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DETERMINING BIOLOGICAL DIVERSITY WITH INNOVATIVE METHODS IN EAST ZANGEZUR REGION, AZERBAIJAN

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SUMMARY

The biological diversity analysis was this study's aim based on the verification of remote sensing data recorded through in-situ surveys for calculating aboveground biomass in forests. The biomass of mountain phytocenoses in the East Zangezur Region, Azerbaijan, represents six groups of formations, ranging from 231.8 to 1401.2 g/m² with absolutely dry weight. The proportions of vascular and spore plants varied, from 59% to 96.8% and from 3.8% to 75.4%, respectively. This study examines the development of interdisciplinary practical work in the field of restoration of natural phytocenoses biological diversity. In 67% of cases, the average phytomass values determined by different methods did not differ significantly from each other. However, the significant differences were evident in the deciduous stands with the highest horizontal canopy closure, with the presence of a second tier (midstory) and abundant sub-canopy vegetation, as well as in vascular and spore-bearing plants.

Keywords: Biological diversity, biomass, phytocenoses, plant communities, vascular and spore plants

Key findings: The study assessed the development of interdisciplinary practical work in the field of restoration of biological diversity of phytocenoses. The study of biological diversity is greatly essential, with major support from a state program in this region of Azerbaijan.

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INTRODUCTION

The currently established network monitoring the carbon pools and greenhouse gas fluxes in ecosystems encompasses a wide range of studies on climate, soil, and forest vegetation characteristics in Azerbaijan. However, the ongoing research primarily focused on the ground-based work and labor-intensive in-situ surveys (Akbarova and Mammadova, 2024; Allahverdi *et al.*, 2026; Bunyatova *et al.*, 2025). Maintaining up-to-date information on forest resources is a key requirement for the effective management of forestry. Furthermore, the volume of carbon accumulation as forest biomass allows the assessment of the state and dynamics of ecosystems, as well as variation trends in modern landscapes. Carbon storage (sequestration) is a key indicator of ecosystem health, assessing their ability to absorb CO_2 from the atmosphere and store it in the biomass and soil. Still, all these require the systematic implementation of scientific research, technological, and practical-oriented solutions, as well as the use of innovative methods in the automation and digitalization of the forestry sector (International Soil Classification System for Naming Soil and Creating Legends for Soil Maps, 2014; Gahramanova *et al.*, 2026).

Remote monitoring of the carbon cycle in forests will provide crucial observations on greenhouse gas absorption and emissions, as well as reduce the uncertainty about carbon stock estimates (Allahverdi *et al.*, 2026). Therefore, it is essential for optimizing and developing regional measures to develop strategies for low greenhouse gas emissions socioeconomic development. Managing carbon cycles in phytocenoses and landscapes can address various practical challenges at present and in the future (Ismayil *et al.*, 2025; Ismayilova *et al.*, 2025). One should also note that quantitative estimates of growing stock, accumulated phytomass, and carbon sequestration in forests may vary widely, characterized by the highest degree of uncertainty with the application of rapidly outdated data as the information base. Intensive research is necessary to quickly assess the stock of live and dead wood, which requires constant data updates. Therefore, it is crucial to develop an effective methodological approach for forest inventory work, including automated elements. This should allow the verification of remote sensing data against ground-based survey data of forest areas to estimate the amount of phytomass in forest areas (Mammadova *et al.*, 2024, 2025a; Macnunlu *et al.*, 2025).

The development of potential remote sensing methods for natural biotopes can considerably fill up existing gaps in forest information acquired for carbon assessments over larger areas. The most appropriate approach appeared to be the employment of methodological processes that closely integrate remote sensing methods, ground-based measurements of their qualitative and quantitative characteristics, and mathematical models of their structure and dynamics (Nazim and Oqtay, 2024; Mirzezadeh *et al.*, 2025a, 2025b). As part of the implementation of the current 'Strategy for the Development of the Forestry Complex of the Republic of Azerbaijan until 2030,' several methods underwent planning to develop digital technologies and implement them in forestry. In the coming years, in the Eastern Zangezur Region of Azerbaijan, the scientific and technological advances should be reliant on the intensive transition to advanced digital and information and communication technologies, including remote sensing (Sadigov *et al.*, 2025; Nasirova *et al.*, 2026).

The regional differentiation task assigned to forestry services, aimed at determining the necessary level of technical and technological support, will improve their efficiency and reduce material costs. Therefore, the ongoing research will enable the development of new algorithms, indicators, and criteria that will significantly improve the effectiveness of forest monitoring and contribute to a notable reduction in financial costs. In light of the above discussion, the relevance of using remote monitoring systems and data verification results based on machine learning models to estimate the amount of phytomass in the forests of the Eastern Zangezur Region, Azerbaijan, requires underscoring. It proves this task as one of the most important steps in implementing the concept of rational nature management (Shukurov *et al.*, 2025a, 2025b).

A system based on the remote assessment of forest biomass and accounting for carbon dynamics is critically essential. This can be successful through various processes that include developing training sets for machine learning models and applying them using artificial intelligence. Furthermore, a comprehensive database of Azerbaijan requires developing to verify the available remote sensing data and in-situ survey materials. This type of research work will be greatly valuable to biologists in the fields of forests and land management, environmental regulation, and industrial and technological regulation of land use and crop production to achieve true carbon neutrality. Meanwhile, it also adheres to the principles of scientifically based rational nature management and the restoration of economically valuable phytocenoses (Mammadova *et al.*, 2025a; Mammadova *et al.*, 2026).

Hence, it is necessary to focus on the widespread implementation of remote methods based on the application of artificial intelligence. This will significantly reduce the work volume, as well as the costs of obtaining up-to-date information on the condition and structure of the forest fund of Eastern Zangezur, Azerbaijan, having had no studies so far, due to the war. Therefore, the relevant study aimed to carry out the biological diversity analysis based on the verification of remote sensing data recorded through in-situ surveys for calculating aboveground biomass in forest areas.

MATERIALS AND METHODS

Study site and procedure

The systematic selection of study objects relied on the selection of forest areas with different species composition, differentiated by age groups, and growing under different forest growth conditions. Uses of several species of spore plants served as food by wild animals; and in the northeast, the lichens served as the main food for predators. In 2023, during a ground-based inventory in the East Zangezur Region, Azerbaijan, 10 sample plots (SPs) succeeded in their establishment and received thorough surveys. These studied plots have locations in diverse forest types and forest growth conditions, in stands not exposed to adverse factors. In 2025, a repeat survey proceeded on the existing SPs to effectively update the said information (Mammadova *et al.*, 2025a; Bunyatova *et al.*, 2025).

The establishment of three additional SPs sought to ensure a representative sample and obtain the complete and reliable information required for remote sensing data authentication. Moreover, an in-situ survey continued on different sites affected by ground fires of varying intensity, which resulted in a considerable decrease in the biological resilience of stands (Mammadova *et al.*, 2026). The silvicultural and taxonomic characteristics of the sample plots obtained through in-situ survey will enable the development of accurate forecast models. With the specific nature of the work, satellite images reflecting the characteristics of stands within the study area were also research objects used. The technical characteristics of the remote sensing dataset determine the formation of training samples for subsequent use in the development of machine learning models designed to evaluate forest inventory indicators and calculate the phytomass (Bunyatova *et al.*, 2025; Verdiyeva *et al*., 2025; Sadigov *et al*., 2026).

Traits measurement

Each studied sample plot underwent a complete tree census, identifying the tree species, a tree-by-tree inventory of trunk diameters, tree heights, crown heights, crown diameters, and overall tree health. Ground cover, young growth, undergrowth, fallen trees, and forest litter also entailed identification and recording (Mammadova *et al.*, 2025a; 2025b). Tree height and the beginning of the living crown reached measuring with an accuracy of 0.5 m, with the trunk diameter measured at the height of 1.3 m, with an accuracy of 1 cm. The considerable accuracy of measurements was necessary for the subsequent precise development of machine learning models. Determining the tree condition took place visually, accounting for the distribution of tree species by thickness grades, based on the Forest Sanitary Safety Rules Republic of Azerbaijan. Crown diameter measurement ensued by projection in two opposite directions (N-S/W-E) using a laser rangefinder with an accuracy of 0.1 m (0.25 m). Undergrowth's determination comprised two parameters: density (dense, medium-dense, and sparse) and size (large, medium, and small), indicating the different species and recording the viability of the undergrowth as well (May 2023 and May 2025) (Nasirova *et al.,* 2026).

For assessing the stands burned by fires, detecting the height of the soot deposits started from the side of trees with the greatest degree of burnt damage. All counted trees had a diameter of 7.9 cm and a height of 1.4 m. Fire severity determination considered the average height of soot deposits on tree trunks (Mammadova *et al.*, 2026). A low-severity fire has a definition of one that produced up to 1 m of soot deposits, a moderate fire has one that produced between 1.1 and 2.0 m, and a high-severity fire is one producing more than 2.0 m of soot deposits. Aboveground phytomass stocks' estimation was by fractions using an allometric equation for each tree based on trunk diameter at 1.3 m and height. For dead trees as per the health scale, the assumed leaf phytomass was zero. The aboveground phytomass calculation for each species at the known height used an allometric equation in accordance with the guidelines for quantifying the greenhouse gas uptake (Bunyatova *et al.*, 2025; Mirzezadeh *et al.,* 2025a and 2025b).

Statistical analyses

The recorded data analysis used STATISTICA 13 software. Correlation and regression analyses allowed for the assessment of the relationships between various parameters influencing the process and identified the dependencies between the studied indicators. Carrying out the analysis of variance sought to determine the strength of the influence of an active factor on the outcome variable. Multivariate regression analysis served to analyze the relationship between several independent predictors and the dependent variable. Pearson's linear correlation coefficients entailed calculations to assess the quantitative relationship between forestry and taxation indicators. The adequacy of the regression model (DBH^2xTHT), upon assessment, used the coefficient of determination (R^2), and the closer R^2 was to one, the better the regression approximated the empirical data, and therefore obtaining the results accurately. During the study, average indicators' calculation used standard and generally accepted methods of descriptive statistics. One should also note that the maximum error in height determination was 25.8%, with an average error of 5.7%. This further allows recommending the widespread use of remote sensing methods for determining tree stand height (Akbarova and Mammadova*,* 2024; Nasirova *et al.,* 2026).

RESULTS AND DISCUSSION

In determining the ground-based forest inventory results and the relationship between key forestry and forestry taxation indicators on sample plots, the study performed the correlation and regression analyses. These allowed for the assessment of the strength of the relationship and identified dependencies between the studied parameters, which appeared to be crucial for their use in remote monitoring (Shukurov *et al.*, 2025a).

The higher the correlation coefficient, the more practical the study results become. The biomass values ranged from the transition from low-productivity, high-altitude communities to highly productive formations. By eliminating the influence of variable tissue moisture, the application of absolutely dry weight allows for accurate comparison of the energy potential of different phytocenoses. The results revealed the correlation analysis of the main taxation indicators confirmed the existing data and provided new information on the close relationship between direct and indirect interpretive indicators—between stand heights

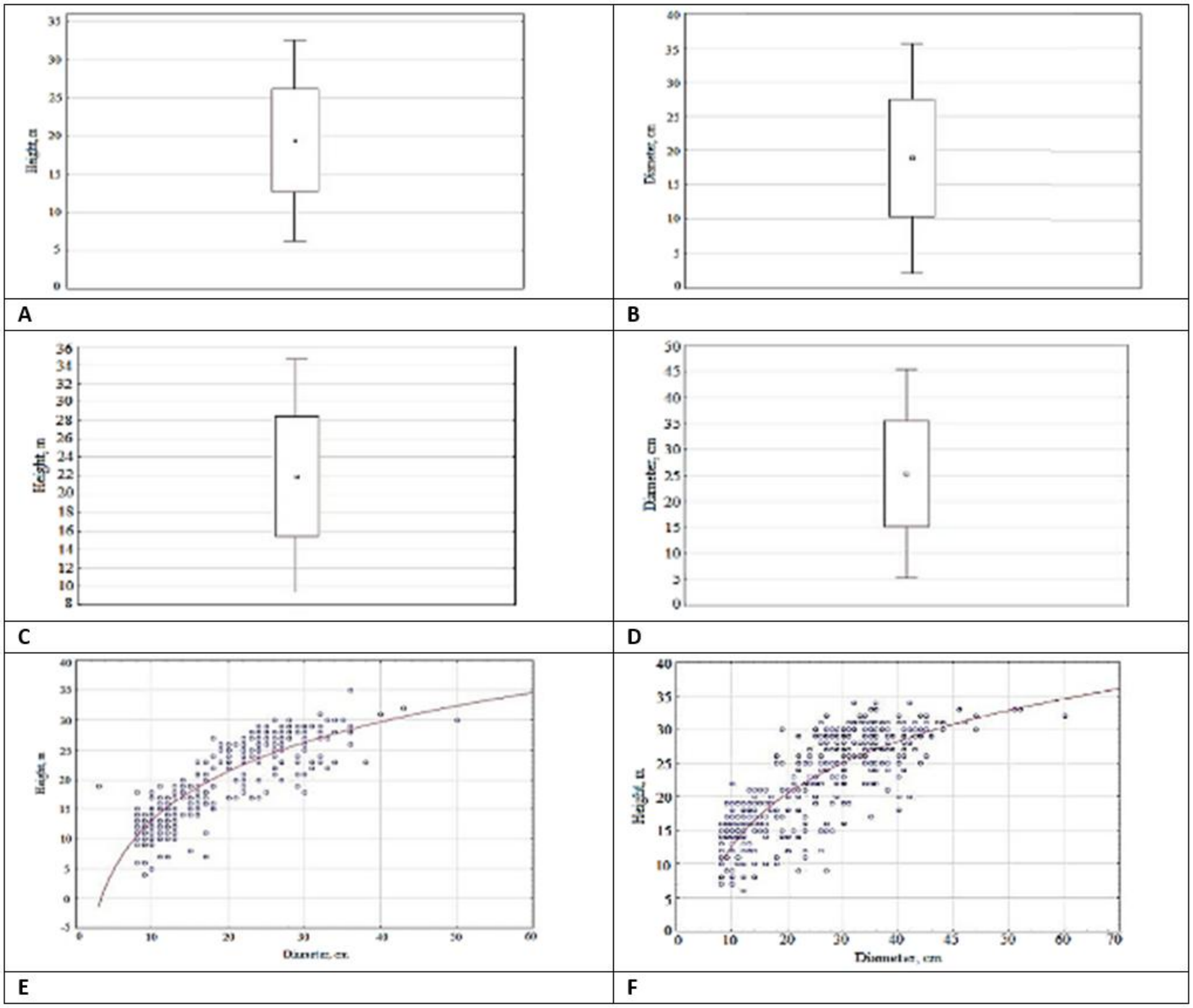

Figure 1. A-B) Average statistical values of taxation indicators in deciduous middle-aged stands; C-D) Middle aged coniferous stands; E) Correlation between them (conifers); and F) Correlation between them (hardwood). Source: author's own elaboration

and trunk diameter in all studied sample plots, ranging from 0.62 to 0.85. The parameters concerning the main forestry and forestry taxation indicators for the sample plots appear in Figure 1 a-f. In increasing the strength of the correlation between direct and indirect features and further improving the effectiveness of predictive modeling, it was necessary to formulate allometric equations and develop models using multiple variables (Ismayil *et al.*, 2025).

One of the most important parts of preparing a machine learning system is the formation of a high-quality training sample. This involves the collection of high-quality source data and performing expert labeling. Orthophoto map objects incurred labels according to tree species, identified during the field survey (blue = oak, green = maple, yellow = linden, and red = unidentified tree) over the original orthophoto map of the given site. By combining the markings with the orthophoto map, two other images came about (Figures 2a and 2b). The accuracy of determining these parameters depends both on the size and quality of the training samples for the artificial intelligence algorithms and on the imagery quality. Cloud cover was often a

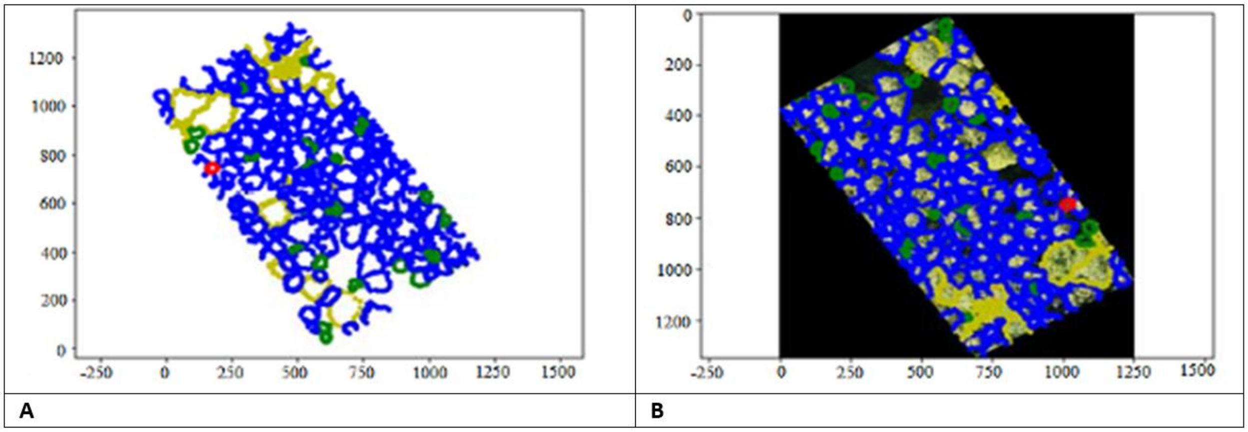

Figure 2. Forest plot markings for tree species: A) Marking the species composition of stands growing on sample plots, and B) Image obtained by combining markings with an orthophoto map.

critical factor for satellite data (Macnunlu *et al.*, 2025). Therefore, the model training should be according to carefully prepared training samples that allow the combination of continuous tree count data from ground-based tree surveys and remote sensing data. The alignment relied on the method for highly accurate determination of tree coordinates, with an error smaller than the size of the object being determined. By determining tree heights in automated mode, both ground and vegetation surfaces first underwent calculation; afterward, the tree heights entailed computation by subtracting the ground z-coordinate from the vegetation surface (Nazim and Oqtay, 2024; Ismayil *et al.*, 2025).

The formulation of the ground and vegetation surfaces had each LAS file converted into two corresponding matrices containing the z-coordinates in their cells. The process of deciphering the tree crown diameters depended on the manual preprocessing of RGB images using specialized QGIS software. In determining crown diameters with automated elements, it was necessary to find the degree of canopy closure. For this purpose, the use of the 'point map' method employed PHOTOMOD 6.0. Canopy closure calculation was the ratio of points falling on the crowns to the total number of points on the map. The lower the canopy closure, the more accurately the crown diameter detection can succeed using an automated AI-based method. However, if the canopy closure was 0.8 or higher, a significant systematic error occurred. Since it was not possible to reliably determine the crown diameter in dense stands automatically, therefore, a proposal emerged to determine the said parameter with elements of automation using the canopy closure index (Macnunlu *et al.*, 2025).

The trunk diameter, age class of the stand, and the density of the stand entailed determination by indirect methods based on empirical data and regression equations developed on their basis. The automated tree species identification results for the studied sample plots showed the highest degree of agreement with the in-situ survey results on average, and the identified discrepancies were within the range of 2%–7%. In stands with high horizontal canopy density in sample plots 2, 3, 5, and 9, the differences in the number of identified trees ranged from 25% to 38%. This may be because of the presence of second-story stands and large undergrowth of associated species, which had inaccurate identification through their images (Mammadova *et al.*, 2025a).

The specific comparison of the practical and theoretical data, two sets of studied samples underwent comparison: young stands (as well as deciduous stands up to 40 years old) and middle-aged and older stands. In these age groups, the stands have significant

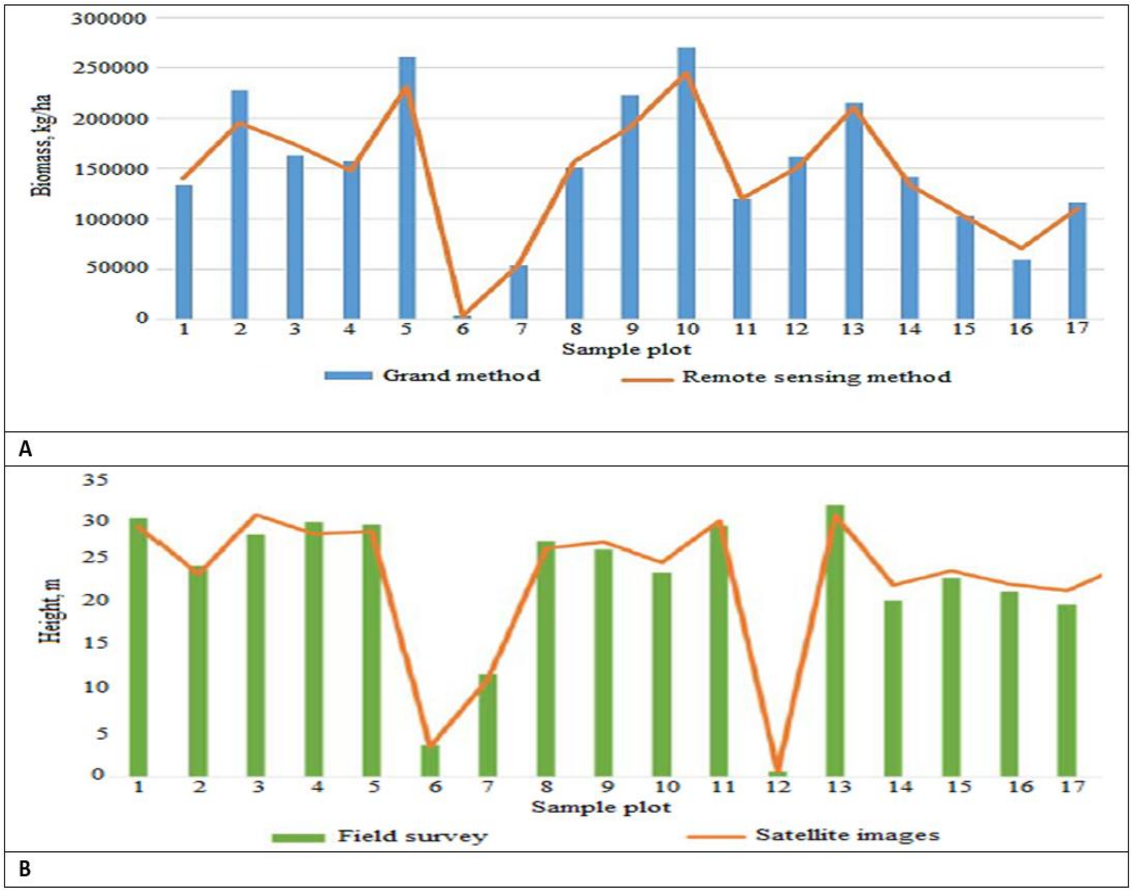

Figure 3. A) Total phytomass in sample plots determined by ground and remote sensing methods, and B) Results of verification of the height of the forest stand based on remote sensing data and field survey data.

differences in the desired taxonomy parameters, which must have separate analysis to obtain a normal distribution of the variation series. Linden grows in a single sample plot (SP 11), and therefore the heights sustained comparison within a single sample. By verifying the number of trees using remote sensing data based on an in-situ survey, we used information on their coordinates, determined by a high-precision receiver, and entered it into a database (Nazim and Oqtay, 2024).

The verification results for determining the number of trees in sample plots, based on the comparison of satellite imagery and in-situ survey data, are available in Figure 3. The findings clearly exhibited that satellite imagery cannot reliably reflect the number of trees in forest areas with the highest or moderate canopy closure, nor can it identify trees located in the second layer. The verification and comparison of the aboveground phytomass using remote sensing data and in-situ survey data revealed significant similarity. In 67% of cases, the average phytomass values determined by different methods did not differ significantly ($P < 0.05$) from each other. Significant differences in 33% of cases were evident between the average aboveground phytomass values obtained through ground-based and remote sensing methods. These were primarily the deciduous stands observed with the highest horizontal canopy density, the presence of a second tier, and abundant understory vegetation. Significant differences existed in the distribution of mosses in community types in various bioclimatic sectors of the region (Nazim and Oqtay, 2024; Ismayil *et al.*, 2025).

The different plant species with their biomass determined comprised the following in the list: *Eremurus spectabillis* M. Bieb., *Asparagus officinalis* L., *A. verticillatus* L., *Silybum marianum* (L.) Gaertn., *Stellaria media* (L.) Cyr., S. *neglecta* Weihe, *Polygonatum orientale* Desf., *Cornus* mas L., *Malva neglecta* Wallr., M. *sylvestris* L., *Portulaca oleracea* L., *Fragaria vesca* L., *Capparis spinosa* L., *Prunus divaricata* Led., P. *spinosa* L., *Pyru caucasica* Fed., P. *salicifolia* Pall., *Rubus caesius* L., *R. buschii* (Rozan.) A. Grossh., *R. caucasicus* Focke., *Urtica urens* L., *U. dioica* L., *Capsella bursa-pastoris* (L.), *Anthriscus caucalis* M. Bieb., *A. cerefolium* (L.) Hoffm., *A. nemorosa* (M. Bieb.) Spreng., *Hippomarathrum microcarpum* (M. Bieb.), *Melissa officinalis* L., *Hypericum perforatum* L., *Origanum vulgare* L., *Saturea hortensis* L., *Thymus transcaucasicus* Ronn., *Zizyphora serpyllacea* M. Bieb., *Plantago lanceolata* L., P. *major* L., *Nasturtium officinale* (L.) R. Br., *Cephalaria gigantea* (Ledeb.) Bobr., *Trifolium pratense* L., *Punica granatum* L., *Iris pseudacorus* L., *Glycyrrhiza glabra* L., *Genista transcaucasica* Schischk., *Rubia tinctorum* L., *Ulmus glabra* Huds., *U. foliacea* Gilib., *U. elliptica* K. Koch, *Juglans regia* L., *Quercus macranthera* Fisch. et C.A. Mey., *Q. iberica Steven*, *Fagus orientalis* Lipsky, *Castanea sativa* Mill., *Corylus colurna* L., *Carpinus orientalis* Mill., *C. caucasica* Grossh., *Taxus baccata* L., and *Acer trautvetteri* Medw. (Nazim and Oqtay, 2024; Ismayilova *et al.*, 2025; Verdiyeva *et al*., 2025).

The wide range of varied values enunciated the presence of different specific niches. The highest values (75.4%) were characteristic of moss-lichen communities, and with freezing and excessive moisture conditions, spore-bearing plants displaced the vascular plants, becoming the primary edificatory. Vascular plants' dominance characteristic (59%–96.8%) with the most favorable conditions, where flowering plants efficiently used the soil and light resources, formed the bulk of organic matter. Reliability of differences between the average values of forest stand phytomass (t), as determined by ground and remote methods: conifers – 1.1* (SP 1); -0.8* (SP 4); -0.5* (SP 7); 1.0* (SP 8); 0.7* (SP 11); -1.2* (SP 13); -0.3* (SP 16); 2.1* (SP 17); -1.2* (SP 18), deciduous – 3.8 (SP 2); -2.9 (SP 5); -3.1 (SP 9); -2.7 (SP 10); -1.1* (SP 14), and mixed forests – 1.4* (SP 3); 0.7* (SP 6); -2.5 (SP 15) (*nonsignificant differences between the mean values at a probability of 0.95 [t 0.05]) (Figures 3 A and B).

CONCLUSIONS

The results revealed the highest amount of phytomass was evident in the deciduous stands, among which the leading position was the sedge-goutweed oak grove (PP 10), with a phytomass of 264.4 t/ha. Next, in descending order of phytomass reserves, were the goutweed oak-linden grove (PP 5), with 254.7 t/ha, and the goutweed oak grove (PP 2), with the phytomass of 233.8 t/ha. The results further concluded the canopy closure—85% on average, w.t. (%): conifers = 88, mixed = 86, and deciduous = 79; crown diameter (depending on canopy closure)—87% on average, w.t. (%): pine = 96, birch = 95, aspen = 75, and alder = 80; tree species—86% on average, w.t. (%): pine = 88, softwood deciduous = 89, and oak = 83; tree height—90% on average, w.t. (%): pine = 96, birch = 97, aspen = 78, and linden = 85.

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