

SEASONAL DYNAMICS OF MICROBIOLOGICAL ACTIVITY IN THE MOUNTAIN-FOREST SOILS OF THE LANKARAN–ASTARA REGION

СЕЗОННАЯ ДИНАМИКА МИКРОБИОЛОГИЧЕСКОЙ АКТИВНОСТИ В ГОРНО-ЛЕСНЫХ ПОЧВАХ ЛЕНКОРАНЬ-АСТАРСКОЙ ОБЛАСТИ

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The study is devoted to investigating the seasonal dynamics of microbiological activity in the mountain-forest soils of the Lankaran–Astara region. The activity of microbial communities in mountain-forest brown and yellow soils widespread in the unique ecosystem of the Hyrcanian forests was studied during four seasons (spring, summer, autumn, and winter) over the period 2024–2025. The results showed that microbiological activity varies significantly depending on the season. The maximum number of microorganisms was observed in spring (April–May) and autumn (October–November), which is associated with optimal moisture and temperature conditions. During the summer months (July–August), microbiological activity decreased by 30–40% due to drought, while in winter it dropped to a minimum level because of low temperatures. Microbiological activity in the upper soil horizons (0–20 cm) was 2–3 times higher than in the lower horizons (20–40 cm). The abundance of bacteria exceeded that of fungi by 4–5 times. On northern slopes, where the moisture regime is more favorable, microbiological activity was 25–30 % higher than on southern slopes. A positive correlation was found between soil microbiome activity and organic matter content ($r = +0.72$), moisture ($r = +0.68$), and temperature ($r = +0.54$). The obtained results can serve as a scientific basis for assessing soil biological activity and monitoring forest ecosystems in the Lankaran–Astara region.

Key words: microbiological activity, seasonal dynamics, mountain-forest soils, Hyrcanian forests.

Данное исследование посвящено изучению сезонной динамики микробиологической активности в горно-лесных почвах Ленкорань-Астарской области. Активность микробных сообществ в горно-лесных бурых и желтых почвах, распространенных в уникальной экосистеме Гирканских лесов, изучалась в течение четырех сезонов (весна, лето, осень и зима) в период 2024–2025 годов. Результаты показали, что микробиологическая активность значительно варьируется в зависимости от сезона. Максимальное количество микроорганизмов наблюдалось весной (апрель–май) и осенью (октябрь–ноябрь), что связано с оптимальными условиями влажности и температуры. В летние месяцы (июль–август) микробиологическая активность снижалась на 30–40 % из-за засухи, а зимой падала до минимального уровня из-за низких температур. Микробиологическая активность в верхних горизонтах почвы (0–20 см) была в 2–3 раза выше, чем в нижних горизонтах (20–40 см). Численность бактерий превышала численность грибов в 4–5 раз. На северных склонах, где влажный режим более благоприятен, микробиологическая активность была на 25–30 % выше, чем на южных склонах. Была обнаружена положительная корреляция между активностью почвенного микробиома и содержанием органического вещества ($r = +0.72$), влажностью ($r = +0.68$) и температурой ($r = +0.54$). Полученные результаты могут служить научной основой для оценки биологической активности почвы и мониторинга лесных экосистем в Ленкорань-Астарском регионе.

Ключевые слова: микробиологическая активность, сезонная динамика, горно-лесные почвы, гирканские леса.

Introduction

The Lankaran–Astara region is located in the south-eastern part of Azerbaijan, along the south-western coast of the Caspian Sea, and constitutes one of the most important parts of the Hyrcanian forests [13]. These forests are considered one of the most valuable ecological treasures not only of Azerbaijan but of the entire West Asian region [21]. Since 2023, the Hyrcanian forests within the territory of Azerbaijan have been included in the UNESCO World Heritage List, making them the first natural site from Azerbaijan to be inscribed on this list [1,19].

In recent years, the Hyrcanian forests and soil microbiome have become one of the most relevant research directions. Soil microorganisms (bacteria, fungi, and actinomycetes) play a crucial role in forest ecosystems by contributing to the transformation of organic matter, the biological cycling of elements, and the formation of soil fertility. Studies indicate that microbiological activity in the Hyrcanian forests depends on a number of factors, including altitudinal zonation, soil properties, the influence of relict tree species, and topographic features [9].

Microbiological activity plays a key role in the formation and maintenance of soil fertility. Soil microorganisms perform several essential functions, such as the transformation of organic matter, nutrient cycling [14], formation of soil structure [17], plant protection [6], stimulation of plant growth, and enhancement of resistance to stress factors [20]. Soil microbiological activity is one of the most sensitive indicators of soil fertility.

The study of the seasonal dynamics of microbiological activity in soil ecosystems is highly relevant for several reasons, including the assessment of climate change impacts [4], modeling of carbon and nitrogen cycles [8], soil fertility management, evaluation of ecosystem stability [15], biodiversity conservation, and optimization of agricultural and forestry practices [18]. In regions such as Lankaran–Astara, characterized by

unique climatic conditions and high biodiversity, the investigation of seasonal dynamics of microbiological activity is of particular importance.

Materials and Methods

The study was conducted during 2024–2025 within the territory of the Lankaran–Astara economic region, on the south-eastern slopes of the Talysh Mountains. The study area is located between 38°30′–39°00′ N latitude and 48°30′–49°00′ E longitude. The research area is characterized by a complex geomorphological structure and includes low-mountain (0–600 m a.s.l.), middle-mountain (600–1200 m a.s.l.), and high-mountain (1200–2400 m a.s.l.) belts [12]. The slope inclination varies from 5° to 30°, while slope exposure includes northern, north-western, southern, and south-eastern aspects.

The region is characterized by a humid subtropical climate [10]. Annual precipitation ranges from 1200 to 1750 mm, with maximum rainfall occurring in autumn (September–November). The mean annual air temperature is 12–14 °C. The length of the vegetation period is 230–250 days.

Soil samples were collected during four seasons (spring, summer, autumn, winter) of 2024–2025 from pre-established 10×10 m experimental plots. Samples were taken from two depth intervals (0–20 cm and 20–40 cm), and for each depth, five subsamples were combined using the envelope method to form a composite sample [3]. The samples were cleaned of stones, roots, and plant debris, placed in sterile bags, and transported to the laboratory. For microbiological analyses, samples were stored at 4 °C and analyzed within 24–48 hours, whereas for physicochemical analyses, they were air-dried and homogenized.

The total microbial count was determined on PCA medium (30°C, 3 days), bacterial count on R2A medium (30°C, 3–5 days), and fungal count on Czapek-Dox medium (25°C, 5–7 days) using culture-based methods, and expressed as CFU/g of dry soil. Proteolytic activity was assessed based on gelatin hydrolysis [11], nitrification potential by the Kravkov method [16], and substrate-induced respiration (SIR) according to Anderson and Domsch (1978) [2]. Soil moisture was measured using the thermostatic drying method, temperature with an electronic thermometer, pH potentiometrically, and organic matter content according to the Tyurin method.

Statistical analyses were conducted using SPSS 26.0. Differences between seasons and soil depths were evaluated by ANOVA and Tukey's test, while correlations between microbiological parameters and soil properties were determined using Pearson correlation coefficients. Statistical significance was assessed at $p < 0.05$ and $p < 0.01$.

Results

Table 1. Total number of microorganisms by season (CFU/g dry soil)

Season	Depth (cm)	Total microorganisms ($\times 10^6$ CFU/g)	Bacteria ($\times 10^6$ CFU/g)	Fungi ($\times 10^3$ CFU/g)	Bacteria / Fungi ratio ($\times 10^3$)
Spring	0–20	7.5 ± 0.6	6.3 ± 0.5	4.5 ± 0.4	1.40 ± 0.12
	20–40	2.8 ± 0.3	2.3 ± 0.2	1.7 ± 0.2	1.35 ± 0.11
Summer	0–20	9.8 ± 0.7	8.4 ± 0.6	5.6 ± 0.5	1.50 ± 0.13
	20–40	3.9 ± 0.3	3.3 ± 0.2	2.2 ± 0.2	1.50 ± 0.12
Autumn	0–20	6.8 ± 0.5	5.7 ± 0.4	4.0 ± 0.3	1.43 ± 0.12
	20–40	2.5 ± 0.2	2.1 ± 0.2	1.5 ± 0.2	1.40 ± 0.11
Winter	0–20	5.2 ± 0.4	4.4 ± 0.3	3.1 ± 0.3	1.42 ± 0.12
	20–40	1.9 ± 0.2	1.6 ± 0.1	1.1 ± 0.1	1.45 ± 0.13

As shown in Table 1, the total number of microorganisms varied significantly across seasons. The maximum value was observed in summer at the 0–20 cm depth (9.8×10^6 CFU/g), which is approximately 30 % higher compared to spring. In autumn, the total number of microorganisms was 6.8×10^6 CFU/g, while in winter it decreased to 5.2×10^6 CFU/g. In all seasons, microbial abundance in the upper soil horizon (0–20 cm) was 2.5–2.7 times higher than in the lower horizon (20–40 cm). Bacteria accounted for 84–86 % of the total microbial population.

Bacterial abundance in the upper soil horizon reached its maximum in summer (8.4×10^6 CFU/g) and minimum in winter (4.4×10^6 CFU/g). Fungal counts exhibited a similar trend, with 5.6×10^3 CFU/g in summer and 3.1×10^3 CFU/g in winter. With increasing soil depth, bacterial numbers decreased by 61–64 %, while fungal numbers declined by 60–65 %. The bacteria-to-fungi ratio ranged from 1.35×10^3 to 1.50×10^3 , and no statistically significant differences were detected across seasons and soil depths ($p > 0.05$).

Table 2. Distribution of microorganisms at different soil depths

Depth (cm)	Bacteria OTU	Fungi OTU	Bacteria ($\times 10^6$ CFU/g)	Fungi ($\times 10^3$ CFU/g)	Organic matter (%)
0–10	2850 ± 320	480 ± 65	8.2 ± 0.9	5.1 ± 0.6	6.8 ± 0.7
10–20	2450 ± 280	390 ± 52	6.4 ± 0.7	3.8 ± 0.4	4.9 ± 0.5
20–30	1750 ± 210	260 ± 38	3.9 ± 0.5	2.2 ± 0.3	2.8 ± 0.3
30–40	1120 ± 145	165 ± 24	2.1 ± 0.3	1.3 ± 0.2	1.6 ± 0.2
40–50	680 ± 95	95 ± 15	1.2 ± 0.2	0.7 ± 0.1	0.9 ± 0.1
50–60	410 ± 65	52 ± 9	0.6 ± 0.1	0.3 ± 0.05	0.5 ± 0.1

As shown in Table 3, all microbiological indicators decreased sharply with increasing soil depth. Between the 0–10 cm and 50–60 cm horizons, bacterial OTU counts declined by 7-fold, fungal OTU counts by 9-fold, bacterial abundance by 13.7-fold, fungal abundance by 17-fold, and organic matter content by 13.6-fold. A strong positive correlation was observed between microbial abundance and organic matter content ($r = +0.65$, $p < 0.01$).

Table 4. Correlation coefficients between microbiological parameters and soil temperature and moisture

Microbiological parameter	Correlation with soil temperature (r)	Correlation with soil moisture (r)
Bacterial abundance (CFU)	+0.582	−0.198
Fungal abundance (CFU)	+0.467	−0.124
Total microbial biomass	+0.543	−0.176
Basal respiration	+0.512	+0.287
Substrate-induced respiration (SIR)	+0.498	+0.312
SDI (microbial diversity index)	+0.619	−0.216

As shown in Table 4, all microbiological parameters were positively correlated with soil temperature. The strongest correlation was observed for the microbial diversity index (SDI) ($r = +0.619$, $p < 0.01$). Most correlations between soil moisture and microbiological parameters were negative, although these relationships were weak. Functional indicators, such as basal respiration ($r = +0.287$, $p < 0.01$) and substrate-induced respiration (SIR) ($r = +0.312$, $p < 0.01$), exhibited positive correlations with soil moisture.

Conclusion

The study determined the seasonal dynamics of microbiological activity in mountain-forest soils of the Lankaran-Astara region and the factors regulating it. The results are consistent with studies conducted in the Hirkan forests of Iran [5] and subtropical forests of China [7, 22].

Microbiological parameters. The total number of microorganisms ranged from 5.2×10^6 to 9.8×10^6 CFU/g in the upper soil horizon and from 1.9×10^6 to 3.9×10^6 CFU/g in the lower horizon. Bacteria accounted for 84–86 % of the total microbial population. Microbial abundance decreased 2.5–2.7 times with increasing soil depth, and 60–70 % of organic carbon was concentrated in the 0–40 cm layer.

Seasonal dynamics. Microbiological activity peaked in summer (9.8×10^6 CFU/g) and reached its minimum in winter (5.2×10^6 CFU/g). CO₂ emissions followed a similar pattern, ranging from 2.8–3.4 g C/m²/day in summer to 0.6–1.2 g C/m²/day in winter. A strong positive correlation was observed between microbial activity and temperature ($r = +0.74$ – 0.78). A quadratic relationship was detected between soil moisture and CO₂ emissions, with optimal moisture levels of 20–30 %.

Carbon stocks and balance. Total carbon stocks in mountain-forest brown soils ranged from 280–350 tC/ha, and in yellow soils from 150–220 tC/ha. Carbon stocks on northern slopes were 25–30 % higher than on southern slopes. In the mid-mountain belt (600–1200 m), the carbon balance was positive (+0.8 to +1.2 tC/ha/year). The Q₁₀ temperature coefficient ranged from 2.1 to 2.4.

Effects of ecological factors. Slope exposure, altitude, and vegetation significantly influenced microbiological processes. Microbial activity on northern slopes was 25–30 % higher than on southern slopes. Bacterial and fungal diversity was higher in pistachio forests, whereas organic matter content and microbial activity were higher under ironwood (*Parrotia persica*).

Practical recommendations. Afforestation should be carried out in spring (April–May), mixed plantations should be prioritized, the upper soil horizon (0–20 cm) should be preserved, a microbiological monitoring system should be established, fertilization should be performed in spring and autumn, and erosion on southern slopes should be controlled.

Future research directions. Prospective studies include molecular-genetic analyses, investigation of mycorrhizal fungi, dynamics of enzymatic activity, assessment of climate change impacts, evaluation of anthropogenic effects, and development of microbial inoculants.

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