

MODERN APPROACHES TO THE STUDY OF ENVIRONMENTAL SOIL PARAMETERS USING REMOTE SENSING IN THE REPUBLIC OF AZERBAIJAN

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ABSTRACT

The studies compared soil parameters in the subtropics of the Lankaran region and the mountain landscapes of the Sheki region. An analysis of enzyme distribution in the soil profile showed that microbial communities with lower species diversity were restricted to the deeper soil layers. Experiments revealed that the addition of substrate and nutrients elicited a significantly stronger response and stimulated enzyme activity outside the original microfoci than within them. Furthermore, the activity of soil enzymes within the original microfoci themselves was less restricted than in the surrounding soil. Enzyme activities (catalase, urease, and phosphatase) in mountain meadow soils on the mountain plateaus of the Lankaran and Sheki regions were studied. For the first time in Azerbaijan, a comparative study of modern research findings from two regions with different ecological conditions was conducted. This is of great importance for the development of agriculture in the country.

Keywords: Remote sensing, Enzyme activity, Vegetation, Natural phytocenoses, Substrate concentration.

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1. INTRODUCTION

The most accurate way to investigate soil changes is to compare the results of innovative methods with those of traditional methods. At present, the comprehensive study of many biologically active enzymes remains a pressing problem in agricultural science. Ecological diagnostic methods are widely used in environmental monitoring systems due to their information content and ability to identify negative impacts at the early stages of degradation (Aliyeva & Mammadova, 2023; Akhundova et al., 2025; Ahmad et al., 2026). Remote sensing methods have become an important tool in topsoil research, enabling spatial assessment of soil properties over large areas at a relatively low cost and high efficiency. Using satellite imagery and airborne sensors, researchers can assess topsoil moisture, organic matter content, salinity, erosion risk, and vegetation-soil interactions. Multispectral and hyperspectral data are particularly useful for detecting subtle spectral differences associated with soil composition, while radar data is effective for monitoring surface moisture status under varying weather conditions. Many studies combine remote sensing with field sampling and geostatistical or machine-learning methods to improve the accuracy of topsoil maps and to support model validation. These approaches are particularly valuable in heterogeneous landscapes, where topsoil conditions vary greatly over short distances and traditional ground-based surveys alone may miss important spatial patterns (Gudmann et al., 2020; Gurbanov et al., 2021; Mammadova et al., 2024; Ali et al., 2026; Khudaverdi et al., 2026). Enzymatic activity is an important characteristic of the quality of biological properties and a sensitive indicator of the ecological state of soils. In most cases, enzymatic activity is closely related to soil organic matter. However, in some cases this connection weakens, and the role of abiogenic factors increases (Akbarova & Mammadova, 2024; Aliyeva, 2026). Altitude and relief are key factors in the spatial distribution of enzymes under mountainous conditions. At the same time, different enzymes exhibit distinct spatial distributions (Ali et al., 2025). The role of soil in preserving plant biological diversity is also significant. In particular, the study of these ecosystems shows that intensive anthropogenic impact (grazing, deforestation, expansion of agricultural lands) makes significant adjustments to natural processes, accelerating the degradation of some phytocenoses and requiring the development of a set of protective measures (Bahram et al., 2025; Ali et al., 2026).

Mapping surface moisture, organic carbon, vegetation indices, and land-use patterns serves as an indicator of microbial habitat quality and substrate availability. Integrating remote sensing data with field measurements and

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laboratory analyses can improve spatial interpretation of microbial respiration, enzyme activity, and soil fertility patterns (Huseynova, 2022; Nasirova, 2023b). Such integrated approaches are particularly effective in heterogeneous landscapes, where biological activity can vary significantly over short distances and where conventional sampling may miss important spatial hotspots of activity. Remote sensing methods offer a valuable approach to studying soil biological activity, providing indirect yet spatially extensive information on environmental conditions that regulate microbial processes. Because soil microorganisms respond strongly to moisture, temperature, organic matter availability, vegetation input, and land degradation, remote sensing data can be used to identify areas of increased or decreased biological activity (Huseynova, 2023; Ismayilova et al., 2025a; Mammadzada et al., 2025; Heydarova, 2026). Mapping soil bioactivity requires an integrated approach that links direct biological measurements with environmental remote sensing data. Because microbial activity is highly dependent on soil moisture, temperature, organic matter, vegetation cover, and landscape position, remote sensing can be used to identify zones with different biological potential in agricultural and natural systems (Mammadov et al., 2025; Novruz et al., 2025). Optical and microwave sensors are particularly useful for determining surface moisture, vegetation viability, and land-use patterns, while digital elevation models help elucidate the topographic factors that influence soil processes. When combined with laboratory metrics such as enzyme activity, microbial biomass, and soil respiration, these data enable digital mapping of soil bioactive zones and the identification of areas where biological function is limited or enhanced. This integrated framework is particularly valuable in heterogeneous landscapes, where soil biological activity varies over short distances, and point sampling alone is insufficient to describe spatial variability (Allahverdi et al., 2026; Nazim et al., 2026; Ikhtiyar et al., 2026). The activities of selected soil enzymes play an important role in identifying soils in both regions, including those under crops and pastureland. Herbarium specimens of endemic, rare, and dominant plant species commonly found in the investigated biotopes were collected, and their biological diversity was determined. Vegetation is considered the most important factor in regulating soil bioactivity (Ismayilova et al., 2025b; Ikhtiyar et al., 2026; Madnee et al., 2025). The vegetation cover consists of annual and perennial grasses, shrubs, and broad-leaved tree species (with conifers being recessive) that create conditions for intensive biological processes in these soils (Nasirova et al., 2023b). Glucose is a readily available source of carbon and energy and is essential for substrate-induced respiration (SIR). The addition of glucose leads to a significant increase in microbial release, which is used to calculate the carbon content of living microbial biomass. Ammonium nitrate is a nitrogen source in two forms (ammonium and nitrate). It helps to determine the effectiveness of nitrogen uptake by soil organisms (Ismayil et al., 2025). Potassium hydrogen phosphate is a source of phosphorus and potassium and an effective phosphate-buffering agent. It helps maintain a stable pH in the environment, as significant pH changes inhibit the growth of bacteria and fungi. The activity level of the enzymes secreted by the cells for the decomposition of organic matter and the rate of natural carbon dioxide release by the microorganisms without the addition of stimulants help in assessing the actual biological parameters of the soil (Mirzazadeh et al., 2025; Mirismayil, 2025; Mammadova et al., 2026a).

2. MATERIALS AND METHODS

Enzymatic activity was determined using traditional soil biodiagnostics methods. Determination of the enzymatic activity of soils is based on accounting for the amount of substrate processed during the reaction or the formation of the reaction product under optimal conditions of temperature, environmental pH, substrate concentration, and soil sample. Foci formation and spatial distribution of the three enzymes were measured using the soil zymography approach first proposed by Spohn and adapted by Heitkoetter and Marschner (Ibrahimova, 2025; Khudaverdi et al., 2025; Mammadova et al., 2025). Special treatment solutions containing glucose ($C_6H_{12}O_6$), ammonium nitrate (NH_4NO_3), dipotassium phosphate (K_2HPO_4) and disodium phosphate (Na_2HPO_4) are used. These solutions are gently sprayed onto the sample surfaces using an iMatrix atomizer at a rate of 1000 kJ/s. The samples are incubated for 10–15 days in sealed boxes in the dark at a constant temperature. Moist wipes in the boxes prevent the substrate from drying out (Bunyatova et al., 2025; Makki et al., 2025).

Innovative methods enable the identification of soil composition and the determination of humus, iron, and carbonate content based on unique spectral properties in the visible and near-infrared ranges, as well as the calculation of thermal anomalies and evaporation that are directly related to microbiological activities and peat degradation or salinization processes. Analyzing vegetation status and biological soil activity enables an indirect assessment of soil health, nitrogen balance, and biodiversity conservation capacity. Areas at risk of erosion, salinization, and desertification, which are crucial for ecosystem stability, are identified (Ibrahimova et al., 2024; Nazim et al., 2026; Mammadova et al., 2026b). Identifying Areas at Risk of Salinization: Assessing soil degradation processes such as erosion, salinization, and desertification requires integrating multiple remote sensing and machine learning methods. Salinization is evaluated by tracking salt-affected soils through multispectral and hyperspectral satellite imagery (e.g., Sentinel-2 and Landsat-5) (Ibrahimova & Imanov, 2025). Researchers use advanced machine learning algorithms, such as LightGBM (Light Gradient Boosting Machine) and SVM (Support Vector Machine), to process spectral indices, including the Salinity Index (SI) and the Normalized Difference

Vegetation Index (NDVI). Assessing Desertification: Vegetation status is evaluated through the Vegetation Condition Index (VCI) and Fractional Vegetation Cover (FVC). A sharp decrease in canopy density or the spread of invasive, non-forage species indicates land degradation (Mirismayil, 2025; Gahramanova et al., 2026; Hasanova Baba-zade et al., 2026; Zafar et al., 2026).

3. RESULTS AND DISCUSSION

3.1. Enzymatic Mapping and Subsurface Soil Dynamics

Through the downward flow of moisture, nutrients and fine substrate are gradually washed into deeper layers. Plant remains and microbial activity actively accumulate in the upper horizon, enriching it. This enzyme mapping method uses disodium phosphate, glucose, and acetyl substrates under UV light after being hydrolyzed by their corresponding enzymes. $C_6H_{12}O_6$, NH_4NO_3 , K_2HPO_4 , and Na_2HPO_4 are the best indicators of manifestation, and Na_2HPO_4 is the best indicator of soil biological parameters (Nazim & Oqtay, 2024; Mammadova et al., 2026a). These patterns have important implications for soil management and carbon and nutrient cycling models. Because enzymatic activity and microbial responsiveness are spatially patchy in lower subsoils, single-point measurements risk under- or overestimating microbial potential and turnover rates (Novruz et al., 2025; Zafar et al., 2026). Management practices that enhance substrate delivery (for example, deep-rooted cover crops, targeted organic amendments, or biochar placement) could reduce substrate limitation in lower horizons, thereby increasing microbial activity and nutrient availability. Conversely, uniform surface-focused treatments may be insufficient to stimulate biogeochemical processes at depth (Nazim et al., 2026; Oqtay et al., 2024). The stronger activation response observed in lower subsoils suggests a sizable pool of viable but dormant microbes that can rapidly respond to localized inputs; quantifying this pool and its turnover could improve predictions of soil respiration and nutrient mineralization under changing land use or climate regimes (Mehdiyeva et al., 2026; Rzayeva et al., 2026). Finally, the higher main enzyme activities measured in Sheki topsoils (mountain meadow) compared with Lankaran topsoils (mountain gray soils) point to vegetation- and soil-type controls on surface biochemical functioning, underscoring the need to tailor management interventions to local pedoecological contexts (Figs. 1 to 6). Among the abiotic parameters studied, the total amount of absorbed bases strongly influences enzyme activity. The activity of all the enzymes studied was independent of the silt content in the soils (Nasirova, 2023a).

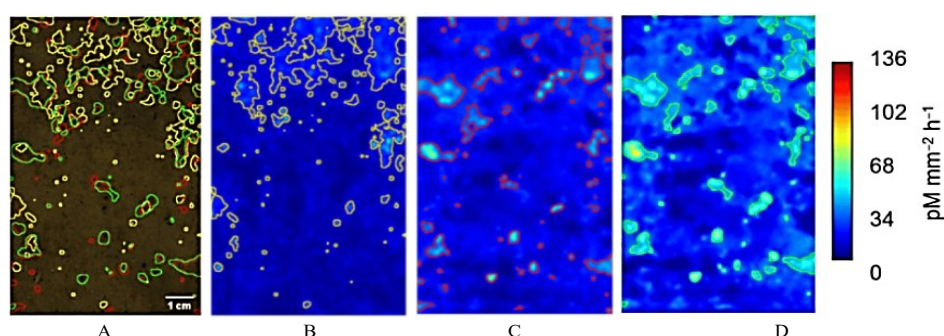


Fig. 1: Top sample phosphatase activity (10 days of incubation). Note: a. upper soil layer sample; b. with added $C_6H_{12}O_6$; c. with added Na_2HPO_4 ; d. with added acetyl. Yellow, red and green lines correspond to the initial hot spots of phosphatase enzyme activity.

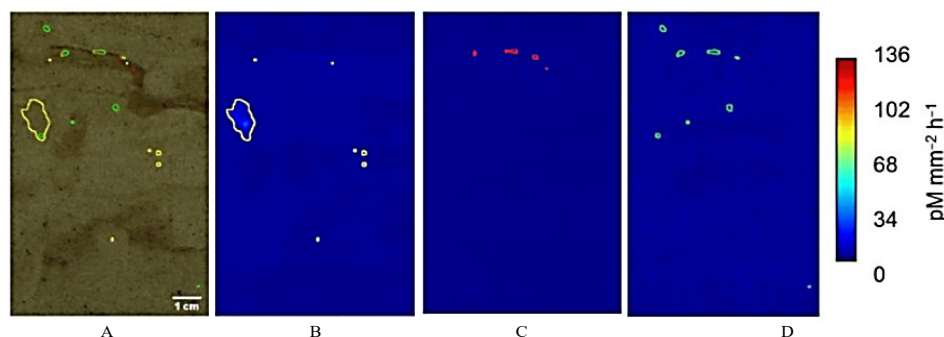


Fig. 2: Photographs of the phosphatase activity in bottom subsoil sample before water addition and 10 days of incubation. a. lower soil layer sample; b. with added $C_6H_{12}O_6$; c. with added Na_2HPO_4 ; d. with added acetyl. Yellow, red, and green lines correspond to the initial hot spots of phosphatase enzyme activity.

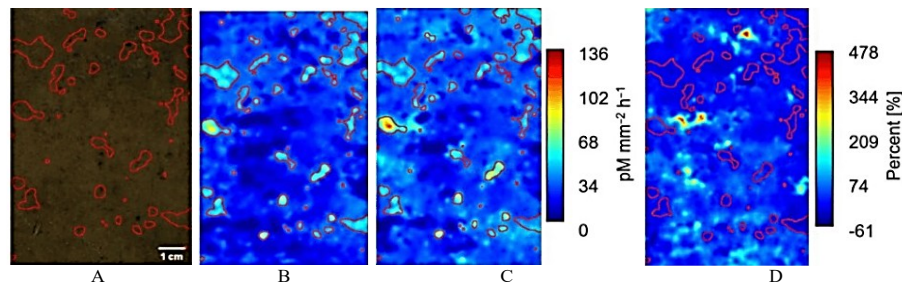


Fig. 3: Urease activity in surface of a topsoil (10 days of incubation). Note: Areas highlighted in red correspond to initial hot spots of enzyme activity. a. upper subsoil (0-15 cm); b. urease, before 10 days of incubation; c. urease after addition of treatment and 10 days of incubation; d. relative change in percent

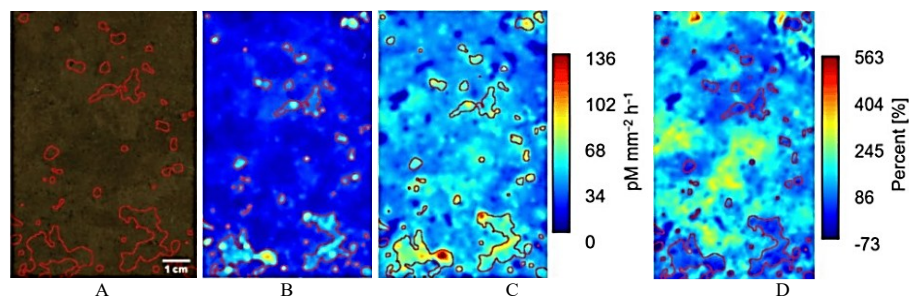


Fig. 4: Urease activity in $\text{pM mm}^{-2} \text{h}^{-1}$ determined on the surface of a topsoil sample before and after addition of combined $\text{C}_6\text{H}_{12}\text{O}_6$ and NH_4NO_3 and 10 days of incubation. Note: Areas highlighted in red correspond to initial hot spots of enzyme activity. a. upper subsoil (0-15 cm); b. Urease, before 10 days of incubation; c. urease after addition of treatment and 10 days of incubation; d. Relative percent change.

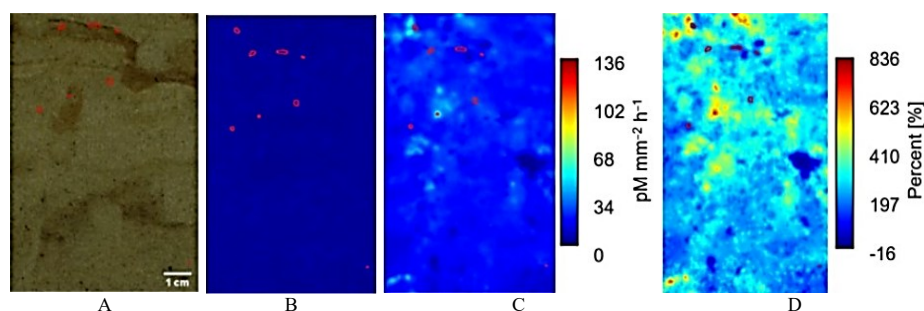


Fig. 5: Catalase activity in $\text{pM mm}^{-2} \text{h}^{-1}$ determined on the surface of a topsoil sample before and after addition of water, 15 days of incubation. Note: Areas highlighted in red correspond to initial hot spots of enzyme activity. a. upper subsoil (0-15 cm); b. catalase, before 15 days of incubation; c. catalase after addition of treatment and 15 days of incubation; d. Relative change in percent.

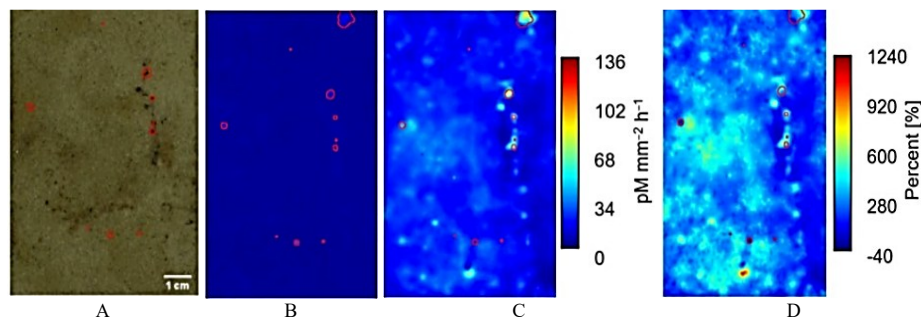


Fig. 6: Catalase activity in $\text{pM mm}^{-2} \text{h}^{-1}$ determined on the surface of a topsoil sample before and after addition of combined $\text{C}_6\text{H}_{12}\text{O}_6$ and NH_4NO_3 and 15 days of incubation. Note: Areas highlighted in red correspond to initial hot spots of enzyme activity. a. lower subsoil; b. catalase, before 15 days of incubation; c. catalase after treatment addition and 15 days of incubation; d. Relative percent change.

Enzyme activity is very closely related to the presence of humus in the soil. The map shows the accumulation zones of total nitrogen and humus in the soil (Fig. 7). Correlation analysis showed a strong association among the studied enzymes. As expected, a close, direct relationship was observed between organic carbon content and the activities of urease, catalase, and phosphatase ($r = 0.69\text{--}0.91$). In the mountainous areas of Sheki, the intensity of enzymatic processes is greater than in the subtropics of Lankaran (Fig. 8).

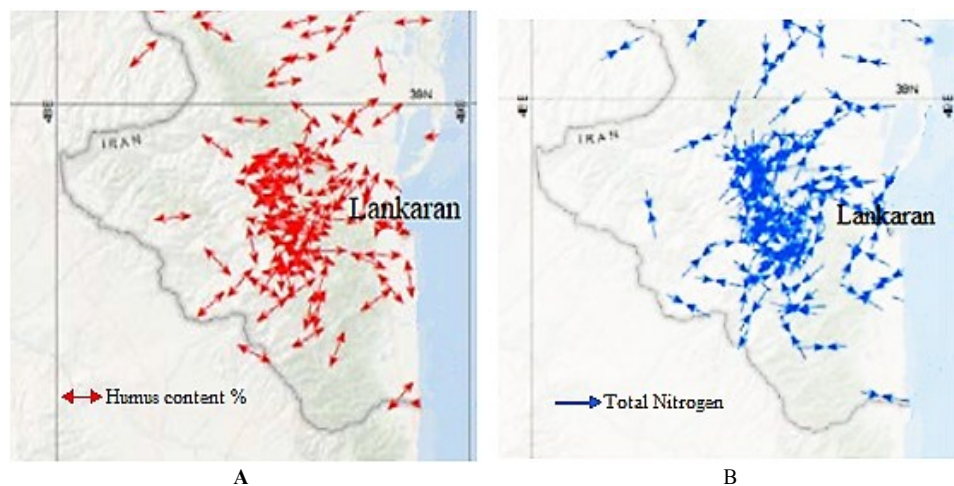


Fig. 7: Humus (a) and total nitrogen (b) content in the subsoil of studied areas.

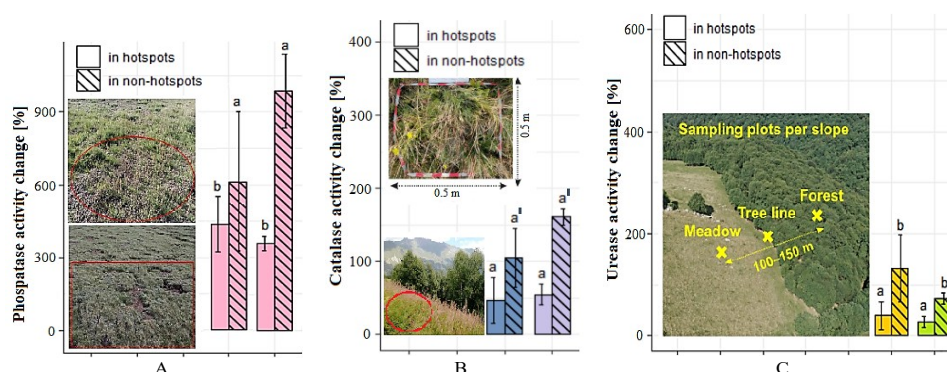


Fig. 8: Main enzyme activity in topsoil of Lankaran and Sheki regions; Note: a. Phosphatase activity of Sheki (a) and Lankaran region (b); b. Catalase activity in the Lankaran (a) and Sheki regions (a'); c. Urease activity of Lankaran (a) and Sheki region (b). (Source: by authors in 2023-2024 years).

As a result of the analysis of multi-temporal space information in the study area, several typical signs of changes in the level of fertility were identified, reflecting the following processes that negatively affect the level of fertility of arable soils: linear erosion, sheet erosion, reducing the humus content of the arable horizon, flooding of arable land in zones of groundwater wedging out, meadowing of arable soils due to difficult ground drainage (Macnunlu et al., 2025; Verdiyeva et al., 2026). Comparison of the data reveals significant differences in the spectral reflectance of soils within the same area. This variation is due to differences in the moisture content of arable soils across survey periods. At the same time, signs of increased linear erosion, soil loss, areas of arable land with unfavorable hydrological conditions, and close underlying carbonate rock deposits, all related to structural features, remain unchanged (Allahverdi et al., 2026; Mammadova et al., 2026b).

4. CONCLUSION

The topsoil and subsoil layers of the study areas differ in the spatial distribution and frequency of enzymatic foci. Less frequent foci in the subsoil are more heterogeneously distributed than the more numerous foci in the topsoil. Heterogeneous substrate and nutrient supply pathways lead to high spatial variability in the subsoil. The addition of substrate and nutrients can activate dormant microorganisms outside the original soil foci. This effect is more pronounced in the subsoil. The combined addition of nutrients and substrate provided insights into the spatial distribution of active and dormant microorganisms. This study underscores the need to consider spatial factors in crop rotation practices, particularly in deeper soil layers where substrate and nutrient deficiencies are more pronounced. The activity of important enzymes in the upper soil layers of the mountain meadows in the Sheki region is higher than in the gray mountain soils of the Lankaran region.

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