7.0	5.0–6.0	7.0–7.5	6.1–7.0	6.5–7.2

The investigation confirmed that mesophilic beech–hornbeam–oak forests of the middle-mountain belt and xerophilous oak–hornbeam forests of the low-mountain belt differ considerably in their soil ecological characteristics. These differences are reflected in the structure and development of soil profiles, humus accumulation patterns, vegetation cover, and the influence of topographic factors such as slope exposure and inclination. Consequently, the assessment and management of forest ecosystems require region-specific ecological criteria and fertility indicators.

Based on the developed ecological fertility models, ecological zoning of the southeastern slope of the Greater Caucasus was carried out, taking into account the soil-ecological conditions of both the low-mountain and middle-mountain regions. The identified ecological zones reflect variations in forest productivity, environmental conditions, and the degree of development of forest soils, thereby providing a scientific basis for differentiating management approaches within the region.

The proposed soil blocks and sub-blocks, incorporated into the ecological fertility models, can serve as a methodological framework for the preparation of ecological passports of forest soils (Ismayilova, 2018). Such passports may be effectively applied in long-term ecological monitoring, assessment of forest ecosystem health, identification of degradation processes, and evaluation of the impacts of natural and anthropogenic factors on forest environments. From a practical perspective, the developed models may contribute to improving the scientific basis for forest conservation and sustainable forest management in Azerbaijan. Their application can support decision-making related to the protection, restoration, and rational use of mountain forest ecosystems, while also facilitating the preservation of their ecological functions and biodiversity under changing environmental conditions.

Thus, the ecological fertility models developed for the forest soils of the southeastern slope of the Greater Caucasus constitute an important tool for understanding the interactions between soils and forest ecosystems and represent a valuable approach for ecological assessment and sustainable management of forest resources (Mammadov & Osmanova, 2025).

Results

The investigation demonstrated that the forest soils of the southeastern slope of the Greater Caucasus differ considerably according to vegetation type, altitudinal zone, and ecological conditions. The analyzed physicochemical properties indicate distinct patterns of soil fertility between the mesophilic beech–hornbeam–oak forests of the middle-mountain belt and the xerophilous oak–hornbeam forests of the low-mountain belt (Table 1). The highest humus content was recorded in leached brown mountain-forest soils developed under mesophilic beech–hornbeam–oak forests, where values ranged from 6.4 to 9.1% in the upper 20 cm of the soil profile. Leached meadow-brown mountain soils also showed high humus accumulation (7.0–8.2%). In contrast, soils under xerophilous oak–hornbeam forests contained lower amounts of humus, varying from 1.9 to 6.5%, with the lowest values observed in carbonate brown mountain-forest soils. Humus reserves showed considerable variation among the studied soil types. In mesophilic forest ecosystems, humus reserves reached 143–170 t ha^{-1} in the 0–20 cm layer and increased to 310–330 t ha^{-1} within the 0–100 cm profile in leached meadow-brown mountain soils. In the xerophilous forest zone, humus reserves generally ranged between 49 and 97 t ha^{-1} in the surface layer and between 187 and 401 t ha^{-1} within the entire one-meter profile. The highest reserve values in the low-mountain forests were recorded in typical brown mountain-forest soils.

The nitrogen content reflected a similar distribution pattern. Surface horizons of mesophilic forest soils contained 0.28–0.43% total nitrogen, whereas xerophilous forest soils contained 0.12–0.31%**.** These differences correspond to the greater accumulation of organic matter under cooler and more humid ecological conditions. Phosphorus concentrations varied within a relatively narrow interval among the investigated soils. Values ranged from 0.20 to 0.30% in the middle-mountain soils and from 0.25 to 0.41% in the low-mountain soils. Potassium content was comparatively stable in all investigated forest soils, varying from 2.1 to 2.7%, with slightly higher concentrations observed in carbonate soils of the xerophilous forest zone. The cation exchange capacity (CEC) ranged from 20.1 to 34.7 meq 100 g^{-1} in the mesophilic forest soils and from 17.6 to 40.1 meq 100 g^{-1} in the xerophilous forest soils. Typical brown mountain-forest soils exhibited the highest CEC values, indicating a relatively high capacity for nutrient retention despite their lower organic matter content. Soil reaction also differed according to ecological conditions. Leached meadow-brown mountain soils were moderately acidic (pH 5.0–6.0), while most other soil types exhibited neutral or slightly alkaline reactions (pH 6.5–7.5). These differences reflect variations in parent material, leaching intensity, and vegetation composition across the study area.

Overall, the obtained results indicate that the fertility of forest soils on the southeastern slope of the Greater Caucasus is primarily controlled by altitude, moisture regime, forest composition, and soil-forming processes. Mesophilic beech–hornbeam–oak forests create favorable conditions for greater humus accumulation and nitrogen enrichment, whereas xerophilous oak–hornbeam forests are characterized by lower organic matter content but relatively stable mineral nutrient status. These findings provide the quantitative basis for constructing ecological fertility models and ecological passports of forest soils and support their application in monitoring the ecological condition and sustainable management of mountain forest ecosystems.

Discussion

Soil Block. The soil and its constituent factors play an important role in the formation of biogeocenoses. Soils are essential in nutrient cycling and the formation of forest biological productivity (Mammadov & Ismayilova, 2025). At the same time, soil serves as a unique carrier of ecological information about forest biogeocenoses. Therefore, in constructing the ecological model of forest soils on the southeastern slope of the Greater Caucasus, the soil block includes more detailed information.

We propose distinguishing the following sub-blocks within the soil block:
1) Soil profile;
2) Soil composition and physicochemical properties.
Soil Profile Sub-block. This sub-block includes the most significant biodiagnostic characteristics. These properties serve as carriers of primary information concerning the processes occurring within forest biogeocenoses (Mammadova & Ismayilova, 2023). The composition and thickness of the forest litter, the thickness of horizons A1, A2, A2B, B1, B2, and C, their relationships and transitional characteristics provide ecological information necessary for explaining erosion, degradation, evolution, and climatic changes.

To characterize the soil profile sub-block of the ecological fertility model for brown mountain-forest soils under mesophilic beech–hornbeam–oak vegetation of the middle mountains, data from profiles No. 1, 2, 3, 5, 6, and 7 located in the Basgal, Topchu, and Galynja forests were integrated. The prevailing forest ecological conditions were characterized by a forest site quality class of II, stand density of 0.7, average stand age of 70 years, crown density of 0.7, live ground cover reaching 60–65%, and northern slope inclinations ranging from 18° to 20°. The generalized morphological characteristics are presented below:

A0 horizon – forest litter at various stages of decomposition, 2–5 cm thick;
A1 horizon – dark black or dark gray in color, nutty-granular structure, relatively soft, 2–17 cm thick;
A2 horizon – brownish-gray in color, coarse granular structure, soft consistency, 13–35 cm thick;
A2B1 horizon – nutty-granular structure, 29–80 cm thick;
B (or B1) horizon – blackish-brown color with distinct, clearly visible rusty spots, granular or nutty-granular structure, moderately compact, 57–120 cm thick;
B2 horizon – light brown in color, coarse, compacted granular structure with brown mottles, 86–160 cm thick.

To characterize the soil profile sub-block of the ecological fertility model for brown mountain-forest and brown forest soils under xerophilous oak–hornbeam vegetation of the low mountains, data from profiles No. 3, 4, 5, 8, 9, 12, 13, and 15 established in the Talystan forestry area were summarized. The forest ecological parameters included a forest site quality class of III, stand density of 0.7, average stand age of 70 years, crown density of 0.7, live ground cover amounting to 18–20%, and southern slope inclinations of 10–12°.

The generalized morphological features include:

A1 horizon – humus horizon; dark blackish-brown color; granular-cloddy structure; soft consistency; thickness 3–22 cm;
A2 horizon – eluviated horizon; brown or brownish color; coarse granular structure; soft consistency; thickness 18–57 cm;
B1 horizon – illuvial horizon; light brown color; nutty-granular structure; moderately compact; thickness 32–34 cm;
B2 horizon – bluish-brown color; fine granular structure; moderately compact; thickness 17–18 cm;
C horizon – parent material, occasionally orange-gray in color and structureless.

These visual and morphological characteristics of forest biogeocenoses represent essential primary sources of information on ongoing ecological processes (Ismayilova, 2023). Based on the indicators of the soil profile sub-block within the ecological fertility model identified in these two soil-ecological regions, it is possible to effectively assess and determine the current ecological status of forest biogeocenoses.

Conclusion

The primary objective of this study was to develop ecological fertility models for the dominant forest soil types on the southeastern slope of the Greater Caucasus: (1) brown mountain forest soils of the middle-mountain zone under mesophilous beech–hornbeam–oak forests and (2) brown mountain forest soils of the low-mountain zone under xerophilous oak–hornbeam communities. These models were developed to characterize the relationships among soil properties, environmental factors, and the ecological condition of forest biogeocenoses (Mammadova & Ismayilova, 2023).

The findings demonstrate that soil profile characteristics serve as reliable indicators of ecological processes within forest ecosystems (Mammadov & Ismayilova, 2025). The composition and thickness of the forest litter layer, the sequence and depth of genetic horizons, their morphological characteristics, and the nature of horizon transitions provide essential information on soil-forming processes, ecosystem functioning, and the stability or degradation of forest biogeocenoses.

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