



Agroforestry as a sustainable land-use model in ecologically sensitive regions: insights from the Bulgarian living lab

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Abstract Agroforestry is increasingly recognized as a multifunctional approach to sustainable land management, climate adaptation, and biodiversity conservation. However, empirical evidence evaluating agroforestry systems in Southeast Europe and the Balkan mountain landscapes remains limited. This study presents a case study from the Strandzha Mountains (Bulgaria) investigating the capacity of agroforestry systems to enhance ecosystem services, biodiversity conservation, and landscape resilience within a Living Lab framework established under the REFOR-EST project. A multidisciplinary comparative analysis was conducted across three land-use systems: an agroforestry apiary system, silvopastoral permanent pasture, and conventional rapeseed monoculture. The assessment integrated physicochemical soil quality indicators, biological soil assessment using the QBS-ar index, floristic and phenological surveys

(2023–2025), and forage productivity analysis. The agroforestry and silvopastoral systems demonstrated substantially higher ecological quality (65–67/100) than intensive agricultural management (43/100). The apiary system exhibited the highest soil organic matter content (5.3%) and elevated biological soil quality (QBS-ar = 45), characterized by specialist euedaphic taxa such as *Protura*, which indicates low anthropogenic disturbance. Floristic surveys documented 210 vascular plant species, including the tertiary relict *Vaccinium arctostaphylos* and protected orchids (*Anacamptis papilionacea* and *Ophrys cornuta*), identifying these systems as important micro-refugia for regional biodiversity conservation. Phenological analyses further revealed a stable flowering continuum that supports pollinator networks throughout the growing season. Agroforestry systems in the Strandzha Mountains effectively integrate productive land use with biodiversity conservation and ecosystem resilience, providing a climate-adaptive and empirically validated framework for sustainable land management in Southeast Europe.

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Introduction

Agroforestry is defined as an integrated land-use system in which perennial woody species are strategically combined with agricultural crops and/or livestock activities within a spatially and temporally organized structure, fostering functional ecological interactions (Nair 1993; Jose 2009). Beyond its structural configuration, agroforestry serves as a cornerstone of ecological intensification, enhancing productivity by optimizing inherent ecosystem processes rather than relying on external resource inputs (Altieri 1995; Wezel et al. 2014). Such systems bolster functional diversity and facilitate complementary resource utilization, thereby optimizing the biogeochemical efficiency of agroecosystems.

Numerous studies have demonstrated that integrating woody vegetation into agricultural landscapes substantially improves soil physicochemical and biological properties. Agroforestry systems enhance soil organic carbon sequestration, improve aggregate stability, stimulate microbial activity, and strengthen belowground ecological functioning, thereby increasing soil resilience and nutrient cycling efficiency (Lal 2004; Six et al. 2004; Nair et al. 2009; Cardinael et al. 2017, 2020). Recent methodological advances additionally emphasize the importance of standardized carbon accounting, belowground assessments, and long-term monitoring for accurately evaluating ecosystem functioning and carbon storage in agroforestry systems (Cardinael et al. 2025).

Agroforestry is increasingly recognized as an important component of Natural Climate Solutions (NCS), contributing to climate change mitigation and adaptation through carbon accumulation in both biomass and soil pools, while simultaneously enhancing ecosystem resilience and multifunctionality (Montagnini and Nair 2004; Griscom et al. 2017; IPCC 2019). In parallel, the structural heterogeneity of agroforestry systems promotes biodiversity conservation and strengthens regulating ecosystem services by expanding habitat availability and resource niches for pollinators and natural enemies of agricultural pests (Perfecto and Vandermeer 2010; Tschardt et al. 2012). Europe-wide meta-analyses have validated substantial benefits regarding erosion control, nutrient retention, hydrological regimes, and biodiversity conservation in comparison to conventional monocultures (Fagerholm et al. 2016; Torralba et al. 2016; Le et al. 2025a,

b). Furthermore, systematic reviews and meta-analytical syntheses on European agroforestry systems consistently demonstrate their multifunctional role in enhancing ecosystem service delivery across multiple spatial scales (Fagerholm et al. 2016; Le et al. 2025a, b). Furthermore, arboreal canopies exert a buffering effect on the microclimate by mitigating temperature fluctuations, reducing wind exposure, enhancing water-use efficiency, and creating heterogeneous microhabitats that support microscale plant diversity and ecological complexity (Lin 2007; IPCC 2019; Le et al. 2025a). Additionally, arboreal canopies exert a buffering effect on the microclimate, mitigating temperature fluctuations, attenuating wind erosion, and enhancing water-use efficiency (Lin 2007; IPCC 2019). These climate-regulating functions are repeatedly confirmed across European agroforestry assessments as key mechanisms for improving system resilience under environmental stress (Fagerholm et al. 2016; Le et al. 2025a, b). These ecological functions are particularly relevant in Southeast Europe and the Balkan Peninsula, where increasing drought frequency and summer heat stress are becoming major constraints for agricultural sustainability under climate change scenarios. Notwithstanding the global consensus, empirical data on the efficacy of specific agroforestry practices in Southeast Europe remain sparse (Mosquera-Losada et al. 2012). While traditional systems such as *dehesa* (Mediterranean oak-based silvopastoral systems in Spain) and *montado* (Portuguese agro-silvopastoral systems combining cork oak woodlands with grazing activities) in Western and Central Europe are extensively documented and institutionally supported, agroforestry applications in the Balkan region are largely fragmented, lacking systematic monitoring or validated operational models (Mosquera-Losada et al. 2012). This data scarcity impedes the assessment of practices such as silvopastoral systems, integrated apiculture, riparian buffers, and shelterbelts. Despite their potential to enhance carbon sequestration and biological control, their local applicability necessitates rigorous empirical verification and adaptation to regional environmental conditions (Moreno et al. 2018). Furthermore, the ecological effects of agroforestry management in Balkan mountain landscapes are often difficult to disentangle from pre-existing differences in soil properties, land-use history, and local environmental heterogeneity. Consequently, there remains a substantial

knowledge gap regarding the ecological performance and climate-adaptive potential of agroforestry systems within Balkan mountain landscapes.

The present study addresses these research gaps within the framework of the project REFOREST—grant agreement No. 101060635—HORIZON-CL6-2021-CLIMATE—01, <https://agroreforest.eu/>, implemented within the Strandzha Living Lab network. Although conducted in a Living Lab context, the study does not specifically evaluate participatory Living Lab methodology or stakeholder co-creation processes but rather focuses on the ecological characterization of existing agroforestry systems. Rather than representing a fully replicated experimental design, the study should be considered a detailed comparative case study of a single operational farm system. The investigation focused on the comparative characterization of three land-use types within the same farm landscape, including silvopastoral and apiary-based agroforestry systems compared with conventionally managed agricultural land, thus enabling an assessment of traditional agroforestry practices in relation to intensive monoculture management.

The monitoring plots established within each land-use type represent subsamples within the same management unit and therefore do not constitute independent experimental replicates. Accordingly, the statistical analyses should be interpreted primarily in a descriptive and comparative manner within the context of the studied farm rather than as universally generalizable experimental evidence. In addition, the interpretation of observed ecological differences should consider the potential influence of pre-existing environmental heterogeneity, including soil properties variability, land-use history, and local site conditions.

The “Bee Farm Strandzha” demonstration site provides an appropriate socio-ecological setting for investigating interactions among soil properties, vegetation diversity, and agroforestry management under real farming conditions. Therefore, the primary objective of this study was to provide a comprehensive ecological characterization of agroforestry systems within a representative Balkan farm landscape, with particular emphasis on soil biological quality, floristic diversity, phenological structure, and forage productivity under contemporary climatic conditions. Particular attention was given to identifying descriptive ecological patterns, potential trade-offs,

and system-specific responses to climatic variability, including the drought conditions observed in 2024.

Rather than aiming to establish causal relationships or universally applicable management models, the study seeks to contribute detailed empirical evidence from Southeast Europe, where integrated agroforestry datasets remain comparatively limited.

To guide the analysis, the following research hypotheses were formulated:

1. Agroforestry-based land-use systems within the studied farm may exhibit differences in soil biological quality, microbial activity, vegetation diversity, and productivity compared to conventionally managed agricultural land. However, these differences should be interpreted within the limitations of the case-study design and underlying environmental heterogeneity.
2. The structural complexity and microclimatic buffering associated with woody vegetation may contribute to greater habitat heterogeneity and extended seasonal availability of floral resources, potentially supporting biodiversity conservation and ecosystem resilience in the montane landscapes of Southeast Europe.

Materials and methods

Study area and characterization of the agroforestry systems

The research was conducted at the “Strandzha” agroforestry farm, located in Southeast Bulgaria within the Strandzha Mountains (42.22–42.23° N; 27.42–27.43° E). The study area is situated at a mean elevation of 297 m a.s.l. and is characterized by a transitional Mediterranean climate, with a mean annual temperature of 13.0–13.8 °C and annual precipitation ranging between 600 and 750 mm. The dominant soil type is Haplic Cambisol (IUSS Working Group WRB 2022), developed over silicate parent material. The topography is gently to moderately undulating (5–12% slope) with southern and southeastern aspects. The farm encompasses approximately 700 ha and integrates diverse agricultural practices, including field crops, livestock husbandry, a 5 ha vegetable garden, a 3 ha orchard, and 16 apiaries.

Agroforestry (AF) practices at the site consist of forest-farming (apiary) and silvopastoral systems (pasture). These integrated frameworks combine woody belts and sparse stands with permanent grasslands and approximately 1,000 honeybee colonies. The apiaries are positioned in open forest clearings at intervals of 2–3 km. Tree density varies between 150 and 320 individuals ha^{-1} , fostering high spatial heterogeneity and robust ecological connectivity.

For the comparative analysis, three representative land-use systems commonly practiced in the Strandzha region were selected to represent a gradient of management intensity and anthropogenic disturbance: a forest-farming agroforestry system (apiary); a silvopastoral agroforestry system (permanent pasture); a conventionally cultivated field sown with *Brassica napus* L., representing an intensive modern monoculture farming system. Approximately 75 hives were in the studied apiary. The conventionally cultivated field was included as a comparative reference site rather than as a true experimental control; the predecessor of *Brassica napus* L. was wheat. Fertilization included 200 kg/ha N, 60 kg/ha P_2O_5 , 60 kg/ha K_2O . Nitrogen was applied 3–4 times. Microelements were also used. Against weeds, the herbicide Galera™ Super was used with active ingredients: clopyralid—240 g/l, picloram 80 g/l, and aminopyralid—40 g/l. To control pests, the bioinsecticide Naturalis (*Beauveria bassiana*, strain ATCC 74040—0.185 g/kg) was applied twice.

The investigated land-use systems were located within the same operational farm landscape but differed partially in terms of vegetation structure, management regime, and soil texture characteristics. The apiary system was predominantly associated with sandy silt loam soils, whereas the conventionally cultivated field was characterized mainly by sandy loam soils. These inherited edaphic differences were considered during data interpretation because they may influence soil biological activity, nutrient dynamics, and organic matter accumulation independently of management practices.

Five permanent monitoring plots, each measuring 10 m $\times$ 10 m, were established within each of the three land-use systems to facilitate multi-parameter cross-validation. The study design followed a nested comparative case-study approach conducted within a single operational Living Lab farm. Therefore, the monitoring plots represented subsamples within the

same management unit rather than fully independent experimental replicates. Field investigations were carried out over the 2023–2024 period and included repeated field investigations. Field studies on botanical composition, ground vegetation cover, and productivity of grasslands in the studied agroforestry systems (apiary and pasture) were conducted during the period April–July of the studied years. Floristic surveys and phenological observations were performed during the growing seasons of the study period. Soil physicochemical and biological analyses were based on samples collected within the established monitoring framework and analyzed as representative composite samples for each investigated land-use system. No pre-intervention or long-term baseline data were available prior to the establishment of the monitoring framework. Consequently, the observed ecological differences among land-use systems may partly reflect historical land use and pre-existing environmental variability in addition to current management effects. Figure 1 shows the geographical position of the Strandzha region within Bulgaria. Figure 2 presents the investigated fields and the distance between them. Information regarding previous land use, grazing intensity, and management history was compiled from farm management records and field observations where available; however, some historical management information remained incomplete.

Soil sampling

Soil samples were collected from the surface horizon (0–20 cm depth). The 20 cm depth was chosen because the root system of herbaceous plants is mainly located in this soil layer. Within each permanent monitoring plot, five individual sub-samples were taken following a diagonal transect scheme and subsequently pooled into a composite sample to minimize spatial variability (ISO 10381–1:2002). Samples designated for chemical analysis were air-dried and passed through a 2-mm sieve. Samples intended for biological analysis were stored at 4 °C and processed within 48 h to maintain microbial viability (Carter and Gregorich 2007). The investigation focused exclusively on the upper soil horizon because this layer is most directly influenced by vegetation cover and management practices and contains the highest biological activity. However, deeper soil horizons were not evaluated; therefore, the study does not

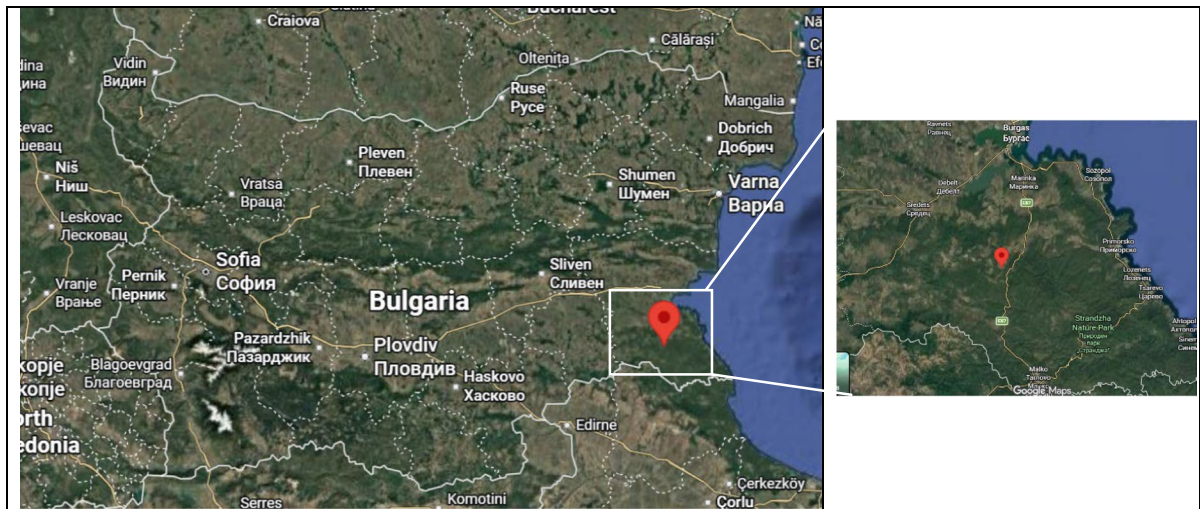


Fig. 1 Map of Bulgaria with the location of the "Strandzha" agroforestry farm marked



Fig. 2 Spatial distribution of the experimental sampling plots within the investigated agroforestry systems and the conventionally cultivated field sown with *Brassica napus* L.: **A** Api-

ary (forest-farming); **B** Pasture (silvopastoral); **C** Conventionally cultivated rapeseed field; **D** Location of the investigated fields

provide a comprehensive assessment of whole-profile carbon sequestration dynamics.

Physicochemical analyses

Soil reaction (pH): Potentiometric determination of pH was performed in a water suspension (1:2.5 w/v ratio) according to standard protocols (ISO 10390:2021).

Organic matter and total nitrogen: Soil Organic Carbon (SOC) and Total Nitrogen (TN) were determined via dry combustion using the Dumas method (Dumas 1831) on an elemental analyzer (ISO 10694:1995; ISO 13878:1998). The C:N ratio was calculated as an indicator of organic matter mineralization potential.

Cation exchange capacity (CEC): CEC was determined by extraction with 1 M ammonium acetate (pH 7.0) followed by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) analysis (Sumner and Miller 1996).

Macro- and micronutrients: Available phosphorus was determined using the Olsen method (Olsen et al. 1954). Exchangeable K, Ca, and Mg were analyzed after extraction with 1 M ammonium nitrate. Micronutrients (Fe, Mn, Zn, Cu, Mo, B) were quantified via ICP analysis following acid digestion (Soltanpour 1991).

Particle size distribution: Soil texture was determined using the hydrometer method, and textural classes were assigned according to the USDA Soil Taxonomy textural triangle (USDA 2017).

Biological analyses

Soil respiration and microbial activity: Microbial activity was assessed using the Solvita® CO₂-Burst test, measuring CO₂ evolution following the rehydration of dried soil. The Solvita CO₂-Burst test was performed according to the manufacturer's protocol under standardized laboratory conditions using field-moist soil samples. Results were recorded according to the manufacturer's instructions without additional conversion procedures.

Microbial biomass and Potentially Mineralizable Nitrogen (PMN) were subsequently calculated (Haney et al. 2008).

Integral soil quality index: Overall soil health was evaluated using an integral Soil Assessment Score

based on the Cornell Soil Health Framework (Moebius-Clune et al. 2016).

Soil mesofauna bioindication

Soil mesofauna was sampled using five soil monoliths per monitoring plot, collected during a single sampling campaign conducted in April 2024. Soil monoliths were subjected to thermal extraction using a Berlese–Tullgren apparatus over 10 days. Extracted organisms were preserved in 70% ethanol and taxonomically identified.

Taxonomic identification was performed using standard soil mesofauna determination keys and eco-morphological classification references commonly applied in European QBS-ar studies (Parisi et al. 2005; Menta et al. 2018). Soil biological quality was assessed using the QBS-ar index (Soil Biological Quality Index) according to Parisi et al. (2005) and updated eco-morphological criteria by Menta et al. (2018). The index represents the sum of Eco-Morphological Index (EMI) values assigned to each taxon based on its degree of edaphic specialization.

Because QBS-ar values may also be influenced by soil texture, moisture conditions, and seasonal climatic variability, interpretation of the obtained gradients considered the potential contribution of inherent environmental variability among the investigated land-use systems. Previous studies have demonstrated that QBS-ar values may vary substantially across seasons and climatic conditions; therefore, the present results should be interpreted as representing the biological status of the investigated systems during the specific sampling period rather than as temporally exhaustive estimates of soil mesofauna dynamics (e.g., Begum et al. 2013; Castillo-Avila and Castillo-Figueroa 2026).

Grassland characterization and productivity (2023–2024)

The study evaluated two distinct swards: a forest-farming system (Apiary; 42.22° N, 27.43° E), and a silvopastoral system (Pasture; 42.23° N, 27.42° E). Samples were collected at all sampling locations on the same days. Five field surveys were conducted using established monitoring plots. The evaluation of pasture productivity was conducted using destructive sampling with a defined grid-mesh frame quadrat

with a size of 100×100 cm. All grass and herbage within the exact mesh frame were clipped to ground level. The following parameters were recorded:

- *Projective cover (%)*: Estimated by visually determined sward density;
- *Botanical composition (%)*: Determined by weight analysis of fresh biomass samples (categorized into grasses, legumes, and forbs).
- *Productivity (fresh and dry matter yield, kg/ha)*: Determined by harvesting monitoring plots and scaling the values. Absolute dry matter content was established gravimetrically by oven-drying samples at 105°C until a constant weight was reached, in strict accordance with AOAC (2007) and EN ISO 6469 protocols.

The productivity assessment covered only two consecutive growing seasons (2023–2024), including a drought-affected year (2024). Consequently, the observed productivity dynamics should be interpreted cautiously, as short-term climatic variability may substantially influence annual biomass production patterns.

Climate characteristics

Meteorological data, such as precipitation and temperature, were obtained from the meteorological station at Strandzha farm (Field Climate, Pesse Instruments). During the observation period, the average annual precipitation was 717.5 mm (peaking at 821.4 mm in 2023), characterized by high intra-annual variability and prolonged drought periods from June to September (Fig. 2). The mean annual temperature was 13.83°C , which is 5.8% above the national average (Source: NIMH), identifying the region as one of the warmest in Bulgaria. Peak temperatures in July and August exceeded 39°C , which, combined with minimal precipitation, induced summer dormancy and desiccation of the herbaceous layer (Fig. 3). The severe drought conditions were recorded in 2024. The annual precipitation amount in 2024 is 613.6 mm. This likely influenced vegetation productivity, soil biological activity, and phenological dynamics across all investigated systems and should therefore be considered an important contextual factor when interpreting interannual variability.

Floristic diversity assessment and phenological monitoring of vascular plant communities

Vascular plant diversity was investigated between 2023 and 2025 across two land-use types: a forest farming agroforestry system (apiary) and a silvopastoral agroforestry system (pasture). Standardized floristic monitoring was implemented, with 6–8 field surveys per year from March to September to ensure comprehensive coverage of the entire growing season (Mueller-Dombois and Ellenberg 1974; Kent 2012).

Vascular plant species were surveyed and documented within permanent monitoring plots in each system. Spatial localization was determined using high-precision GPS. Taxonomic affiliation was determined based on the following established regional references: *Flora of the People's Republic of Bulgaria* (Vols. I–X; Jordanov 1963–1989), *Flora of Bulgaria* (Vols. I–II; Stoyanov et al. 1966–1967), *Field Guide to the Vascular Plants in Bulgaria* (Kožuharov 1992), and *Key to the Plants of Bulgaria* (Delipavlov and Cheshmedzhiev 2003).

The biodiversity assessment encompassed an analysis of species richness, taxonomic structure, functional group classification, and the characterization of biological types. Furthermore, a phenological assessment of flowering was performed to analyze the continuity of the floral resource, a critical factor for sustaining pollinator communities (Potts et al. 2010; Tschardt et al. 2012). This integrated approach facilitated the robust evaluation of the structural and functional diversity of vascular plants within these agroforestry systems (Jose 2009; Torralba et al. 2016).

However, the study did not include direct pollinator observations or quantitative measurements of nectar and pollen resources. Therefore, interpretations regarding pollinator-resource continuity are based on flowering phenology and plant community composition rather than direct measurements of pollinator activity or resource quality.

Statistical analysis

One-way ANOVA was applied to assess differences in the density of the grass cover, botanical composition, and productivity across the investigated fields. Data processing was performed using the IBM SPSS Statistics 26.0 software. Prior to the analysis, the

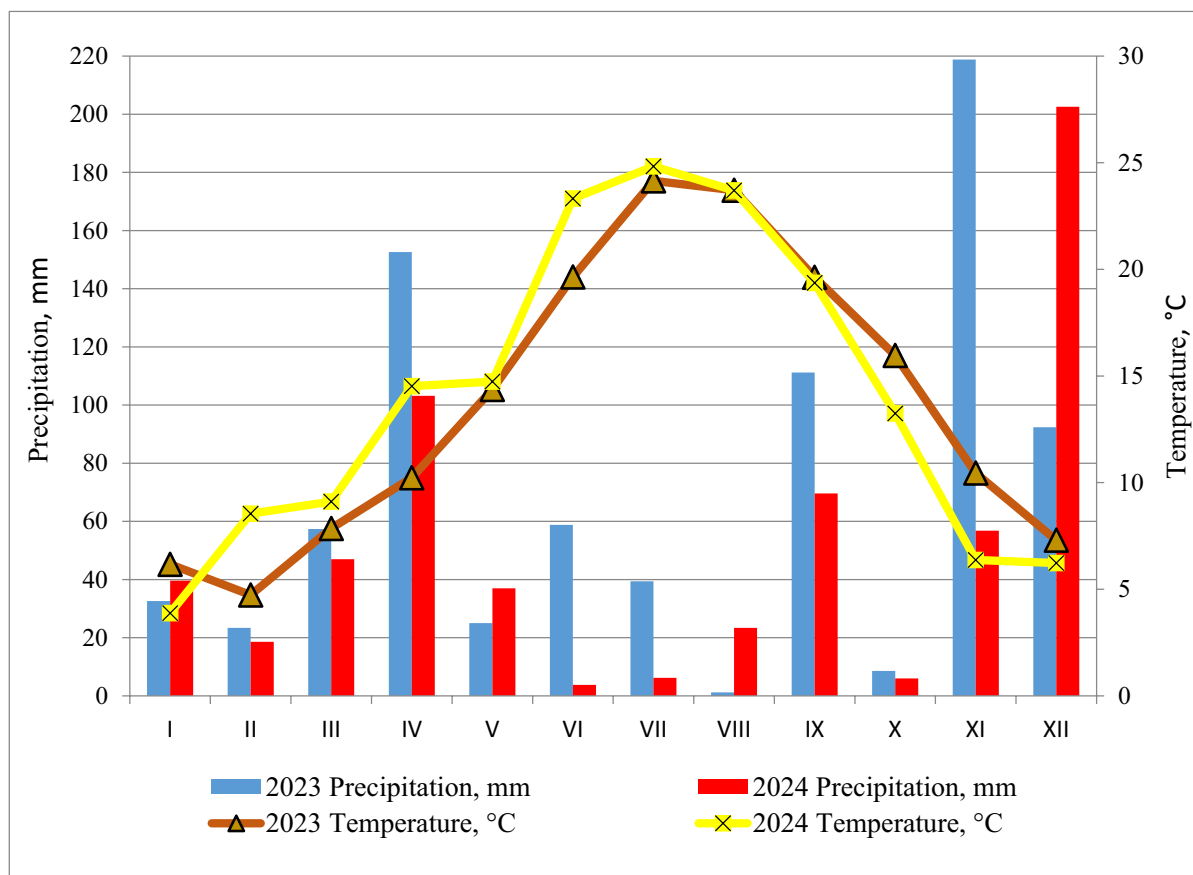


Fig. 3 Climatic characteristics for the period 2023–2024

assumptions of normality and homogeneity of variance were evaluated using the Shapiro–Wilk and Levene tests, respectively. Where necessary, the data were log-transformed to improve conformity with parametric assumptions.

As botanical composition represents multivariate community data, the resulting percentages were interpreted primarily descriptively. The use of more advanced multivariate approaches, such as NMDS, PERMANOVA, or ANOSIM, may provide additional resolution and should be considered in future investigations with larger replicated datasets.

Given the nested case study design and the absence of fully independent site-level replication, statistical analyses were used primarily to describe within-farm variation and comparative patterns among subsamples rather than to support broad inferential conclusions at regional or ecosystem scales. Accordingly, emphasis was placed on descriptive ecological trends,

relative differences, and integrated interpretation of multiple indicators, rather than solely on statistical significance.

Results and discussion

Comparative analysis of soil properties across the three land-use types

The analyses revealed a clear differentiation in soil properties among the forest-farming agroforestry system (apiary), the silvopastoral agroforestry system (pasture), and the conventionally managed *Brassica napus* field, reflecting varying degrees of anthropogenic impact and management intensity (Table 1). The conventionally cultivated field was included as a comparative reference system representing the intensive agricultural management commonly practiced in

Table 1 Comparative analysis of chemical, physical, and biological soil properties across the two investigated agroforestry management systems and conventional managed field in the Strandzha Living Lab

Soil parameter	Unit	Forest-farming system (Apiary)	Silvopastoral system (Pasture)	Conventionally managed field
<i>Chemical properties</i>				
pH (H ₂ O)	–	7.6	6.2	5.6
Organic Matter	%	5.3	2.7	1.7
Cation Exchange Capacity (CEC)	meq/100 g	16.8	23.3	22.0
Organic Carbon	%	3.1	1.6	1.0
Total Nitrogen	%	0.28	0.164	0.107
C:N Ratio	–	10.6	9.6	9.2
Phosphorus (P)	ppm	14	16	7
Potassium (K)	ppm	268	121	98
<i>Physical analysis</i>				
Sand	%	29.75	21.30	68.43
Silt	%	52.57	51.20	21.61
Clay	%	17.68	27.50	9.96
Texture Class	–	Silt Loam	Clay Loam	Sandy Loam
<i>Biological analysis & indices</i>				
Solvita CO ₂ -Burst	ppm	76	99	55
Microbial Biomass	mg/kg	1702	2208	1482
Potentially Mineralizable N	kg N/ha	48	66	44
Soil Quality Index	/100	65	67	43

the region rather than as a fully independent experimental control. Because the investigated systems differed not only in management regime but also partially in soil texture and potentially in land-use history, the observed patterns should be interpreted cautiously as descriptive ecological differences within a single operational farm landscape rather than as direct causal effects of agroforestry management.

Soil granulometric composition, physicochemical properties, and quality indices

Soils within the forest-farming agroforestry system (apiary) exhibited a neutral to slightly alkaline pH (7.6), providing favorable conditions for microbial activity and nutrient availability. The highest recorded values of organic matter (OM) (5.3%) and organic carbon (C_{org}) (3.1%) indicate substantial accumulation of organic material. These patterns are likely associated with the combined influence of continuous litter deposition, woody vegetation cover, reduced mechanical disturbance, and site-specific edaphic conditions, including the coarser texture of the apiary soils. In the forest-farming agroforestry

system (apiary), the soil was classified as sandy silt loam according to the USDA soil texture classification, with a particle-size distribution of 29.75% sand, 52.57% silt, and 17.68% clay. This relatively balanced texture provides favorable conditions for both aeration and capillary water retention, potentially supporting the comparatively higher levels of soil organic carbon observed at this site. This high OM content is a direct consequence of biomass accumulation and lignified litterfall from woody species such as *Quercus* and *Carpinus*. These findings align with Cardinael et al. (2017), who define agroforestry as one of the most effective strategies for increasing soil C sequestration in the temperate zone. Furthermore, the C:N ratio (10.6) in this system suggests a well-balanced mineralization process and the stability of organic fractions.

In the silvopastoral agroforestry system, soils showed a lower pH (6.2) and exhibited the finest textural composition, classified as clay loam with a clay fraction of 27.50%. This high content of fine colloidal particles directly contributed to the highest measured cation exchange capacity (CEC = 23.3 meq 100 g⁻¹), indicating a strong buffering capacity,

enhanced nutrient cation retention, aggregate stabilization, and protection of organic matter from rapid decomposition. Despite a lower OM content (2.7%) compared to the forest-farming plot, these soils maintained a favorable C:N ratio (9.6) and the highest integrated soil assessment score (67), reflecting the superior functional stability of this system. In both agroforestry models, the C:N ratios (9.6–10.6) indicate an active yet balanced mineralization process. The high soil quality index values suggest that permanent vegetation cover and extensive grazing management contribute to greater functional resilience and improved soil ecosystem stability under climatic stress conditions.

Conversely, the conventionally managed field exhibited acidic soils (pH 5.6) with the lowest values of C_{org} (1.0%) and total nitrogen (N_{tot}) (0.107%). These significantly lower C levels serve as a clear indicator of degradation processes and increased erosion risk. The soil was dominated by the coarse fraction (sandy loam, with 68.43% sand), explaining its significantly lower water-holding capacity, reduced sorption potential, and relatively easy leaching of mineral nitrogen in the soil profile. Lower C:N values in arable fields correlate with accelerated mineralization resulting from intensive aeration and mechanical disturbance. The low C:N ratio (9.2) of the conventionally managed field indicates favorable conditions for net mineralization of organic nitrogen and potential release of mineral forms of nitrogen available to plants. However, the total organic matter content (1.7%) remains low because conventional tillage, high macroporosity, and enhanced aeration accelerate the degradation of soil organic carbon compared to semi-natural ecosystems. Reduced phosphorus (P) content (7 ppm) and lower potassium (K) levels (98 ppm) indicate limited nutrient availability. Furthermore, this soil exhibited lower microbial activity (55 ppm), microbial biomass carbon (MBC, 1482 mg kg⁻¹), and potentially mineralizable nitrogen (PMN, 44 kg ha⁻¹). Taken together, these combined physicochemical and biological properties resulted in a significantly lower integrated soil quality index (SQI=43), reflecting the reduced soil fertility, microbial functioning, and overall ecological resilience typical of intensively managed agricultural systems. Overall, these results highlight a clear gradient in soil quality, with agroforestry systems sustaining significantly higher OM levels and greater functional stability than conventional

agriculture. These findings underscore the critical role of land-use management as a primary driver of long-term soil fertility and ecosystem functioning. They further support the hypothesis that traditional agroforestry practices enhance soil multifunctionality and reinforce the adaptive capacity of agricultural landscapes in ecologically sensitive regions.

The comparative analysis revealed pronounced textural differences among the investigated systems, ranging from relatively balanced textures in the forest-farming system to clay-rich soils in the silvopastoral system and coarse-textured soils in the conventionally cultivated field. These inherent edaphic differences represent an important confounding factor in the interpretation of physicochemical and biological indicators and limit the ability to clearly distinguish management effects from pre-existing soil conditions. Consequently, the present study cannot fully disentangle the relative contributions of soil texture, historical land use, and management regime to the observed ecological patterns. Nevertheless, despite these textural differences, the substantially improved soil quality indicators observed in the agroforestry systems suggest that management regime and vegetation structure are key drivers of soil ecological resilience within the Strandzha Living Lab.

However, because the study was conducted within a single farm system without independent site replication or baseline data, these differences cannot be attributed exclusively to management practices. Soil texture inheritance, historical land use, and local environmental heterogeneity likely also contributed substantially to the observed variation.

Soil biological activity and mesofaunal community structure

The comparative analysis of biological parameters revealed pronounced differences in the functional activity of soil ecosystems depending on the land-use type. The highest microbial activity (Solvita CO₂-C—99 ppm) and microbial biomass carbon (MBC) (2208 mg kg⁻¹) were recorded in the silvopastoral agroforestry system. These results are associated with denser grass cover, well-developed root systems, and the continuous input of organic residues, which stimulate microbial mineralization processes and N cycling. The higher level of potentially mineralizable nitrogen (PMN) (66 kg ha⁻¹) further confirms

Table 2 Soil fauna and specifically microarthropods (Eco-Morphological Index EMI)

Parameter	Pasture	Apiary	Conventionally cultivated field
Class Insecta Order Hymenoptera	5		
Class Insecta Order Diptera	1		
Class Collembola (springtails) Order Poduromorpha	4	4	4
Class Collembola Family Onychiuridae	10		
Class Collembola (springtails) Order Dicyrtomidae		1	6
Acari (mites)	20	20	20
<i>Protura</i>		20	
Total Soil Biological Quality-arthropods (QBS) index	40	45	30

an active biological turnover and a strong functional capacity for nutrient supply. At the same time, the finer soil texture and elevated clay content may also have contributed to microbial stabilization and nutrient retention.

Soils in the forest-farming agroforestry system (apiary) were characterized by moderate microbial activity (76 ppm) and MBC (1702 mg kg⁻¹) yet exhibited the highest QBS-ar index (45). The QBS-ar is established here as a sensitive marker of anthropogenic pressure. The value of 45, supported by the presence of specialized euedaphic groups such as *Protura*, proves a preserved structure of the soil horizons and improved ecological conditions for soil mesofauna. This suggests a more stable and diverse soil biotic community, resulting from lower levels of mechanical disturbance and greater long-term ecosystem stability. These findings align with the research of Menta et al. (2018), which indicates that the absence of deep plowing allows for the conservation of sensitive soil taxa. Nevertheless, the contribution of site-specific edaphic conditions to the observed mesofaunal structure cannot be excluded.

Conversely, the conventionally cultivated field exhibited the lowest values of microbial activity (66 ppm), MBC (1482 mg kg⁻¹), and PMN (44 kg ha⁻¹). The lowest QBS-ar index (30) and the dominance of widespread mite groups (Acari) indicate "biological homogenization" and reduced functional activity of the soil mesofauna. These patterns are characteristic of intensively managed agricultural systems, where frequent tillage, reduced organic matter inputs, and chemical disturbances negatively affect soil biological quality and ecosystem functioning.

Overall, the results indicate that agroforestry systems maintain higher biological activity and superior

ecological soil quality compared with conventional agriculture. However, given the observational nature of the study and the absence of true experimental replication, these findings should be interpreted primarily as descriptive ecological associations within the investigated farm landscape.

The highest biological soil quality was recorded in the forest-farming agroforestry system (apiary), where the index reached QBS = 45 (Table 2). Highly specialized taxa such as *Protura* (EMI = 20) and Acari (EMI = 20) were identified, together with representatives of Collembola (suborder Poduromorpha, EMI = 4). The presence of *Protura*, which are highly sensitive to mechanical disturbance and chemical stress, represents a strong indicator of stable soil structure and well-preserved ecological niches typical of minimally disturbed systems. The key differentiating factor in term of EMI values between apiary and pasture was presence of *Protura*.

In the silvopastoral agroforestry system, a QBS value of 40 was recorded. The taxonomic composition was more diverse and included representatives of Insecta (orders Hymenoptera and Diptera), together with Collembola (family Onychiuridae, EMI = 10) and Acari. The relatively high EMI value for Onychiuridae indicates a stable subsurface soil environment undisturbed by plowing, allowing the development of specialized edaphic forms with limited mobility.

The lowest biological quality was observed in the conventionally cultivated agroecosystem, where the index decreased to QBS = 30. The community structure was simplified and dominated by more tolerant and widely distributed groups such as Acari and surface-dwelling Collembola (EMI 4–6). The absence of highly specialized edaphic taxa suggests simplified

habitat structure and reduced ecological stability under intensive agricultural management.

Overall, the results clearly demonstrate that the transition from semi-natural agroforestry systems to intensively cultivated land leads to a substantial decline in soil biological capacity. While agroforestry systems function as reservoirs of specialized mesofauna, the conventional field shows clear signs of ecological stress. The agroforestry systems acted as local refugia for specialized soil mesofauna, whereas the conventional agricultural system showed clear evidence of ecological simplification and functional degradation. These findings correspond with the lower levels of soil organic carbon and microbial biomass observed in cultivated soils and confirm that the QBS-ar index is a reliable indicator for monitoring soil biological quality under different land-use regimes (Parisi et al. 2005; Menta et al. 2018). Overall, the QBS-ar values recorded across all land-use types (30–45) are low compared to typical European agroforestry and grassland baselines (70–120+) (Parisi et al. 2005; Menta et al. 2018). Furthermore, the proximity between the values of the silvopastoral pasture (40) and the conventional field (30) indicates non-negligible environmental and physical disturbance. This pattern can be attributed to three main drivers: (1) topsoil desiccation, as sampling coincided with severe 2024 summer heatwaves ($> 39^{\circ}\text{C}$), forcing euedaphic microarthropods to migrate deeper ($> 20\text{ cm}$) or enter aestivation; (2) livestock trampling, where physical topsoil compaction in the pasture reduces macroporosity and restricts sensitive taxa similarly to mechanical tillage; and (3) sampling seasonality, as a single summer snapshot fails to capture seasonal biological peaks typical of humid spring and autumn conditions. Multi-seasonal profiling across deeper soil horizons is necessary to fully assess the functional potential of these soil communities.

Nevertheless, the interpretation of QBS-ar values should consider the potential influence of temporal and environmental variability. In the present study, soil mesofauna sampling was conducted during a spring seasonal campaign, which may not fully capture intra-annual fluctuations in soil biological activity.

Previous studies have demonstrated that QBS-ar values and mesofaunal abundance can vary substantially depending on seasonality, soil moisture, slope exposure, and climatic conditions. Castillo-Avila

Table 3 Temporal dynamics of ground vegetation cover (%) in agroforestry systems (pasture and apiary) in the Strandzha Living Lab, 2023–2024

Year	N	Pasture Density of the grass cover, % $\bar{x} \pm SD$	Apiary Density of the grass cover, % $\bar{x} \pm SD$
2023	10	90.5 $\pm$ 2.26*	86.4 $\pm$ 5.64*
2024	15	89.3 $\pm$ 6.60***	59.7 $\pm$ 11.41***

and Castillo-Figueroa (2026), in their investigation of tropical montane agroforestry systems in the Andes, reported pronounced variability in QBS-ar values across forest succession stages and emphasized the sensitivity of soil mesofauna to local environmental gradients. Similarly, Begum et al. (2013) demonstrated significant seasonal fluctuations in soil mesofauna density in Nepalese hill agroecosystems, strongly associated with precipitation dynamics, slope aspect, and land-use intensity. Considering the pronounced summer drought conditions recorded during 2024 in the Strandzha region, similar seasonal effects on mesofaunal activity cannot be excluded in the present study. Consequently, the obtained QBS-ar values should be interpreted primarily as indicative comparative patterns within the investigated systems rather than as temporally stable estimates of soil biological quality.

Assessment of pasture productivity

The analysis of basal cover revealed distinct interannual variability directly associated with microclimatic conditions and land-use regimes within each system (Table 3).

During the first year of observation (2023), basal cover values in both systems were relatively similar and high, ranging from 86.4 to 90.5%. However, in 2024, a substantial reduction in vegetation density was observed in the forest-farming system (apiary), where basal cover declined to 59.7%. In contrast, the silvopastoral system (pasture) demonstrated remarkable functional stability, maintaining a high basal cover of 89.3%. The difference in mean values was statistically significant at $p < 0.001$. On average over the study period, grass sward density in the pasture system was 22.5% higher than that recorded in the apiary system. One possible explanation for this

Table 4 Botanical composition and functional group distribution (%) within the investigated agroforestry systems (silvopasture and apiary) in the Strandzha Living Lab, 2023–2024

Year Sampling plot	2023		2024	
	Pasture	Apiary	Pasture	Apiary
Perennial cereal grasses, %	65.1 ^{ns}	53.8 ^{ns}	58.2 ^{ns}	41.5 ^{ns}
Legumes, %	16.2 ^{ns}	5.8 ^{ns}	26.2*	10.9*
Miscellaneous forbs, %	18.7*	40.4*	15.6***	47.6***

*represent significant differences at $p < 0.05$; *** represent significant differences at $p < 0.001$

pattern is that the more continuous grass-dominated vegetation in the silvopastoral system maintained greater short-term drought resistance under the specific climatic conditions observed during 2024. However, as the monitoring period covered only two consecutive years, one of which was climatically extreme, the observed differences may also reflect short-term climate variability rather than stable long-term ecosystem resilience. Statistically significant differences in basal cover were detected between the pasture and apiary systems in both years. The differences for 2024 were highly statistically significant ($p < 0.001$). Nevertheless, because the monitoring plots were subsamples within a single farm system rather than independent experimental replicates, the results should be interpreted with caution and primarily as indicators of within-farm comparative variation rather than as broadly generalizable ecological responses.

$\bar{x}$ —mean value; SD – standard deviation; n – number of experimental points; * represent significant differences at $p < 0.05$; *** represent significant differences at $p < 0.001$.

Floristic structure and plant diversity analysis

The floristic structure of the study areas is dominated by perennial grasses, with their proportion in the pasture ranging from 58.2% to 65.1% (Table 4). Perennial grasses were the dominant functional group in both investigated agroforestry systems; however, their relative share was consistently lower in the apiary system, which may be associated with increased shading and modified competitive interactions under partial tree canopy cover. No statistically significant differences were observed in the share of perennial grasses between the pasture and the apiary over the

two years, and their spatial distribution within the apiary remained relatively uniform (Fig. 4).

Substantial differences were observed among other functional groups. The proportion of legumes in the silvopastoral system is approximately 2.5 times higher (averaging 21.2%) compared to the apiary (8.4%), which directly influences biomass nutritional value and soil nitrogen dynamics. This pattern may reflect more favorable conditions for leguminous species development in the open grazed habitats, where higher light availability and lower litter accumulation facilitate their persistence. Statistically significant differences ($p < 0.05$) between the two study places were observed only in 2024.

The most significant differences were recorded in the proportion of forbs. The percentage of miscellaneous forbs was much higher in the apiary compared to that of the pasture. The difference in mean values was statistically significant at $p < 0.05$ for 2023 and at $p < 0.001$ for 2024, although these comparisons should be interpreted cautiously as the monitoring plots represent subsamples within a single farm management unit rather than fully independent experimental replicates. Spatial variations in forb concentration were more pronounced in the apiary than in the pasture (Fig. 4). This pattern may reflect more favorable conditions for leguminous species development in the open-grazed habitats, where higher light availability and lower litter accumulation facilitate their persistence. This heterogeneity can be associated with the structurally diverse microenvironment surrounding the beehives and adjacent woody vegetation, where localized shading, moisture retention, and organic matter accumulation create favorable conditions for a wider range of herbaceous species. This heterogeneity is driven by the formation of microhabitats around the beehives, which create localized zones of shading and soil enrichment with organic residues. In contrast, extensive grazing in the pasture acts as a homogenizing factor, ensuring relatively uniform trampling and biomass consumption. Consequently, the apiary is characterized by a more mosaic-like spatial structure and distinct ecotonal zones surrounding the hives.

This spatial heterogeneity promotes the development of a broader spectrum of niche-specific forb species with fragmented distribution, whereas the pasture maintains a more unified phytocoenotic structure. The high proportion of forbs in the apiary (averaging 44.0%) suggests that forest-farming systems

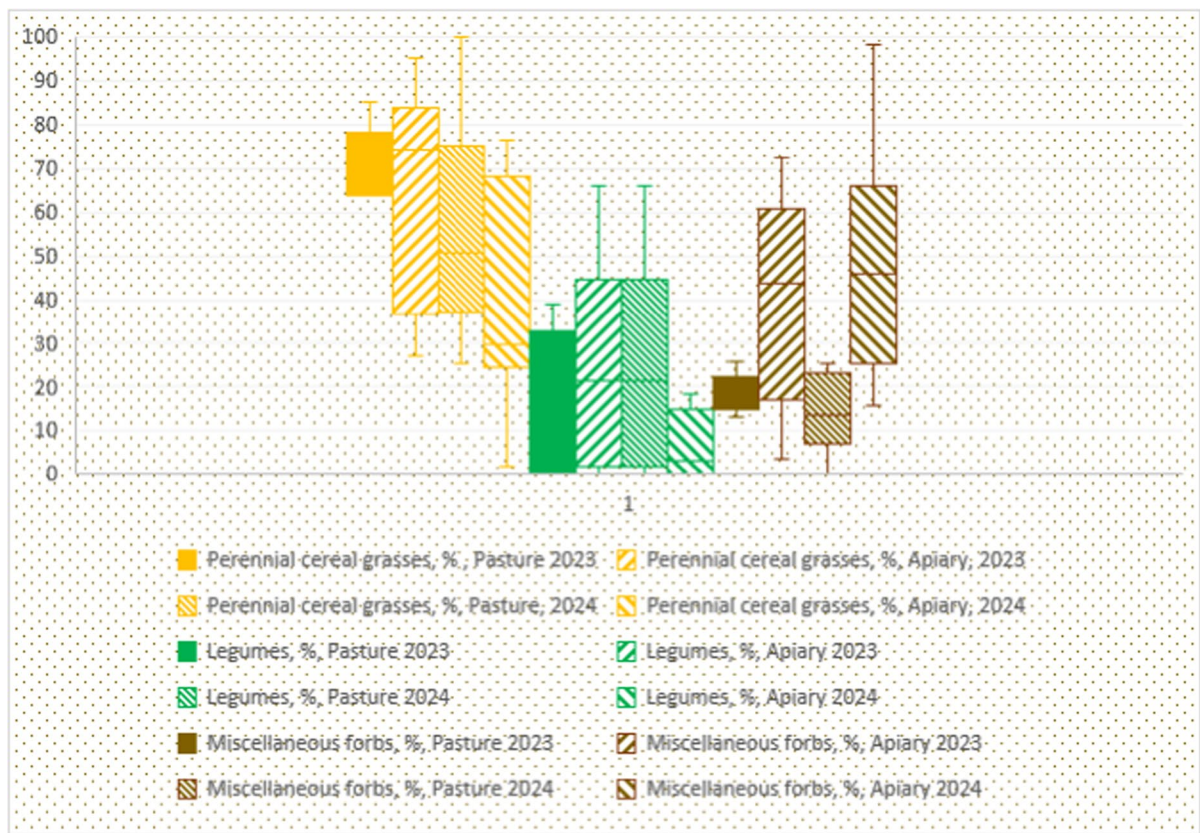


Fig. 4 Botanical composition and functional group distribution (%) in the investigated agroforestry systems in the Strandzha Living Lab, 2023–2024

may support increased floristic complexity and ecological multifunctionality by maintaining a wider diversity of microhabitats and floral resources for pollinators. However, direct measurements of nectar production, pollen quality, or pollinator activity were not performed in the present study; therefore, the continuity of pollinator resources should be interpreted as an indirect floristic indication rather than as direct evidence of pollination service stability.

Productivity and vegetation dynamics

The variation in green mass and dry matter productivity reveals a distinct advantage of the silvopastoral model over the forest-farming system (Table 5). The differences between pasture and apiary were highly statistically significant at $p < 0.001$ in both years. This yield gap, 206.9% and 200.0% in terms of green mass and dry matter respectively, was likely driven

Table 5 Average productivity of green mass and dry matter by year (2023–2024), expressed in kg/ha, for the investigated agroforestry systems (pasture and apiary) in the Strandzha Living Lab

Sampling plot/Year	Green mass yield, kg/ha		Dry matter yield, kg/ha	
	Pasture	Apiary	Pasture	Apiary
2023	15,150***	5595***	4696***	1896***
2024	14,363***	4021***	4234***	1080***

***represent significant differences at $p < 0.001$

by the optimal tree canopy density in the silvopastoral system, which balanced the microclimatic buffering effect with sufficient light availability. The higher productivity recorded in the pasture system may be associated with the combined effects of more open light conditions, grass-dominated vegetation structure,

and finer-textured soils with greater nutrient and water retention capacity. In contrast, the higher spatial variability observed in the pasture (Fig. 5) reflects the inherent heterogeneity of grazing management, specifically the patchy distribution of nutrients resulting from livestock excreta, whereas the apiary maintains a more uniform, albeit light-limited, vegetation cover. The markedly higher productivity recorded in the silvopastoral system during the drought year of 2024 should be interpreted cautiously. Because the investigation was conducted within a single farm and covered only a short observation period, the observed interannual differences may partly reflect site-specific climatic variability, pre-existing soil conditions, grazing-related nutrient redistribution, or other local environmental factors rather than a universally applicable resilience effect of silvopastoral management. The resilience observed during the drought of 2024 confirms the effectiveness of the microclimatic buffer within the silvopastoral system, where canopy shade effectively mitigated thermal stress, ensuring stand stability despite the spatial mosaic induced by grazing.

Floristic composition and structural–functional analysis of plant diversity in agroforestry systems

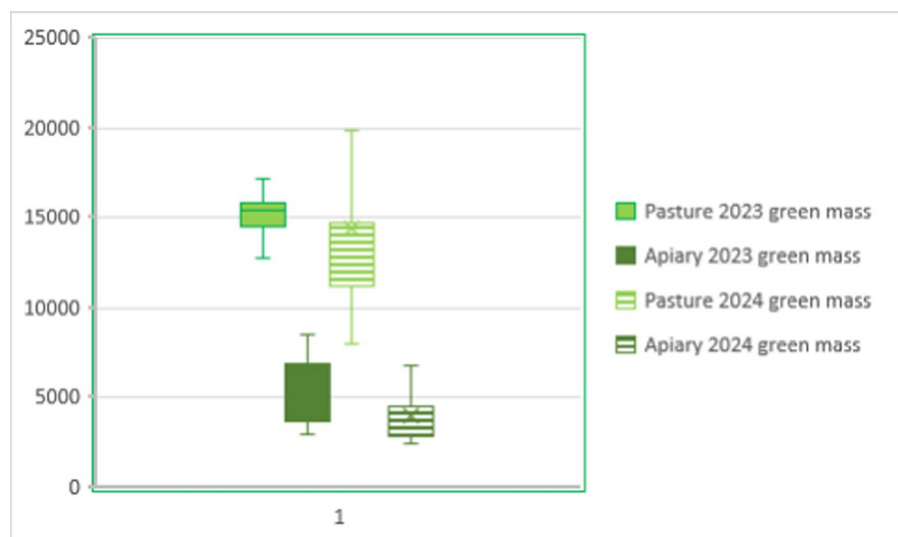
Taxonomic composition

Based on field surveys conducted between 2023 and 2024, a total of 210 plant species belonging to 156 genera and 49 families were identified in the

monitoring plots of the two agroforestry systems of the “Living Laboratory”—Strandzha (Appendix 1). Sampling was conducted repeatedly within the same permanent plots, and floristic records from all monitoring campaigns were pooled to characterize the cumulative vegetation composition and phenological structure of the studied systems. Of these, 209 species were common to both systems, differing in abundance and spatial distribution. In contrast, the protected species *Vaccinium arctostaphylos* L. was found exclusively within the “apiary” forest-farming system. The taxonomic analysis of these relatively small study areas revealed high floristic richness, characterized by the absence of pronounced dominance by individual families and a relatively even distribution among the leading taxa. Such a pattern indicates structural habitat heterogeneity and the presence of diverse ecological niches (Grime 2001). At the same time, because no baseline vegetation data prior to the establishment of the current management systems were available, it is not possible to fully distinguish the effects of current land use from pre-existing environmental heterogeneity and historical vegetation development.

The highest relative representation was recorded for Fabaceae (8.57%) and Poaceae (8.10%), followed by Lamiaceae (7.14%), Asteraceae and Rosaceae (6.67% each), and Brassicaceae and Apiaceae (6.19% each). Collectively, these seven families account for approximately half of the total species composition, a pattern typical of temperate grassland and agrolandscape ecosystems in Southeastern Europe.

Fig. 5 Average productivity of green mass by year (2023–2024), expressed in kg/ha, for the investigated agroforestry systems (pasture and apiary) in the Strandzha Living Lab



The substantial representation of Fabaceae and Poaceae highlights the forage and ecological potential of the systems, particularly their role in biological nitrogen fixation and the maintenance of trophic networks. At the same time, the notable presence of Lamiaceae, Asteraceae, Rosaceae, and Apiaceae contributes to the high melliferous potential of both agroforestry systems, indicating the availability of flowering resources throughout much of the vegetative season. However, the present study did not directly quantify nectar production, pollen nutritional quality, or pollinator visitation intensity. The remaining 50.48% of the species diversity is distributed among numerous families with low individual representation (typically one to two species), grouped under the category “Others”. Such a diffuse taxonomic structure is characteristic of semi-natural ecosystems with pronounced environmental heterogeneity and limited competitive exclusion. Such a diffuse taxonomic structure is characteristic of ecologically stable semi-natural ecosystems and reflects the absence of strong competitive exclusion, which is commonly observed in degraded or heavily anthropogenically influenced habitats (Tilman et al. 1997). Rather than indicating underutilized vegetation resources, this pattern suggests that the studied agroforestry systems maintain high conservation value while simultaneously supporting a broad range of ecosystem services. The percentage distribution of the recorded species by genera is presented in Table 6.

The analysis of the taxonomic structure at the genus level revealed a high degree of phytodiversity, characterized by low dominance of individual taxa and a relatively even distribution of species richness. This pattern reflects the ecological plasticity of the plant community within the studied semi-natural habitats.

The genus *Trifolium* showed the highest frequency of occurrence and species representation (six species), emphasizing the functional importance of leguminous components in the agroecosystem for maintaining nitrogen balance and providing nectar resources for pollinators. This was followed by the genus *Verbascum* (four species), as well as several genera represented by three species each, including *Lathyrus*, *Ranunculus*, *Crataegus*, *Galium*, *Viola*, *Bromus*, and *Lolium*.

Table 6 Percentage distribution of species by genus in the studied agroforestry systems (apiary and pasture) during the 2023–2024 period in the Strandzha Living Lab

Genus	Percentage distribution of species
<i>Trifolium</i>	2,90%
<i>Verbascum</i>	1,90%
<i>Lathyrus</i>	1,40%
<i>Ranunculus</i>	1,40%
<i>Crataegus</i>	1,40%
<i>Galium</i>	1,40%
<i>Viola</i>	1,40%
<i>Bromus</i>	1,40%
<i>Lolium</i>	1,40%
Other (≤ 2 species)	86,00%

Most of the recorded genera were represented by only one or two species. This fragmented genus-level representation contributed to high cumulative genus richness and reflected the structurally heterogeneous character of the investigated agroforestry landscape. This taxonomic distribution indicates the presence of a wide range of microhabitats and ecological niches typical of silvo-agricultural and silvo-pastoral agroforestry systems maintained under extensive management regimes.

However, distinct quantitative variations in genus distribution and spatial coverage were observed between the two systems. The silvo-agricultural (apiary) system exhibited greater coverage and higher population densities of genera within Lamiaceae (e.g., *Salvia*, *Thymus*, *Prunella*, *Mentha*) and Rosaceae (e.g., *Crataegus*, *Prunus*, *Rosa*, *Fragaria*), with melliferous species being markedly more abundant due to partial canopy shade and microhabitat heterogeneity around the hives. Conversely, the silvo-pastoral (pasture) system displayed higher ground coverage and frequency of grass genera within Poaceae (e.g., *Bromus*, *Lolium*, *Poa*, *Dactylis*) alongside forage legume genera within Fabaceae (e.g., *Trifolium*, *Medicago*), driven by open light conditions and grazing management.

The absence of pronounced monodominance represents an important indicator of ecosystem stability and highlights the high conservation value of the studied area (Tilman et al. 1997; Grime 2001). The

observed taxonomic heterogeneity may also contribute to greater adaptive capacity under drought and climatic variability, potentially supporting the long-term ecological sustainability of agroforestry land use in the Strandzha region. However, given that the present investigation was conducted as a single-farm comparative case study, these floristic patterns should be interpreted as locally representative rather than universally applicable to all Balkan agroforestry systems.

Conservation-significant taxa

Within the total floristic composition, three species possess a designated conservation status. All three species (*Vaccinium arctostaphylos*, *Anacamptis papilionacea*, and *Ophrys cornuta*) were observed in both agroforestry systems. However, *V. arctostaphylos* exhibited smaller populations in the silvopastoral system, whereas the populations of both orchid species were small across both systems. Prominent among these is the Tertiary relict *Vaccinium arctostaphylos* L., the presence of which indicates preserved microclimatic conditions and a high degree of ecological authenticity of the habitat. This species is protected under the Biological Diversity Act (2002) and is listed as "Endangered" in the Red Data Book of the Republic of Bulgaria (2015) (online edition).

The Orchidaceae representatives *Anacamptis papilionacea* L. and *Ophrys cornuta* M. Bieb. are subject to the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES 1973) and are protected under the Biological Diversity Act (2002). The occurrence of these orchid taxa suggests the persistence of relatively undisturbed soil conditions and stable mycorrhizal associations that are generally sensitive to intensive anthropogenic disturbance.

Despite the relatively low proportion of protected taxa, their presence corroborates the conservation value of the studied areas and underscores the role of the structurally heterogeneous agroforestry landscape in preserving ecologically sensitive species. These findings support the potential compatibility between traditional low-intensity agroforestry management and biodiversity conservation objectives within semi-natural Balkan landscapes.

Biological types and vertical structure

The biological spectrum of the study area is characterized by a marked predominance of herbaceous species, with perennials being the dominant group, followed by annuals and biennials (Fig. 6).

Such a structure is characteristic of semi-natural grassland ecosystems in the temperate zone and reflects the dominance of competitive and stress-tolerant life strategies according to the C-S-R (Competitors-Stress tolerators-Ruderals) model of Grime (2001), which is typical for habitats under a moderate regime of anthropogenic impact. The dominance of perennial herbaceous species suggests long-term adaptation to recurrent seasonal climatic fluctuations and relatively stable disturbance regimes. The structural dominance of perennial herbaceous species represents a fundamental evolutionary adaptation to cyclic seasonal climates. This functional composition ensures the long-term stability and resilience of the plant community by maintaining consistent biomass production and nutrient cycling despite environmental fluctuations (Grime 2001; Tilman et al. 2006).

The woody component is primarily represented by species from the genera *Quercus*, *Carpinus*, *Crataegus*, *Cornus*, *Prunus*, and *Fraxinus*, predominantly located at the periphery of the pasture and in proximity to the apiary. This spatial organization establishes a distinct vertical stratification and enhances the structural heterogeneity of the agroforestry system. The tree-shrub belt modifies the light regime and microclimatic parameters within the ground layer, creating microhabitats that support higher local diversification; such effects of woody elements on ecosystem services and structural diversity are summarized in the review by Jose (2009).

In addition to their stabilizing role regarding the soil surface and erosion processes, woody elements enhance spatial connectivity between individual plots and facilitate the functioning of trophic networks. In this context, the higher QBS-ar index values recorded in zones with a pronounced woody component are interpreted as an indicator of an improved functional state of the soil mesofauna, consistent with the methodological framework for assessing Soil Biological Quality developed by Menta et al. (2018) and may indicate improved habitat suitability for specialized soil mesofauna. However, because soil texture and historical land-use differences were not fully

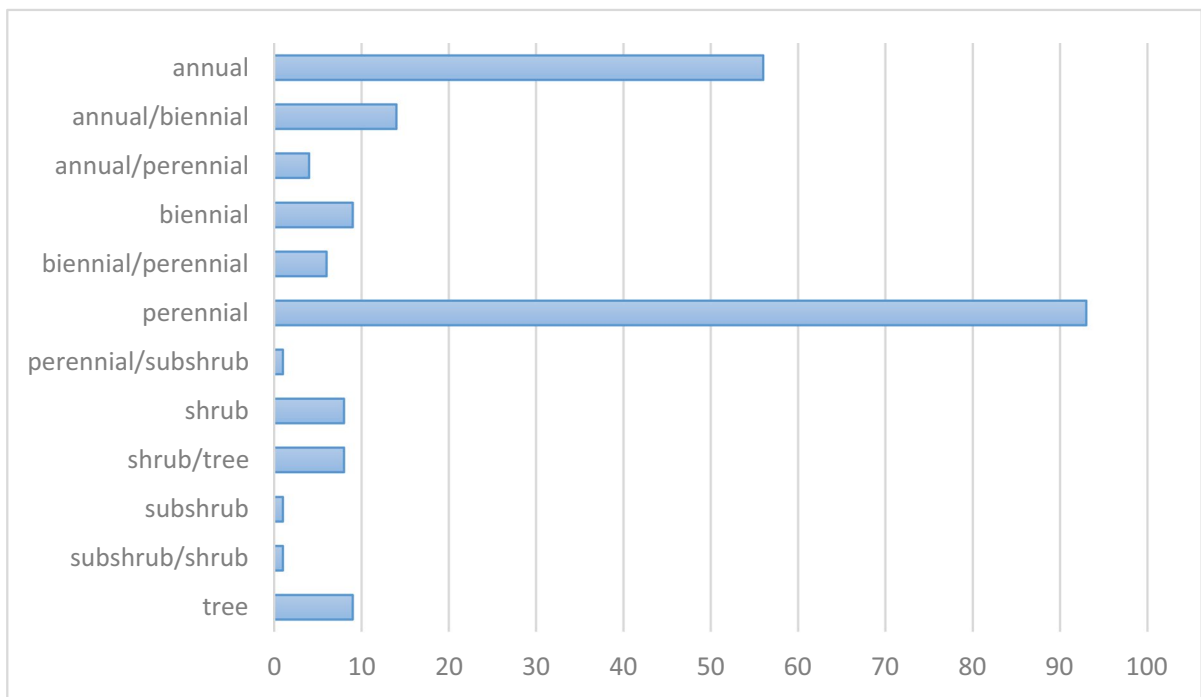


Fig. 6 Distribution of the recorded species by biological type in the studied agroforestry systems in the Strandzha Living Lab

controlled experimentally, these relationships should be interpreted as associative rather than strictly causal. The ecological functionality of newly established agroforestry systems is typically not expressed immediately, as the development of shade regulation, habitat complexity, belowground interactions, and soil-regenerating processes requires extended temporal periods. Consequently, the ecological characteristics observed in the present study likely reflect the long-term continuity and relative maturity of the investigated agroforestry landscape rather than short-term management effects alone.

Seasonal flora dynamics and phenological structure of plant resources

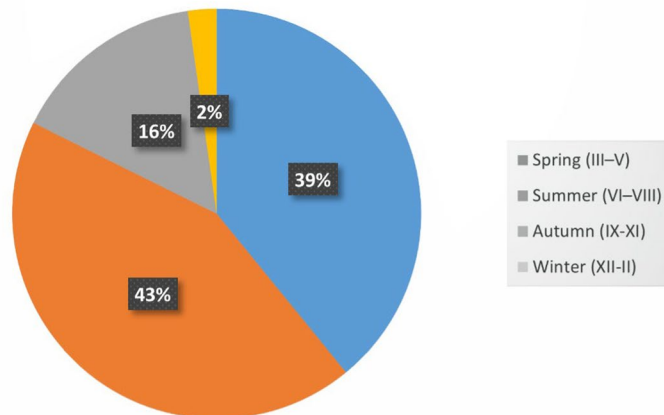
The seasonal dynamics of the flora reflect the climatic characteristics of the region (Fig. 7, Appendix 2) and demonstrate a pronounced intra-annual differentiation in species activity. The observed phenological structure aligns with general ecological patterns governing plant community development in the temperate zone, where resource seasonality and competitive

interactions determine the temporal distribution of growth and reproductive activity (Grime 2001).

During early spring (March–April), an increased activity of ephemeroids and short-cycle species is observed, exploiting high soil moisture and elevated light availability prior to the canopy leaf-out. This strategy is characteristic of taxa adapted to seasonally limited resources and dynamic light conditions throughout the growing season (Grime 2001). The spring maximum (190 species; March–May) initiates the primary vegetative cycle and provides early nutritional resources for pollinators.

The summer period (June–August) is characterized by the highest flowering intensity (210 species), representing the annual phenological peak. Such a concentration of reproductive activity under optimal thermal and photoperiodic conditions is typical of temperate ecosystems (Grime 2001). The significant proportion of melliferous species during this period is essential for the stability of pollination networks, particularly in the context of global pollinator declines and land-use changes (Potts et al. 2010; Ollerton et al. 2011). The pronounced overlap between the spring and summer maxima ensures a continuous supply of

Fig. 7 Seasonal distribution of flowering records (%) observed in the vascular flora of the agroforestry systems in the Strandzha Living Lab



nectar and pollen, mitigating the risk of temporary resource deficits and supporting the resilience of trophic interactions (Ollerton et al. 2011). This phenological succession is regarded as a key factor for the functional sustainability of ecosystems. However, because direct measurements of nectar quantity, pollen nutritional value, or pollinator visitation were not included in the study design, conclusions regarding pollinator-resource continuity should be regarded as indirect ecological interpretations derived from flowering phenology.

In autumn (September–October), the number of flowering species decreases to approximately 75, dominated by taxa with extended summer flowering or secondary phenological maxima. Minimal phenological activity is recorded during the winter period (December–February), with only 11 species in bloom. This distribution reflects a distinct seasonality characteristic of temperate ecosystems and aligns with established global and European trends regarding the sensitivity of phenological phases to climatic variations and global climate change (Parmesan and Yohe 2003; Menzel et al. 2006).

Functional structure and resource potential of the flora

The analysis of ecosystem services provided by the plant communities reveals a high economic potential

for the investigated agroforestry systems. Medicinal plants represent the dominant functional group, accounting for 26% of the total species composition (Fig. 8). This high density of medicinal flora is corroborated by the presence of 38 species officially listed under the Medicinal Plants Act (2000). Among these, *Achillea millefolium*, *Hypericum perforatum*, *Taraxacum officinale*, and *Urtica dioica* possess the highest resource value. The taxonomic structure of this group is dominated by the families Asteraceae, Lamiaceae, Rosaceae, and Fabaceae, which are among the ten largest families in the Bulgarian flora.

Parallel to medicinal properties, melliferous and edible plants each occupy an equal share of 12%, highlighting the multifunctionality of the phytocoenoses in supporting apiculture and local food chains. The functional categories presented in Fig. 8 were not mutually exclusive; individual species may simultaneously possess medicinal, melliferous, ornamental, toxic, or dye-producing properties. For analytical consistency, each species was assigned to its predominant documented ecological or economic use according to Bulgarian floristic references (Delipavlov and Cheshmedzhiev 2003). Forage species (9%) and weed vegetation (9%) constitute significant components of the biodiversity structure; their presence serves as an indicator of the low-intensity management applied, which facilitates the maintenance of natural successional processes. The remaining

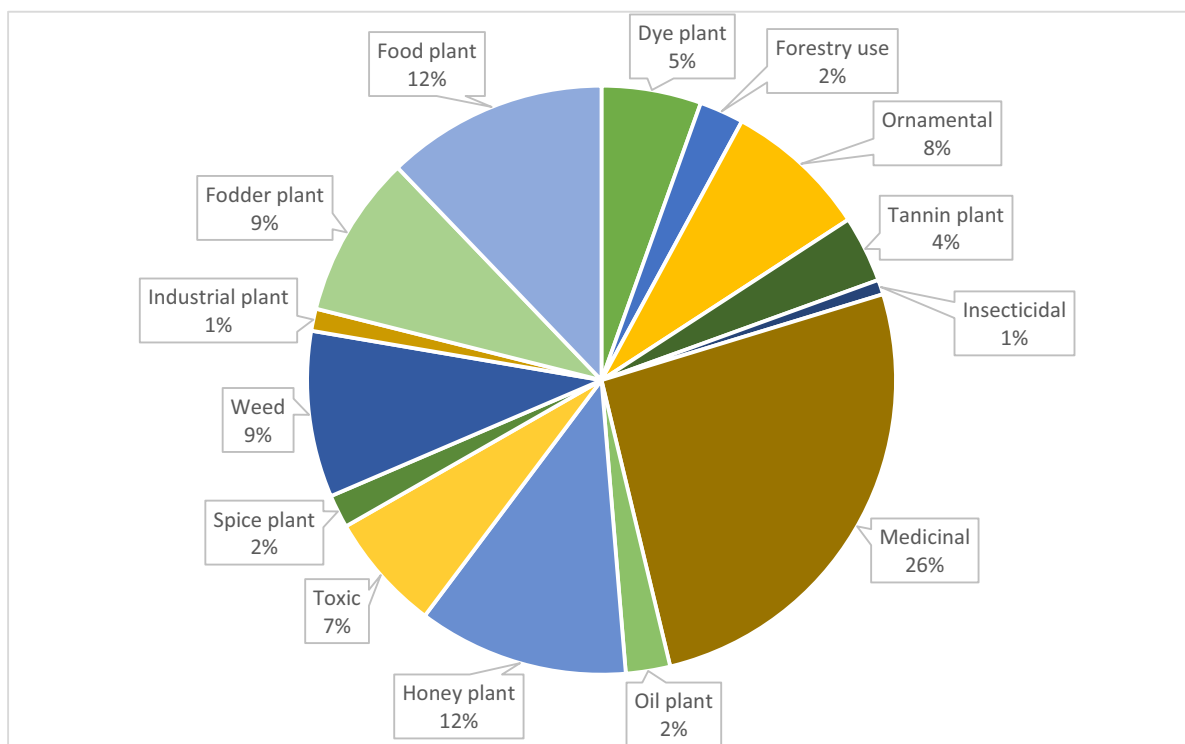


Fig. 8 Functional structure of the flora in the studied agroforestry systems of the Strandzha Living Lab based on the economic value of the species

functional categories include ornamental (8%), toxic (7%), and dye-yielding (5%) plants. Groups that are less represented yet essential for landscape diversification include tannins (4%), oilseeds (2%), forestry-related (2%), spice (2%), insecticidal (1%), and technical (1%) species.

These data categorically indicate that the agroforestry systems in Strandzha function as complex reservoirs of bioresources. They combine production functions (honey and forage yield) with the conservation of wild plant resources, ensuring the resilience of ecosystem services under climate change conditions. The integration of such a broad spectrum of useful plants within a single "Living Lab" demonstrates the effectiveness of this model for the balanced management of territories with high natural and cultural value. Overall, the investigated agroforestry systems functioned as multifunctional reservoirs of plant resources combining forage production, melliferous potential, and biodiversity conservation within the same landscape. Nevertheless, given the single-farm case-study design and the limited temporal scope of

the investigation, these findings should be interpreted as locally representative descriptive evidence rather than as universally applicable models for all Balkan agroforestry systems.

Conclusions

The results from the present study within the Strandzha Living Lab provide robust empirical evidence regarding the multifunctionality of agroforestry systems as instruments for ecological regeneration in ecologically sensitive regions.

The observed variations in parameters across the three land-use types confirm the hypothesis that the integration of woody vegetation creates positive functional interactions, thereby enhancing ecosystem resilience. The comparative analysis conducted along the gradient of anthropogenic impact provides clear quantitative evidence of the superiority of agroforestry models in terms of soil health and biodiversity maintenance compared to intensive conventional

agriculture. The Soil Quality Index (SQI) in the silvo-apicultural (65/100) and silvopastoral systems (67/100) reveals significantly higher functional stability relative to the intensively cultivated rapeseed field, which shows low values (43/100) along with clear signs of soil degradation and erosion risk. Conventional management leads to a deterioration of physicochemical parameters, manifested by a moderately acidic soil reaction (pH 5.6), low levels of organic carbon (1.0%) and total nitrogen (0.107%), as well as severely limited nutrient availability (phosphorus—7 ppm, potassium—98 ppm).

This research establishes agroforestry not merely as an agricultural alternative, but as a highly effective strategy for landscape resilience. Our data clearly demonstrate that incorporating woody species into apicultural and silvopastoral systems produces a powerful synergistic effect: these systems simultaneously regenerate soil health (soil organic matter reaches 5.3%) and preserve biodiversity critical to the region (210 species). In the silvo-apicultural system (apiary), a peak accumulation of organic matter (5.3%) and organic carbon (3.1%) was established, which is a direct consequence of biomass accumulation and lignified litterfall from tree species such as *Quercus* and *Carpinus*. This system provides a stable environment with minimal mechanical disturbances, as confirmed by the presence of highly sensitive specialized edaphic groups such as *Protura*.

On the other hand, the silvopastoral system is distinguished by the highest microbial activity (Solvita CO₂-C—99 ppm), microbial biomass (2208 mg/kg), and potentially mineralizable nitrogen (66 kg N/ha), supported by a high cation exchange capacity (23.3 meq/100 g) due to its clay-rich texture (clay loam), which protects organic matter from accelerated mineralization.

Regarding above-ground biodiversity, the investigated environments function as key "micro-refugia" in the region, harboring a total of 210 plant species across 156 genera and 49 families. Among them, of conservation significance is the tertiary relict *Vaccinium arctostaphylos* L. (an endangered species protected under the Biological Diversity Act and included in the Red Data Book of the Republic of Bulgaria), which was recorded in both agroforestry systems, with higher abundance in the apiary system. The presence of protected orchids such as *Anacamptis papilionacea* L. and *Ophrys cornuta* M. Bieb. further

attests to the preserved mycorrhizal soil structure and low anthropogenic disturbance. The phenological flowering analysis confirms the maintenance of a sustainable floral continuum due to the rich representation of families such as Fabaceae, Poaceae, Lamiaceae, Asteraceae, Rosaceae, and Apiaceae, which ensures a continuous resource of nectar and pollen for local pollinators.

In the context of the current climate crisis, this multifunctional model provides a vital buffering capacity. Through active microclimate regulation, agroforestry systems mitigate extreme thermal stress and maintain stable bioproductivity in areas where conventional agriculture already exhibits signs of functional collapse. Productivity outcomes confirm the high agroecological efficiency of the silvopastoral model, which supports a 22.5% higher mean sward density compared to the apiary, a higher proportion of nitrogen-fixing legume components (averaging 21.2%), and a significantly higher mean yield of green mass (by 206.9%) and dry matter (by 200.0%). This system demonstrates exceptional adaptive capacity and a buffering effect against extreme droughts and high temperatures (exceeding 39 °C) during the summer of 2024, as the tree canopy successfully mitigates thermal stress and retards the drying of the herbaceous layer.

Our findings provide a scientific foundation for future policy development under the European Green Deal, demonstrating that economic viability and conservation priorities can coexist in complete operational harmony. This study establishes the Strandzha region as a benchmark for sustainable and adaptive land use, with principles applicable across the Balkan Peninsula and the Mediterranean basin. The empirical data gathered within the "Living Lab" framework of the European project REFOREST categorically demonstrate that the implementation of scientifically substantiated agroforestry practices in sensitive montane and semi-montane regions is a critically necessary strategy for restoring soil fertility, protecting endangered flora and fauna, and building landscape resilience against the challenges of global climate change.

Despite these significant results, the limited duration of the monitoring period necessitates caution when generalizing the findings and highlights the need for long-term research to assess accurately biogeochemical fluxes. Future research must focus on long-term, continuous monitoring of biogeochemical

fluxes and deep-soil carbon sequestration dynamics across the soil profile to ascertain the enduring impacts of these systems on climate change mitigation. It is also imperative to develop detailed cost–benefit analysis models over an extended timeline, providing farmers with practical projections of financial sustainability during the transition period from conventional land management to agroforestry. Furthermore, subsequent research phases should implement advanced metagenomic analyses to investigate shifts in the soil microbiome structure, fully detail the specific pollinator-plant trophic networks, and evaluate the potential for scaling up and transferring the developed models to other ecologically vulnerable montane and semi-montane regions across the Balkan Peninsula and the Mediterranean basin.

From a management perspective, these data provide a relevant case for integrating agroforestry into the Common Agricultural Policy (CAP), particularly within the Natura 2000 network, where it could serve as a model for balancing production and conservation through multi-parameter monitoring of soil health, microbial dynamics, and biodiversity indicators.

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Author contributions Conceptualization: NG, ST, SA; Methodology: NG, ST, MG, TZ; Formal analysis and investigation: NG, ST, MG, TZ; Writing—original draft preparation: NG, ST, SA; Figure preparation: ST, SA; Writing—review and editing: NG, ST, SA; Supervision: NG, SA. All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Appendix 1

List of vascular plant species recorded in the investigated agroforestry systems (apiary and pasture) during the period 2023–2025 in the “Strandzha Living Lab”

Family	Latin name of the species	Bulgarian name of the species	Biological type
Amaranthaceae	<i>Chenopodium album</i> L	byala kucheshka loboda	annual
Amaryllidaceae	<i>Allium paniculatum</i> L	metlichest luk	perennial
Apiaceae	<i>Aegopodium podagraria</i> L	sedmolist	perennial
Apiaceae	<i>Aethusa cynapium</i> L	obiknoven div magdanov	annual/biennial
Apiaceae	<i>Anthriscus caucalis</i> M.Bieb	otroven azmatsuk	annual
Apiaceae	<i>Anthriscus sylvestris</i> (L.) Hoffm	gorski azmatsuk	perennial
Apiaceae	<i>Eryngium campestre</i> L	polski vetrogon	perennial
Apiaceae	<i>Heracleum sphondylium</i> L	obiknoven devesil	perennial
Apiaceae	<i>Orlaya daucoides</i> (L.) Greuter	morkovovidno sramlivche	annual
Apiaceae	<i>Sanicula europaea</i> L	evropeyska debryanka	perennial
Apiaceae	<i>Chaerophyllum nodosum</i> (L.) Crantz	vazlovat miroides	annual
Apiaceae	<i>Chaerophyllum temulum</i> L	zamayvasht baldaran	biennial/perennial
Apiaceae	<i>Scandix pecten-veneris</i> L	venerino chapliche	annual
Apiaceae	<i>Smyrniun perfoliatum</i> L	pronizanolisten tribel	biennial
Apiaceae	<i>Torilis arvensis</i> (Huds.) Link	polski torilis	annual
Araceae	<i>Arum elongatum</i> Steven	udalzhen zmiyarnik	perennial
Asparagaceae	<i>Ornithogalum sigmoideum</i> Freyn & Sint	nisak garvanov luk	perennial

Family	Latin name of the species	Bulgarian name of the species	Biological type
Asparagaceae	<i>Muscari botryoides</i> (L.) Mill	gorsko kukuviche grozde	perennial
Asparagaceae	<i>Ruscus aculeatus</i> L	bodliv zalist, samodivski chemshir	perennial
Asparagaceae	<i>Scilla bifolia</i> L	dvulisten sinchets	perennial
Asteraceae	<i>Arctium lappa</i> L	obiknoven repey	biennial
Asteraceae	<i>Cirsium vulgare</i> (Savi) Ten	obiknovena palamida	biennial
Asteraceae	<i>Crepis sancta</i> (L.) Babc	palestinska dripavka	annual
Asteraceae	<i>Achillea millefolium</i> L	byal ravnets	perennial
Asteraceae	<i>Bellis perennis</i> L	obiknovena parichka	perennial
Asteraceae	<i>Cichorium intybus</i> L	sinya zhlichka, tsikoria	perennial
Asteraceae	<i>Erigeron acris</i> L	obiknovena zloetnitsa	annual/perennial
Asteraceae	<i>Hypochaeris radicata</i> L	korenest svinyak	perennial
Asteraceae	<i>Leucanthemum vulgare</i> Lam	obiknovena margaritka	perennial
Asteraceae	<i>Mycelis muralis</i> L	mitselis, stenna salata	perennial
Asteraceae	<i>Silybum marianum</i> (L.) Gaertn	marianov byal tran	annual
Asteraceae	<i>Centaurea solstitialis</i> L	slancheva metlichina	perennial
Asteraceae	<i>Taraxacum officinale</i> F.H.Wigg	lechebno gluharche	perennial
Asteraceae	<i>Tragopogon dubius</i> Scop	samnitelna kozya brada	annual/biennial
Betulaceae	<i>Carpinus orientalis</i> Mill	kelyav gabar	shrub/tree
Betulaceae	<i>Carpinus betulus</i> L	obiknoven gabar	tree
Betulaceae	<i>Corylus avellana</i> L	obiknovena leska	shrub
Brassicaceae	<i>Arabidopsis thaliana</i> (L.) Heynh	obiknoven arabidopsis	annual/biennial
Brassicaceae	<i>Alliaria petiolata</i> (M.Bieb.) Cavara & Grande	lazhichina, chesnova treva	annual/biennial
Brassicaceae	<i>Berteroa mutabilis</i> (Vent.) DC	izmenchiva turia	biennial/perennial
Brassicaceae	<i>Cardamine bulbifera</i> (L.) Crantz	lukovichen zabnik	perennial
Brassicaceae	<i>Cardamine hirsuta</i> L	vlaknesta gorva	annual/biennial
Brassicaceae	<i>Capsella bursa-pastoris</i> (L.) Medik	ovcharska torbichka	annual/biennial
Brassicaceae	<i>Brassica napus</i> L	edra rapitsa	annual
Brassicaceae	<i>Erysimum cuspidatum</i> (M.Bieb.) DC	ostrovarha boyanka	biennial
Brassicaceae	<i>Lepidium draba</i> L	rodilna treva	perennial
Brassicaceae	<i>Myagrum perfoliatum</i> L	probitolistna skarbitsa	annual
Brassicaceae	<i>Mummenhoffia alliacea</i> (L.) Esmailbegi & Al-Shehbaz	lukova popova lazhihka	annual
Brassicaceae	<i>Rorippa pyrenaica</i> (All.) Rchb	pireneyski porech	perennial
Brassicaceae	<i>Rorippa prolifera</i> (Heuff.) Neilr	nezhen porech	annual/biennial
Boraginaceae	<i>Buglossoides arvensis</i> (L.) I.M.Johnst	polska beloochitsa	annual
Boraginaceae	<i>Buglossoides purpureoerulea</i> (L.) I.M.Johnst	violetova beloochitsa	perennial
Boraginaceae	<i>Echium italicum</i> L	italiansko usoyniche	biennial
Boraginaceae	<i>Echium vulgare</i> L	obiknoveno usoyniche	biennial/perennial
Boraginaceae	<i>Myosotis incrassata</i> Guss	debelodrazhchesta nezabravka	annual
Boraginaceae	<i>Neotostema apulum</i> (L.) I.M.Johnst	apiliyska neatostema	annual
Boraginaceae	<i>Nonea pulla</i> (L.) DC	tamno shekerche	annual/perennial
Campanulaceae	<i>Campanula rapunculoides</i> L	ednostranna kambanka	perennial
Caprifoliaceae	<i>Knautia integrifolia</i> (Honck. ex L.) Bertol	tselolistno chervenoglavche	annual
Caprifoliaceae	<i>Lonicera xylostium</i> L	mahnat nokat	shrub
Caprifoliaceae	<i>Valeriana pumila</i> (L.) Willd	malka motovilka	annual
Caryophyllaceae	<i>Dichodon viscidus</i> (M.Bieb.) Holub	samnitelen rozhets	annual
Caryophyllaceae	<i>Silene coronaria</i> (L.) Clairv	chervena svilarka	perennial

Family	Latin name of the species	Bulgarian name of the species	Biological type
Caryophyllaceae	<i>Stellaria graminea</i> L	trevna zvezditsa	perennial
Caryophyllaceae	<i>Stellaria holostea</i> L	edrotsvetna zvezditsa	perennial
Cistaceae	<i>Cistus creticus</i> L	pamukliyka	subshrub/shrub
Cistaceae	<i>Helianthemum nummularium</i> (L.) Mill	obiknoven zhaltak	subshrub
Convolvulaceae	<i>Convolvulus arvensis</i> L	polska povetitsa	perennial
Cornaceae	<i>Cornus mas</i> L	obiknoven dryan	shrub/tree
Crassulaceae	<i>Sedum annuum</i> L	ednogodishna tlastiga	annual
Cyperaceae	<i>Carex caryophyllaea</i> J.F.Gmel	proletna ostritsa	perennial
Euphorbiaceae	<i>Euphorbia cyparissias</i> L	obiknovena mlechka	perennial
Euphorbiaceae	<i>Euphorbia helioscopia</i> L	slancheva mlechka	annual
Euphorbiaceae	<i>Euphorbia platyphyllos</i> L	razshirenolistna mlechka	annual
Euphorbiaceae	<i>Euphorbia stricta</i> L	mirizliva mlechka	annual
Ericaceae	<i>Vaccinium arctostaphylos</i> L	kavkazka borovinka	shrub
Fabaceae	<i>Anthyllis vulneraria</i> L	tselebna ramenka	perennial
Fabaceae	<i>Astragalus glycyphyllos</i> L	sladkolistno sgrabiche	perennial
Fabaceae	<i>Chamaecytisus austriacus</i> (L.) Link	avstriyski zanovets	shrub
Fabaceae	<i>Medicago arabica</i> (L.) Huds	arabska lyutserna	annual
Fabaceae	<i>Medicago polymorpha</i> L	izmenchiva lyutserna	annual
Fabaceae	<i>Melilotus albus</i> Medik	byala komuniga	annual/biennial
Fabaceae	<i>Lathyrus aphaca</i> L	zhalto sekirche	annual
Fabaceae	<i>Lathyrus laxiflorus</i> (Desf.) Kuntze	rehavotsvetno sekirche	perennial
Fabaceae	<i>Lathyrus tuberosus</i> L	grudesto sekirche	perennial
Fabaceae	<i>Ononis spinosa</i> L	bodliv gramotran	perennial
Fabaceae	<i>Trifolium campestre</i> Schreb	polska detelina	biennial
Fabaceae	<i>Trifolium cherleri</i> L	herlerova detelina	annual
Fabaceae	<i>Trifolium hybridum</i> L	hibridna detelina	perennial
Fabaceae	<i>Trifolium incarnatum</i> L	inkarnatna detelina	annual/biennial
Fabaceae	<i>Trifolium nigrescens</i> Viv	cherneeshta detelina	annual
Fabaceae	<i>Trifolium repens</i> L	byala detelina	perennial
Fabaceae	<i>Vicia sativa</i> subsp. <i>nigra</i> Ehrh	tesnolistna glushina	annual
Fabaceae	<i>Vicia sativa</i> L	proleten fiy	annual
Fagaceae	<i>Quercus cerris</i> L	tser	tree
Fagaceae	<i>Quercus petraea</i> (Matt.) Liebl	skalen dab	tree
Fagaceae	<i>Quercus pubescens</i> Willd	kosmat dab	tree
Gentianaceae	<i>Centaurium erythraea</i> Rafn	cherven kantarion	biennial
Geraniaceae	<i>Erodium cicutarium</i> (L.) L'Hér	tsikutovo chasovniche	annual
Geraniaceae	<i>Geranium columbinum</i> L	galabov zdravets	annual
Geraniaceae	<i>Geranium dissectum</i> L	nasechenolisten zdravets	annual
Geraniaceae	<i>Geranium molle</i> L	nezhen zdravets	annual/biennial
Geraniaceae	<i>Geranium sanguineum</i> L	karvav zdravets	perennial
Hypericaceae	<i>Hypericum maculatum</i> Crantz	petnista zvanika	perennial
Hypericaceae	<i>Hypericum perforatum</i> L	zhalt kantarion	perennial
Iridaceae	<i>Crocus flavus</i> Weston	zhalt minzuhar	perennial
Juglandaceae	<i>Juglans regia</i> L	obiknoven oreh	tree
Juncaceae	<i>Juncus tenuis</i> Willd	tanka dzuka	perennial
Lamiaceae	<i>Ajuga laxmannii</i> (L.) Benth	laksmanovo sreshtniche	perennial
Lamiaceae	<i>Chaiturus marrubiastrum</i> (L.) Ehrh. ex Rchb	pchelnikov hayturus	annual/biennial

Family	Latin name of the species	Bulgarian name of the species	Biological type
Lamiaceae	<i>Lamium purpureum</i> L	chervena martva kopriya	annual
Lamiaceae	<i>Mentha suaveolens</i> Ehrh	kragloslistna menta	perennial
Lamiaceae	<i>Origanum vulgare</i> L	obiknoven rigan	perennial
Lamiaceae	<i>Prunella vulgaris</i> L	obiknovena prishnitsa	perennial
Lamiaceae	<i>Salvia forskahlei</i> L	kachulest konski bosilek	annual/biennial
Lamiaceae	<i>Salvia pratensis</i> L	livaden konski bosilek	biennial/perennial
Lamiaceae	<i>Teucrium capitatum</i> L	byalo podabiche	perennial
Lamiaceae	<i>Thymus pulegioides</i> L	planinska mashterka	perennial/subshrub
Lamiaceae	<i>Salvia aethiopis</i> L	etiopski konski bosilek	perennial
Lamiaceae	<i>Salvia virgata</i> Jacq	pratoviden konski bosilek	perennial
Lamiaceae	<i>Sideritis montana</i> L	planinski mirizliv buren	annual
Lamiaceae	<i>Stachys germanica</i> L	germanski chistets	perennial
Lamiaceae	<i>Ziziphora capitata</i> L	glavesta zizifora	annual
Linaceae	<i>Linum bienne</i> Mill	zimen len	annual/biennial
Malvaceae	<i>Malva sylvestris</i> L	gorski slez	annual/perennial
Oleaceae	<i>Fraxinus ornus</i> L	mazhdryan	tree
Orchidaceae	<i>Ophrys scolopax</i> subsp. <i>cornuta</i> (Steven) E.G.Camus	dvurogo brambarche	perennial
Orchidaceae	<i>Anacamptis papilionacea</i> (L.) R.M.Bateman, Pridgeon & M.W.Chase	peperudotsveten anakamptis	perennial
Orobanchaceae	<i>Parentucellia latifolia</i> (L.) Caruel	shirokolist parentutsia	annual
Oxalidaceae	<i>Oxalis corniculata</i> L	rogchesto kiseliche	perennial
Papaveraceae	<i>Papaver dubium</i> L	dalgoploden mak	annual
Papaveraceae	<i>Papaver rhoeas</i> L	polski mak	annual
Papaveraceae	<i>Fumaria rostellata</i> Knaf	chovchest rosopas	annual
Papaveraceae	<i>Corydalis solida</i> (L.) Schwarz	platinogrudesta lisichena	perennial
Plantaginaceae	<i>Digitalis lanata</i> Ehrh	valnest naprastnik	biennial/perennial
Plantaginaceae	<i>Plantago major</i> L	shirokolist zhivovlyak	perennial
Plantaginaceae	<i>Plantago lanceolata</i> L	tesnolisten zhivovlyak	perennial
Plantaginaceae	<i>Veronica hederifolia</i> L	brashlyanolistno velikdenche	annual
Plantaginaceae	<i>Veronica spicata</i> L	sbit stepnik	perennial
Poaceae	<i>Aegilops triuncialis</i> L	triuntsievo divo zhito	annual
Poaceae	<i>Bromus sterilis</i> L	dalgoosilesta ovsiga	annual
Poaceae	<i>Bromus hordeaceus</i> L	meka ovsiga	annual
Poaceae	<i>Bromus inermis</i> Leyss	bezosilesta ovsiga	perennial
Poaceae	<i>Anthoxanthum odoratum</i> L	obiknovena mirizlivka	perennial
Poaceae	<i>Cynodon dactylon</i> (L.) Pers	troskot	perennial
Poaceae	<i>Dactylis glomerata</i> L	ezhova glavitsa	perennial
Poaceae	<i>Danthonia alpina</i> Vest	dvuzaba trizabka	annual/perennial
Poaceae	<i>Digitaria sanguinalis</i> (L.) Scop	karvava rosichka	annual
Poaceae	<i>Lolium pratense</i> (Huds.) Darbysh	livadna vlasatka	perennial
Poaceae	<i>Hordeum bulbosum</i> L	lukovichen echemik	perennial
Poaceae	<i>Hordeum vulgare</i> L	obiknoven (shestdelen) echemik	annual
Poaceae	<i>Lolium temulentum</i> L	piyavets	annual
Poaceae	<i>Lolium perenne</i> L	angliyski raygras	perennial
Poaceae	<i>Poa nemoralis</i> L	gorska livadina	perennial
Poaceae	<i>Poa pratensis</i> L	livadna livadina	perennial

Family	Latin name of the species	Bulgarian name of the species	Biological type
Poaceae	<i>Phleum pratense</i> L	livadna timoteyka	perennial
Polygalaceae	<i>Polygala comosa</i> Schkuhr	kachulesta telcharka	perennial
Polygonaceae	<i>Polygonum arenastrum</i> Boreau	pyasachna pacha treva	annual
Polygonaceae	<i>Polygonum aviculare</i> L	obiknovena pacha treva	annual
Polygonaceae	<i>Rumex obtusifolius</i> L	tapolisten lapad	perennial
Primulaceae	<i>Cyclamen coum</i> Mill	proletno boturche	perennial
Primulaceae	<i>Lysimachia arvensis</i> (L.) U.Manns & Anderb	polsko ognivche	annual/biennial
Ranunculaceae	<i>Anemone ranunculoides</i> L	lyutikovidna sasanka	perennial
Ranunculaceae	<i>Clematis recta</i> L	izpraven povet	shrub
Ranunculaceae	<i>Delphinium consolida</i> L	obiknovena ralitsa	annual
Ranunculaceae	<i>Isopyrum thalictroides</i> L	kokoshka	perennial
Ranunculaceae	<i>Helleborus odoratus</i> Waldst. & Kit. ex Willd	mirizliv kukuryak	perennial
Ranunculaceae	<i>Nigella arvensis</i> L	polska chelebitka	annual
Ranunculaceae	<i>Ranunculus acris</i> L	obiknoveno lyutiche	perennial
Ranunculaceae	<i>Ranunculus repens</i> L	palzyashto lyutiche	perennial
Ranunculaceae	<i>Ranunculus velutinus</i> Ten	kadifenovlaknesto lyutiche	perennial
Ranunculaceae	<i>Thalictrum minus</i> L	drebnno obichnice	perennial
Rosaceae	<i>Agrimonia eupatoria</i> L	lecheben kamshik	perennial
Rosaceae	<i>Fragaria vesca</i> L	diva yagoda	perennial
Rosaceae	<i>Filipendula vulgaris</i> Moench	livadno orehche	perennial
Rosaceae	<i>Sanguisorba minor</i> Scop	drebnna dinka	perennial
Rosaceae	<i>Crataegus germanica</i> (L.) Kuntze	obiknovena mushmula	shrub/tree
Rosaceae	<i>Crataegus monogyna</i> Jacq	obiknoven glog	shrub/tree
Rosaceae	<i>Crataegus pentagyna</i> Waldst. & Kit. ex Willd	cheren glog	shrub/tree
Rosaceae	<i>Geum urbanum</i> L	gradsko omayniche	perennial
Rosaceae	<i>Rosa canina</i> L	obiknovena shipka	shrub
Rosaceae	<i>Rubus caesius</i> L	polska kapina	shrub
Rosaceae	<i>Potentilla erecta</i> (L.) Raeusch	izpraven ochibolets	perennial
Rosaceae	<i>Prunus cerasifera</i> Ehrh	dzhanka	shrub/tree
Rosaceae	<i>Prunus spinosa</i> L	tranka	shrub
Rosaceae	<i>Sorbus domestica</i> L	skorusha	tree
Rubiaceae	<i>Galium aparine</i> L	lepka, gergevka, obiknoveno enyo- vche	annual
Rubiaceae	<i>Galium odoratum</i> Scop	mirizlivo enyovche	perennial
Rubiaceae	<i>Galium verum</i> L	istinsko enyovche	perennial
Rubiaceae	<i>Sherardia arvensis</i> L	polski gradnik	annual
Sapindaceae	<i>Acer campestre</i> L	polski klen	tree
Sapindaceae	<i>Acer pseudoplatanus</i> L	yavor	tree
Scrophulariaceae	<i>Scrophularia nodosa</i> L	vazlesto zhiveniche	perennial
Scrophulariaceae	<i>Verbascum densiflorum</i> Bertol	gastotsveten lopen	biennial
Scrophulariaceae	<i>Verbascum glabratum</i> Friv	gol lopen	biennial/perennial
Scrophulariaceae	<i>Verbascum phoeniceum</i> L	finikiyski lopen	perennial
Scrophulariaceae	<i>Verbascum speciosum</i> Schrad	prekrasen lopen	biennial
Solanaceae	<i>Datura stramonium</i> L	obiknoven tatul	annual
Solanaceae	<i>Solanum villosum</i> Mill	zhalto kuche grozde	annual
Verbenaceae	<i>Verbena officinalis</i> L	lechebna varbinka	perennial
Viburnaceae	<i>Adoxa moschatellina</i> L	obiknovena moshkovitsa	perennial

Family	Latin name of the species	Bulgarian name of the species	Biological type
Viburnaceae	<i>Sambucus ebulus</i> L	trevist baz, bazak	perennial
Viburnaceae	<i>Sambucus nigra</i> L	cheren baz	shrub/tree
Viburnaceae	<i>Viburnum lantana</i> L	cherna kalina	shrub/tree
Violaceae	<i>Viola tricolor</i> L	tritsvetna temenuga	annual
Violaceae	<i>Viola riviniana</i> Rchb	gorska temenuga	perennial
Violaceae	<i>Viola arvensis</i> Murray	polska temenuga	annual
Urticaceae	<i>Parietaria officinalis</i> L	lekovita razvalenka	perennial
Urticaceae	<i>Urtica urens</i> L	gratska kopriya	annual
Urticaceae	<i>Urtica dioica</i> L	obiknovena kopriya	perennial

Appendix 2

Distribution of vascular plant species recorded in the investigated agroforestry systems (apiary and pasture) during the period 2023–2025 in the “Strandzha Living Lab”, according to their flowering phenology.

Period of flowering	Species
Spring (III–V)	<i>Aegopodium podagraria</i> , <i>Anthriscus caucalis</i> , <i>Anthriscus sylvestris</i> , <i>Sanicula europaea</i> , <i>Chaerophyllum nodosum</i> , <i>Chaerophyllum temulum</i> , <i>Scandix pecten-veneris</i> , <i>Smyrnum perfoliatum</i> , <i>Arum elongatum</i> , <i>Ornithogalum sigmoideum</i> , <i>Muscari botryoides</i> , <i>Ruscus aculeatus</i> , <i>Scilla bifolia</i> , <i>Crepis sancta</i> , <i>Bellis perennis</i> , <i>Hypochaeris radicata</i> , <i>Silybum marianum</i> , <i>Taraxacum officinale</i> , <i>Tragopogon dubius</i> , <i>Carpinus orientalis</i> , <i>Carpinus betulus</i> , <i>Corylus avellana</i> , <i>Arabidopsis thaliana</i> , <i>Alliaria petiolata</i> , <i>Cardamine bulbifera</i> , <i>Cardamine hirsuta</i> , <i>Capsella bursa-pastoris</i> , <i>Brassica napus</i> , <i>Erysimum cuspidatum</i> , <i>Lepidium draba</i> , <i>Myagrum perfoliatum</i> , <i>Mummenhoffia alliacea</i> , <i>Rorippa pyrenaica</i> , <i>Rorippa prolifera</i> , <i>Buglossoides arvensis</i> , <i>Buglossoides purpureocaerulea</i> , <i>Echium italicum</i> , <i>Echium vulgare</i> , <i>Myosotis incassata</i> , <i>Neotostema apulum</i> , <i>Nonea pulla</i> , <i>Knautia integrifolia</i> , <i>Lonicera xylosteum</i> , <i>Valeriana pumila</i> , <i>Dichodon viscidus</i> , <i>Stellaria graminea</i> , <i>Stellaria holostea</i> , <i>Cistus creticus</i> , <i>Helianthemum nummularium</i> , <i>Convolvulus arvensis</i> , <i>Cornus mas</i> , <i>Sedum annuum</i> , <i>Carex caryophyllaea</i> , <i>Euphorbia cyparissias</i> , <i>Euphorbia helioscopia</i> , <i>Euphorbia platyphyllos</i> , <i>Euphorbia stricta</i> , <i>Vaccinium arctostaphylos</i> , <i>Anthyllis vulneraria</i> , <i>Chamaecytisus austriacus</i> , <i>Medicago arabica</i> , <i>Medicago polymorpha</i> , <i>Lathyrus aphaca</i> , <i>Trifolium cherleri</i> , <i>Trifolium hybridum</i> , <i>Trifolium incarnatum</i> , <i>Trifolium nigrescens</i> , <i>Trifolium repens</i> , <i>Vicia sativa</i> subsp. <i>nigra</i> , <i>Vicia sativa</i> , <i>Quercus cerris</i> , <i>Quercus petraea</i> , <i>Quercus pubescens</i> , <i>Erodium cicutarium</i> , <i>Geranium columbinum</i> , <i>Geranium dissectum</i> , <i>Geranium molle</i> , <i>Geranium sanguineum</i> , <i>Hypericum maculatum</i> , <i>Hypericum perforatum</i> , <i>Crocus flavus</i> , <i>Juglans regia</i> , <i>Ajuga laxmannii</i> , <i>Lamium purpureum</i> , <i>Origanum vulgare</i> , <i>Prunella vulgaris</i> , <i>Salvia forskahlei</i> , <i>Salvia pratensis</i> , <i>Teucrium capitatum</i> , <i>Thymus pulegioides</i> , <i>Salvia aethiopsis</i> , <i>Sideritis montana</i> , <i>Ziziphora capitata</i> , <i>Linum bienne</i> , <i>Malva sylvestris</i> , <i>Fraxinus ornus</i> , <i>Ophrys scolopax</i> subsp. <i>cornuta</i> , <i>Anacamptis papilionacea</i> , <i>Parentucellia latifolia</i> , <i>Papaver dubium</i> , <i>Papaver rhoeas</i> , <i>Fumaria rostellata</i> , <i>Corydalis solida</i> , <i>Digitalis lanata</i> , <i>Plantago lanceolata</i> , <i>Veronica hederifolia</i> , <i>Veronica spicata</i> , <i>Aegilops triuncialis</i> , <i>Bromus sterilis</i> , <i>Bromus hordeaceus</i> , <i>Anthoxanthum odoratum</i> , <i>Dactylis glomerata</i> , <i>Danthonia alpina</i> , <i>Digitaria sanguinalis</i> , <i>Hordeum bulbosum</i> , <i>Hordeum vulgare</i> , <i>Lolium temulentum</i> , <i>Poa nemoralis</i> , <i>Poa pratensis</i> , <i>Phleum pratense</i> , <i>Polygala comosa</i> , <i>Polygonum arenastrum</i> , <i>Polygonum aviculare</i> , <i>Cyclamen coum</i> , <i>Lysimachia arvensis</i> , <i>Anemone ranunculoides</i> , <i>Clematis recta</i> , <i>Delphinium consolida</i> , <i>Isopyrum thalictroides</i> , <i>Helleborus odorus</i> , <i>Ranunculus acris</i> , <i>Ranunculus repens</i> , <i>Ranunculus velutinus</i> , <i>Thalictrum minus</i> , <i>Fragaria vesca</i> , <i>Filipendula vulgaris</i> , <i>Sanguisorba minor</i> , <i>Crataegus germanica</i> , <i>Crataegus monogyna</i> , <i>Crataegus pentagyna</i> , <i>Geum urbanum</i> , <i>Rosa canina</i> , <i>Rubus caesius</i> , <i>Prunus cerasifera</i> , <i>Prunus spinosa</i> , <i>Sorbus domestica</i> , <i>Galium aparine</i> , <i>Galium odoratum</i> , <i>Sherardia arvensis</i> , <i>Acer campestre</i> , <i>Acer pseudoplatanus</i> , <i>Scrophularia nodosa</i> , <i>Verbascum glabratum</i> , <i>Datura stramonium</i> , <i>Verbena officinalis</i> , <i>Adoxa moschatellina</i> , <i>Sambucus ebulus</i> , <i>Sambucus nigra</i> , <i>Viburnum lantana</i> , <i>Viola tricolor</i> , <i>Viola riviniana</i> , <i>Viola arvensis</i> , <i>Parietaria officinalis</i> , <i>Urtica urens</i> , <i>Urtica dioica</i>

Period of flowering	Species
Summer (VI–VIII)	<i>Chenopodium album</i> , <i>Allium paniculatum</i> , <i>Aegopodium podagraria</i> , <i>Aethusa cynapium</i> , <i>Anthriscus caucalis</i> , <i>Anthriscus sylvestris</i> , <i>Eryngium campestre</i> , <i>Heracleum sphondylium</i> , <i>Orlaya daucoides</i> , <i>Sanicula europaea</i> , <i>Chaerophyllum nodosum</i> , <i>Chaerophyllum temulum</i> , <i>Scandix pecten-veneris</i> , <i>Smyrnum perfoliatum</i> , <i>Torilis arvensis</i> , <i>Arum elongatum</i> , <i>Arctium lappa</i> , <i>Cirsium vulgare</i> , <i>Crepis sancta</i> , <i>Achillea millefolium</i> , <i>Bellis perennis</i> , <i>Cichorium intybus</i> , <i>Erigeron acris</i> , <i>Hypochaeris radicata</i> , <i>Mycelis muralis</i> , <i>Silybum marianum</i> , <i>Centaurea solstitialis</i> , <i>Taraxacum officinale</i> , <i>Tragopogon dubius</i> , <i>Alliaria petiolata</i> , <i>Berteroa mutabilis</i> , <i>Cardamine bulbifera</i> , <i>Cardamine hirsuta</i> , <i>Brassica napus</i> , <i>Erysimum cuspidatum</i> , <i>Lepidium draba</i> , <i>Myagrum perfoliatum</i> , <i>Rorippa pyrenaica</i> , <i>Buglossoides purpureocerulea</i> , <i>Echium italicum</i> , <i>Echium vulgare</i> , <i>Nonea pulla</i> , <i>Campanula rapunculoides</i> , <i>Knautia integrifolia</i> , <i>Lonicera xylosteum</i> , <i>Dichodon viscidus</i> , <i>Silene coronaria</i> , <i>Stellaria graminea</i> , <i>Cistus creticus</i> , <i>Helianthemum nummularium</i> , <i>Convolvulus arvensis</i> , <i>Sedum annuum</i> , <i>Euphorbia cyparissias</i> , <i>Euphorbia helioscopia</i> , <i>Euphorbia platyphyllos</i> , <i>Euphorbia stricta</i> , <i>Vaccinium arctostaphylos</i> , <i>Anthyllis vulneraria</i> , <i>Astragalus glycyphyllos</i> , <i>Chamaecytisus austriacus</i> , <i>Medicago arabica</i> , <i>Medicago polymorpha</i> , <i>Melilotus albus</i> , <i>Lathyrus aphaca</i> , <i>Lathyrus laxiflorus</i> , <i>Lathyrus tuberosus</i> , <i>Ononis spinosa</i> , <i>Trifolium campestre</i> , <i>Trifolium hybridum</i> , <i>Trifolium incarnatum</i> , <i>Trifolium repens</i> , <i>Vicia sativa</i> subsp. <i>nigra</i> , <i>Vicia sativa</i> , <i>Centaurium erythraea</i> , <i>Erodium cicutarium</i> , <i>Geranium columbinum</i> , <i>Geranium dissectum</i> , <i>Geranium molle</i> , <i>Geranium sanguineum</i> , <i>Hypericum maculatum</i> , <i>Hypericum perforatum</i> , <i>Juncus tenuis</i> , <i>Ajuga laxmannii</i> , <i>Chaiturus marrubiastrum</i> , <i>Lamium purpureum</i> , <i>Mentha suaveolens</i> , <i>Origanum vulgare</i> , <i>Prunella vulgaris</i> , <i>Salvia forskahlei</i> , <i>Salvia pratensis</i> , <i>Teucrium capitatum</i> , <i>Thymus pulegioides</i> , <i>Salvia aethiopsis</i> , <i>Salvia virgata</i> , <i>Sideritis montana</i> , <i>Stachys germanica</i> , <i>Ziziphora capitata</i> , <i>Linum bienne</i> , <i>Malva sylvestris</i> , <i>Parentucellia latifolia</i> , <i>Oxalis corniculata</i> , <i>Papaver dubium</i> , <i>Papaver rhoeas</i> , <i>Fumaria rostellata</i> , <i>Digitalis lanata</i> , <i>Plantago major</i> , <i>Plantago lanceolata</i> , <i>Veronica spicata</i> , <i>Aegilops triuncialis</i> , <i>Bromus sterilis</i> , <i>Bromus hordeaceus</i> , <i>Bromus inermis</i> , <i>Anthoxanthum odoratum</i> , <i>Cynodon dactylon</i> , <i>Dactylis glomerata</i> , <i>Danthonia alpina</i> , <i>Digitaria sanguinalis</i> , <i>Lolium pratense</i> , <i>Hordeum bulbosum</i> , <i>Hordeum vulgare</i> , <i>Lolium temulentum</i> , <i>Lolium perenne</i> , <i>Poa nemoralis</i> , <i>Poa pratensis</i> , <i>Phleum pratense</i> , <i>Polygonum arenastrum</i> , <i>Polygonum aviculare</i> , <i>Rumex obtusifolius</i> , <i>Lysimachia arvensis</i> , <i>Clematis recta</i> , <i>Delphinium consolida</i> , <i>Nigella arvensis</i> , <i>Ranunculus acris</i> , <i>Ranunculus repens</i> , <i>Thalictrum minus</i> , <i>Agrimonia eupatoria</i> , <i>Fragaria vesca</i> , <i>Filipendula vulgaris</i> , <i>Sanguisorba minor</i> , <i>Crataegus monogyna</i> , <i>Rubus caesius</i> , <i>Potentilla erecta</i> , <i>Galium aparine</i> , <i>Galium odoratum</i> , <i>Galium verum</i> , <i>Scrophularia nodosa</i> , <i>Verbascum densiflorum</i> , <i>Verbascum glabratum</i> , <i>Verbascum phoeniceum</i> , <i>Verbascum speciosum</i> , <i>Datura stramonium</i> , <i>Solanum villosum</i> , <i>Verbena officinalis</i> , <i>Sambucus ebulus</i> , <i>Sambucus nigra</i> , <i>Viburnum lantana</i> , <i>Viola tricolor</i> , <i>Parietaria officinalis</i> , <i>Urtica urens</i> , <i>Urtica dioica</i>
Autumn (IX–XI)	<i>Chenopodium album</i> , <i>Cirsium vulgare</i> , <i>Achillea millefolium</i> , <i>Bellis perennis</i> , <i>Cichorium intybus</i> , <i>Erigeron acris</i> , <i>Hypochaeris radicata</i> , <i>Leucanthemum vulgare</i> , <i>Silybum marianum</i> , <i>Centaurea solstitialis</i> , <i>Taraxacum officinale</i> , <i>Trifolium repens</i> , <i>Capsella bursa-pastoris</i> , <i>Lepidium draba</i> , <i>Convolvulus arvensis</i> , <i>Euphorbia helioscopia</i> , <i>Euphorbia platyphyllos</i> , <i>Euphorbia stricta</i> , <i>Anthyllis vulneraria</i> , <i>Melilotus albus</i> , <i>Ononis spinosa</i> , <i>Trifolium hybridum</i> , <i>Erodium cicutarium</i> , <i>Geranium sanguineum</i> , <i>Hypericum perforatum</i> , <i>Lamium purpureum</i> , <i>Mentha suaveolens</i> , <i>Origanum vulgare</i> , <i>Prunella vulgaris</i> , <i>Teucrium capitatum</i> , <i>Thymus pulegioides</i> , <i>Sideritis montana</i> , <i>Malva sylvestris</i> , <i>Oxalis corniculata</i> , <i>Papaver rhoeas</i> , <i>Plantago major</i> , <i>Plantago lanceolata</i> , <i>Veronica spicata</i> , <i>Cynodon dactylon</i> , <i>Digitaria sanguinalis</i> , <i>Lolium temulentum</i> , <i>Polygonum arenastrum</i> , <i>Polygonum aviculare</i> , <i>Rumex obtusifolius</i> , <i>Lysimachia arvensis</i> , <i>Delphinium consolida</i> , <i>Nigella arvensis</i> , <i>Ranunculus acris</i> , <i>Thalictrum minus</i> , <i>Fragaria vesca</i> , <i>Rubus caesius</i> , <i>Galium verum</i> , <i>Verbascum densiflorum</i> , <i>Verbascum glabratum</i> , <i>Verbascum phoeniceum</i> , <i>Verbascum speciosum</i> , <i>Datura stramonium</i> , <i>Solanum villosum</i> , <i>Verbena officinalis</i> , <i>Sambucus ebulus</i> , <i>Sambucus nigra</i> , <i>Viola tricolor</i> , <i>Viola arvensis</i> , <i>Urtica urens</i> , <i>Urtica dioica</i>
Winter (XII–II)	<i>Corylus avellana</i> , <i>Cornus mas</i> , <i>Carex caryophyllaea</i> , <i>Euphorbia helioscopia</i> , <i>Crocus flavus</i> , <i>Corydalis solida</i> , <i>Cyclamen coum</i> , <i>Helleborus odoratus</i> , <i>Veronica hederifolia</i> , <i>Isopyrum thalictroides</i> , <i>Capsella bursa-pastoris</i>

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