

Operationalizing Cattle–Environment Interactions in a Traditional Silvopastoral System: CEII (Cattle–Environment Interaction Index) and SWAI (Silvopastoral Water Accessibility Index) for Assessing Vegetation and Topographic Controls in Türkiye

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Research Article

Keywords: Silvopastoral systems, socio-ecological systems, free-ranging cattle, cattle–environment interactions

Posted Date: July 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10228154/v1>

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Version of Record: A version of this preprint was published at Tropical Animal Health and Production on October 20th, 2026. See the published version at <https://doi.org/10.1007/s11250-026-05434-7>.

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Abstract

This study conceptualizes traditional silvopastoral cattle production systems in the Beşparmak Mountains as an adaptive agro-silvopastoral socio-ecological system shaped by dynamic interactions among vegetation composition, land-use configuration, water accessibility, topographic heterogeneity, and human management practices. As a methodological innovation, the study introduces two composite indicators—the Cattle–Environment Interaction Index (CEII) and the Silvopastoral Water Accessibility Index (SWAI)—to operationalize and quantify multidimensional interactions governing system organization and animal–environment relationships. Findings show that the system functions beyond a resource-extractive production regime, operating instead as a biophysical and management-mediated mechanism regulating key ecological processes. Agricultural production areas act as functional transition zones characterized by partial spatial overlap between grazing activity and animal movement, while hygrophilous water-associated habitats serve as critical aggregation nodes where drinking and short-duration resting behaviors are concentrated. The heterogeneous vegetation mosaic developed on gneissic bedrock supports selective grazing behavior, while livestock spatial distribution and foraging decisions are constrained by feed selectivity, microclimatic variability, and thermal comfort conditions. Among the examined drivers, water accessibility emerges as the primary determinant shaping movement trajectories and grazing intensity patterns. At the system level, these interactions contribute to regulating ecosystem functions, particularly fuel load reduction, biomass regulation, and nutrient cycling. The proposed CEII and SWAI effectively capture and operationalize the coupled socio-ecological complexity of the system. Despite the growing dominance of industrialized livestock systems in Türkiye, this traditional silvopastoral system persists as a resilient rural production model characterized by ecological plasticity and its ability to integrate livestock production with ecosystem functionality.

Keywords: Silvopastoral systems, socio-ecological systems, free-ranging cattle, cattle–environment interactions

Introduction

Livestock production systems occupy approximately one-third of the Earth’s ice-free terrestrial surface and are recognized as one of the major anthropogenic drivers of global land-use change. These systems are not merely components of food production, but complex socio-ecological structures that influence biodiversity dynamics, carbon cycling, and the organization of agro-silvopastoral systems. While industrial and high-input production

models are predominantly associated with habitat loss, greenhouse gas emissions, and land degradation, low-input and traditional grazing systems, under appropriate conditions, can contribute to agro-silvopastoral multifunctionality and enhance ecosystem resilience through the conservation of diverse plant communities, improved soil health, enhanced nutrient recycling, and the maintenance of ecological processes that support long-term ecosystem stability (Carvalho et al. 2021; Ickowicz et al. 2023; Maree et al. 2025).

In recent years, the relevant literature has increasingly framed pastoral systems within the context of socio-ecological resilience and agro-silvopastoral multifunctionality (Byrnes et al. 2014; Aaron et al. 2024; Fonseca et al. 2024; Mouratiadou et al. 2024; Geck et al. 2025). This perspective conceptualizes pastoral systems not merely as production systems, but as integrated socio-ecological entities shaped by interactions between ecological processes (e.g., vegetation regeneration, species distribution, and disturbance regimes) and social processes (e.g., local knowledge systems, governance structures, and livelihood strategies).

Within this framework, silvopastoral systems have emerged as multifunctional agro-silvopastoral landscapes characterized by high structural heterogeneity, in which trees, shrubs, and grazing livestock coexist and interact. Existing studies have demonstrated that these systems support biodiversity conservation, regulate fire regimes, and enhance carbon sequestration (de Macedo Carvalho et al. 2024; Mackay-Smith et al. 2025). However, a substantial body of the literature has predominantly focused on the well-documented Dehesa and Montado systems of the Western Mediterranean Basin, which are widely recognized as benchmark silvopastoral landscapes (Jose and Dollinger 2019; Plieninger et al. 2021; Amorim et al. 2023; Mackay-Smith et al. 2025; Dahhou et al. 2026). These systems represent traditional land-use models in which livestock production is conducted under open oak woodland conditions, delivering high biodiversity values and multiple ecosystem services.

In contrast, empirical evidence on the ecological and socio-economic dynamics of traditional silvopastoral cattle production systems in other parts of the Aegean and Mediterranean basins remains limited. Consequently, the generalizability of existing theoretical frameworks across heterogeneous socio-ecological contexts is still subject to debate. This limitation reveals two key gaps in the literature: first, the dominance of a Western Mediterranean-centered epistemological framework in silvopastoral theory; and second, the insufficient representation of the high socio-ecological heterogeneity of the Aegean–Mediterranean transition zone. In addition, the limited empirical understanding of fine-scale interactions between livestock mobility and vegetation dynamics constrains process-based interpretations of these systems.

Against this background, the Beşparmak Mountains (ancient Latmos), located in southwestern Türkiye within the Aegean–Mediterranean climatic transition zone, provide a highly heterogeneous landscape in which forest,

rangeland, and agricultural areas are extensively interwoven (Bayraka 2023). This ecotonal landscape constitutes a natural model system for testing theoretical assumptions under real-world conditions. Within this mosaic, consisting of maquis formations, Turkish red pine (*Pinus brutia* Ten.) forests, and agricultural fields, silvopastoral cattle production exhibits strong convergence with silvopastoral system dynamics, particularly in terms of low external input use and extensive spatial mobility (Yavuzer 2014; Akbaş 2020; Karaca et al. 2022).

The aim of this study is to characterize the traditional silvopastoral cattle production system that persists in the Aegean–Mediterranean transition zone despite the increasing dominance of industrial livestock production models, and to assess its human–animal–environment interactions within an integrated, data-driven framework. The system is conceptualized as a socio-ecological structure shaped by interactions among livestock mobility, vegetation dynamics, water accessibility, and local management practices.

In contrast to conventional index-based approaches that are often unidimensional, infrastructure-oriented, and static in their representation of resource access, this study develops two field-based composite indicators—the Cattle–Environment Interaction Index (CEII) and the Silvopastoral Water Accessibility Index (SWAI)—to enable a comparative and quantifiable assessment of system functioning relative to industrial production models. These indices capture environmental interaction patterns and water accessibility dynamics, providing a robust analytical framework for the comparative evaluation of structural and functional system properties.

Materials and Methods

Study Area

This study was conducted in the Beşparmak Mountains (ancient Latmos), located within the Aegean–Mediterranean transition zone of southwestern Türkiye. The mountain system forms part of the northwestern sector of the Western Menteşe Mountains and extends predominantly within the provincial boundaries of Aydın, with a smaller portion reaching Muğla Province. The study area is geographically surrounded by the districts of Çine, Karpuzlu, Koçarlı, and Söke in Aydın Province, and Milas and Yatağan in Muğla Province (Figure 1).

The Beşparmak Mountains constitute a highly heterogeneous agro-silvopastoral system in which forest, rangeland, and agricultural areas are closely interwoven. Characterized by a mosaic of maquis shrublands, Turkish red pine (*P. brutia*) forests, agricultural lands, and natural rangelands, the area exhibits the typical ecological features of a Mediterranean mountain ecosystem. Owing to the persistence of traditional free-ranging cattle husbandry based on low external inputs, the region represents one of the few remaining socio-ecological systems where livestock mobility and vegetation dynamics remain strongly interconnected, providing an ideal natural setting for investigating animal–environment interactions.

The study was conducted across 22 villages located within the provinces of Aydın and Muğla. The distance of settlements from district centers ranged from 6 to 55 km (mean: 23.5 km), while the average elevation, population size, and number of households were 423 m, 640 inhabitants, and 210 households, respectively. Land-use patterns were characterized by a mean agricultural area of 1,684 ha, a mean forest area of 1,145 ha, and a mean rangeland area of 548 ha per settlement (Table 1, Table S1).

Research Design

This study was grounded in an integrated conceptual framework that combines the Socio-Ecological Systems (SES) approach with agro-silvopastoral systems ecology. The research employed a multiscale mixed-methods design, enabling the simultaneous examination of household-level socio-economic structures and ecosystem-level processes. Within this framework, interactions among livestock mobility, vegetation dynamics, and local management practices were evaluated from a process-based perspective. Data were collected from 104 cattle-producing households using semi-structured interviews, complemented by field observations and secondary data sources

Data Collection

Data collection followed a multi-source approach integrating field observations, official records, and semi-structured interviews. This design was intended to facilitate a comprehensive assessment of the socio-ecological processes underlying the silvopastoral production system.

Field surveys were conducted across different elevational zones, and vegetation types were systematically recorded. Hygrophilous, agricultural, maquis and phrygana, forest, and ruderal-segetal vegetation types were identified and characterized based on species composition, vegetation cover, and structural attributes. These characteristics were documented using standardized field observation forms and photographic records. Cattle-vegetation interactions were assessed through direct observations focusing on the spatial distribution of grazing activity and vegetation preferences.

Socio-economic data related to cattle production were obtained from records maintained by the Turkish Ministry of Agriculture and Forestry and local administrative units (village head offices). In addition, structured and semi-structured interviews with livestock-producing households were conducted to collect information on production organization, grazing area utilization, and local management practices.

Grazing system characteristics were evaluated in relation to seasonal herd movements, grazing intensity, and management strategies based on local ecological knowledge. Interactions between livestock mobility and agro-silvopastoral system attributes were subsequently analyzed at both spatial and behavioral scales.

Data Structure and Standardization

Data Normalization

As the dataset comprised variables measured on different scales and units (e.g., hectares, counts, frequencies, and farm-level observations), all variables were standardized prior to analysis to ensure comparability. To achieve this, variables were rescaled to a common range between 0 and 1 using the min–max normalization procedure (Stylianou et al. 2020; Mazziotta and Pareto 2022). Detailed information on the normalized variables is provided in Supplementary Tables S2, S3, and S4.

For each variable, the normalized value was calculated as follows:

$$Z_{ij} = \frac{X_{ij} - X_{j \min}}{X_{j \max} - X_{j \min}}$$

Where Z_i denotes the normalized value of variable j for settlement i , X_{ij} represents the observed value of variable j in settlement i , and $X_{j \max}$ and $X_{j \min}$ correspond to the maximum and minimum observed values of variable j , respectively. The term $(X_{j \max} - X_{j \min})$ therefore represents the observed range of the variable.

Vegetation–Grazing Interaction Analysis

Relationships between vegetation types and cattle behavioral patterns were assessed using a thematic ecological coding approach based on field observations. This framework was developed to systematically characterize interactions between livestock activities and the major vegetation units of the agro-silvopastoral system.

The coding scheme was structured at three hierarchical levels:

- **Vegetation type classification:** Land-cover units were classified according to dominant vegetation characteristics as maquis shrublands, forest areas, agricultural lands, and ruderal-segetal habitats.
- **Animal behavioral categories:** Observed cattle activities were categorized into grazing, resting, and water consumption behaviors.
- **Interaction intensity:** Vegetation–animal interactions were evaluated using an ordinal scale based on expert assessment and classified as low, moderate, or high interaction intensity.

This approach represents a field-based semi-quantitative coding framework designed to evaluate the influence of grazing activities on the spatial and ecological heterogeneity of agro-silvopastoral systems. By integrating vegetation characteristics with observed livestock behaviors, the framework provides a structured basis for assessing animal–environment interactions across different habitat types.

Cattle–Environment Interaction Index (CEII)

The Cattle–Environment Interaction Index (CEII) was developed to quantify the net socio-ecological effects of traditional silvopastoral cattle production systems by evaluating the balance between ecosystem services generated

by the system and the environmental pressures associated with livestock activities. The index is a composite indicator based on an event-based ratio approach and was designed to enable the comparison of heterogeneous ecological interactions within a common analytical framework.

The event data used in the analysis were obtained through semi-structured surveys and stakeholder interviews conducted at the settlement level. Respondents were asked to report both beneficial and adverse events associated with traditional silvopastoral cattle production system during the most recent production season. To minimize recall bias, predefined event categories and standardized reference scenarios were employed throughout the interview process. The variables included in the index were subsequently derived by aggregating reported events at the settlement level.

Because the use of raw event frequencies may implicitly assume that all events exert identical ecological significance, potentially introducing methodological bias, the CEII was formulated using a weighted event-score approach. Given the absence of direct empirical measurements of event magnitude and impact, an equal-weighting scheme was initially adopted across all event categories. This approach represents a commonly applied baseline assumption in the development of composite indicators under conditions of limited empirical evidence. To evaluate the robustness of this assumption, the sensitivity of the index to alternative weighting structures was subsequently assessed through sensitivity analysis.

Accordingly, Benefit Scores (*BS*) and Damage Scores (*DS*) were calculated for each settlement and subsequently combined to construct the Cattle–Environment Interaction Index (CEII).

a. Beneficiary Score (*BS*)

Within the CEII framework, ecosystem services associated with traditional silvopastoral cattle production systems were classified into six categories: natural fertilization, support for olive grove management, fire risk reduction, vegetation and biomass control, soil aeration, and support for ecological production systems.

For each settlement, a composite benefit score was calculated by aggregating the frequencies of reported ecosystem service events across the six categories. The benefit score was expressed as:

$$BS_i = \sum_k (x_{ik} w_k)$$

Where BS_i denotes the total benefit score for settlement i , x_{ik} represents the number of reported events associated with benefit category k in settlement i , and w_k is the weight assigned to benefit category k .

b. Damage Score (*DS*)

Environmental pressures associated with silvopastoral cattle production systems were classified into three principal categories: damage to olive groves, damage to agricultural lands, and impacts on water resources. These categories were selected to represent the most frequently reported adverse environmental effects associated with livestock activities in the study area.

For each settlement, a composite environmental pressure score was calculated by aggregating the frequency of reported adverse events across the three categories. The pressure score was computed as follows:

$$DS_i = \sum_k (y_{ik} w_k)$$

Where DS_i denotes the total damage score for settlement i , y_{ik} represents the number of reported events associated with damage category k in settlement i , and w_k is the weight assigned to damage category k .

Functional Structure of the CEII

To quantify the net socio-ecological effects of the traditional silvopastoral cattle production system, the benefit score (BS) and damage score (DS) components were integrated within a unified analytical framework and combined into a composite indicator. The resulting Cattle–Environment Interaction Index ($CEII$) was formulated as follows:

$$CEII_i = \frac{BS_i}{\ln(DS_i + e)}$$

Where $CEII_i$ represents the cattle–environment interaction index for settlement i , BS_i is the total benefit score, and DS_i is the total damage score. The constant e denotes Euler’s number (≈ 2.718), introduced to ensure numerical stability and prevent undefined values in the log-transformed component.

The distribution of the damage score (DS) exhibited pronounced positive skewness (skewness > 1). Consequently, a logarithmic transformation was applied to improve distributional properties, reduce the influence of extreme values, and achieve scale compression. Accordingly, the damage component of the CEII was expressed as $\ln(DS + e)$, whereas the benefit score (BS) was retained in its original linear form.

This formulation is consistent with the assumption that benefits and environmental pressures exhibit distinct functional responses within socio-ecological systems. While ecosystem service benefits tend to accumulate in an approximately linear manner, environmental pressures frequently display saturation effects and diminishing marginal impacts at higher intensity levels. Under these conditions, logarithmic transformation provides a theoretically and methodologically justified approach for reducing the disproportionate influence of extreme damage values on the composite index.

234 Furthermore, the $\ln(DS + e)$ transformation attenuates the dominance of high damage scores while preserving
235 meaningful variation among low and moderate levels of environmental pressure. The Euler constant ($e \approx$
236 2.718) was added prior to transformation to reduce the sensitivity of the logarithmic function near zero, avoid
237 undefined values, and improve numerical stability during index computation.

238 The influence of these assumptions on model outcomes was subsequently evaluated through sensitivity analyses.
239 The results demonstrated a high degree of consistency in CEII rankings across alternative specification scenarios,
240 supporting the robustness of the proposed index structure.

241 Due to its ratio-based structure, the CEII does not have a theoretical upper bound and is therefore expected to
242 exhibit a positively skewed distribution. This characteristic was confirmed through skewness and kurtosis
243 statistics. Given the heterogeneous distribution of reported events among settlements, a relative classification
244 approach based on empirical quartiles was adopted rather than applying fixed threshold values. Accordingly, CEII
245 values were classified into four categories based on their empirical distribution (Table 2).

246 This classification approach is a robust relative evaluation method commonly applied in socio-ecological studies
247 to account for spatial heterogeneity in observational datasets.

248 **Validation of the CEII**

249 The construct validity of the proposed Cattle–Environment Interaction Index (CEII) was assessed using a multi-
250 method validation framework. In this context, the consistency of the index with ecological reality was evaluated
251 through field observations, a known-groups approach, and the structural properties of the socio-ecological system.
252 First, field observations revealed spatial patterns consistent with the interaction structure represented by the CEII.
253 The pronounced use of hygrophilous areas in proximity to water sources, high grazing pressure in maquis and
254 phrygana formations, and the predominance of forested areas as low-intensity grazing and resting zones all
255 demonstrated strong agreement with the interaction gradients captured by the index.

256 Second, within the known-groups framework, settlements expected to differ in socio-ecological characteristics
257 were compared. Settlements with higher water accessibility, lower dependence on mechanized inputs, and higher
258 reported ecosystem service provision (Karpuzlu, Söke, Milas, and Yatağan) were classified as high-interaction
259 groups, whereas settlements characterized by limited water accessibility and higher reported environmental
260 pressures (Çine and Koçarlı) were categorized as low-interaction groups.

261 The observed CEII values exhibited a clear separation between these groups. High-interaction settlements
262 consistently displayed higher CEII values, whereas low-interaction settlements showed comparatively lower

values. These results indicate that the CEII is capable of capturing structural heterogeneity within the socio-ecological system.

Taken together, these findings suggest that the CEII demonstrates strong construct validity. The index not only aligns with empirically observed ecological interaction patterns at the field scale but also effectively discriminates between pre-defined the socio-ecological groups.

Integrated Interpretation of the CEII and Quartile Indices

The CEII and Q indices developed in this study represent complementary dimensions of the socio-ecological system. While the CEII captures the balance between environmental pressures and ecosystem service intensity, the Q index reflects structural constraints related to resource accessibility. The joint application of these two indices enables a more comprehensive assessment of the interactions between environmental pressures and resource accessibility in silvopastoral systems.

Sensitivity Analysis of the CEII

To evaluate the robustness of the equal-weighting assumption, perturbation scenarios of $\pm 10\%$ and $\pm 20\%$ were applied to the total benefit score (BS). The resulting CEII rankings were then compared with the baseline ranking using Spearman's rank correlation coefficient to assess ordinal consistency under alternative weighting specifications.

Silvopastoral Water Accessibility Index (SWAI)

The Silvopastoral Water Accessibility Index (SWAI) was developed to jointly evaluate both the compositional structure of water sources and the structural dependency dimension of water accessibility in silvopastoral systems. Min-max normalization was not adopted, as it is considered insufficient to capture the qualitative and directional characteristics of water access and is sensitive to extreme values. Instead, the index was constructed as a two-component framework comprising water source composition and tractor dependency.

a. Resource Composition Score (RCS)

The Resource Composition Score (RCS) is defined as the weighted average of water source accessibility, excluding tractor-dependent systems, reflecting the compositional structure of available water resources.

$$RCS_i = \frac{\sum_{k \in K^+} w_k n_{ik}}{\sum_{k \in K^+} n_{ik}}$$

Where RCS_i denotes the weighted average resource composition score for settlement i , based on water sources excluding tractor-based water transportation systems. i represents the settlement (district), and k denotes the type of water source, where K^+ includes all non-tractor-based water sources. n_{ik} indicates the number of farms in

settlement i utilizing water source k , and w_k represents the weight assigned to each water source type based on accessibility continuity, seasonal reliability, and logistical requirements.

Weights were assigned based on accessibility continuity, seasonal reliability, and logistical burden criteria (Table 3).

b. Tractor Dependency Ratio (TDR)

The Tractor Dependency Ratio (TDR) captures the extent of reliance on tractor-based water transportation within the system and is therefore incorporated as a negative component in the index formulation.

$$TDR_i = \frac{n_{i_tractor}}{N_i}$$

where TDR_i denotes the proportion of farms dependent on tractor-based water transportation in settlement i . $n_{i_tractor}$ represents the number of farms relying on tractors for water transport, and N_i is the total number of farms in settlement i . The TDR is bounded between 0 and 1, with higher values indicating greater structural dependence on tractor-based water supply systems.

The final silvopastoral water accessibility index (SWAI) was formulated by combining the positive contribution of resource composition (RCS) with the negative effect of tractor dependency (TDR), as follows:

$$SWAI_i = RCS_i \times (1 - TDR_i)$$

Where $SWAI_i$ is the silvopastoral water accessibility index for settlement i , RCS_i is the resource composition score reflecting the quality and accessibility of available water sources, and TDR_i is the tractor dependency ratio. The term $(1 - TDR_i)$ acts as a penalty factor that incorporates the structural constraints associated with tractor-dependent water access, thereby reducing the final index value as dependency increases.

This formulation ensures that water accessibility decreases proportionally as tractor dependency increases and reduces the SWAI value to zero when $(TDR_i = 1)$. Consequently, the index is normalized within a bounded range of 0 to 1, facilitating direct comparison across settlements.

To evaluate the influence of the weighting scheme on index outcomes, a sensitivity analysis was conducted by perturbing the assigned weights by $\pm 10\%$. The resulting SWAI rankings exhibited a high degree of stability, indicating the robustness of the proposed index structure.

For interpretative purposes, SWAI values were classified into five categories according to predefined threshold values (Table 4).

Statistical and Thematic Analysis Strategy

Data analysis was conducted within a framework combining descriptive statistics, comparative assessments, and rank-based analytical approaches. All statistical analyses were performed using SAS (1999) and Microsoft Excel.

The analytical framework focused on identifying relative differences and spatial patterns among settlements rather than evaluating absolute values. Accordingly, variables were analyzed comparatively at both settlement and district levels to reveal underlying socio-ecological heterogeneity.

To assess the robustness of the proposed indices, sensitivity analyses were conducted and ranking stability was evaluated under alternative specification scenarios. The consistency of rankings was quantified using Spearman's rank correlation coefficient. This non-parametric measure was selected because it does not require distributional assumptions and provides robust estimates in datasets characterized by relatively small sample sizes and heterogeneous data structures.

The analytical strategy emphasized the evaluation of structural consistency, relative patterns, and ranking stability rather than formal hypothesis testing. Consequently, results were interpreted within a comparative and exploratory framework, focusing on the identification of socio-ecological gradients and system-level relationships. The overall analytical design was developed to accommodate the multi-scale and heterogeneous nature of socio-ecological data and to provide an integrated assessment of interactions among environmental, management, and production-related variables.

Results

The findings indicate that the traditional silvopastoral cattle production system constitutes a multifunctional socio-ecological production system that integrates crop production, livestock husbandry, and the use of natural resources at the settlement level.

Vegetation in the study area was classified into seven major types: maquis, forest, agricultural land, ruderal-segetal vegetation, phrygana, hygrophilous habitats, and grassland formations. These vegetation types reflect the environmental heterogeneity of the region and provide a diverse ecological matrix for livestock grazing and silvopastoral interactions.

Field observations revealed pronounced spatial and functional differentiation between vegetation types and cattle grazing behavior (Table 5).

The highest grazing pressure was observed in maquis, phrygana, ruderal-segetal vegetation, and grassland formations. These habitats were characterized as "active-use zones", where grazing constituted the dominant behavioral activity and utilization intensity was consistently high. In contrast, forest vegetation exhibited a lower level of interaction, with resting and shade-seeking behavior predominating over grazing activity. The closed-canopy structure emerged as the principal physical factor limiting grazing utilization within forested habitats.

Moderate levels of interaction were recorded in agricultural lands, where cattle exhibited both grazing and transit behaviors. Field observations revealed a partial spatial overlap between agricultural production areas and grazing activities, indicating that these areas function as transitional zones within the agro-silvopastoral system. Hygrophilous habitats were identified as livestock aggregation areas associated with water availability. In these habitats, the dominant activities were water consumption and short-duration resting rather than grazing. This pattern highlights the pivotal role of water resources in shaping the spatial clustering of livestock behavior.

Overall, the interaction between vegetation types and cattle behavior formed a systematic gradient in terms of grazing pressure and habitat utilization. Open vegetation formations with low canopy cover were associated with high grazing pressure, whereas forested habitats were characterized by lower utilization intensity and limited grazing activity. Field observations further demonstrated that cattle perform functional transitions among vegetation types throughout their daily movement cycles. Maquis and phrygana formations served as the principal grazing habitats, while forested areas functioned primarily as resting and shading zones. Ruderal–segetal habitats provided supplementary forage resources along movement corridors, whereas grasslands experienced the highest grazing intensity among all vegetation formations.

Species-level observations revealed pronounced selective foraging behavior. Cattle preferentially consumed oak species, olive leaves, grasses (Poaceae), and legumes (Fabaceae), whereas species such as oleander, chaste tree, and plants possessing thorny or densely pubescent leaf structures were generally avoided. These observations indicate that grazing behavior is influenced not only by vegetation structure but also by species-specific morphological and chemical characteristics that determine forage preference and palatability.

Producer perceptions indicated that the environmental impacts of the traditional silvopastoral cattle production system were predominantly associated with ecosystem service provision (Table 6).

Among the reported benefits, fire risk mitigation and natural fertilization emerged as the most frequently cited ecosystem services. Contributions related to vegetation control and olive grove maintenance were reported less frequently, whereas soil aeration represented the least commonly reported benefit category. This distribution suggests that producers perceive the traditional silvopastoral cattle production system not merely as a livestock production activity but also as a multifunctional provider of ecosystem services.

Reports of environmental damage were generally limited in frequency and magnitude (Table 7).

The vast majority of participants reported that the traditional silvopastoral cattle production system does not generate substantial environmental damage. Among the relatively few negative impacts reported, damage to olive groves was cited more frequently, whereas impacts on water resources and cultivated land were reported only

sporadically. These findings suggest that, within the study area, perceived ecosystem services substantially outweigh perceived environmental pressures in stakeholder evaluations of the system.

The CEII results, derived from the integrated assessment of benefit and damage components, revealed considerable socio-ecological heterogeneity among districts (Table 8).

The quartile-based classification indicates that some districts are clustered within the high and very high interaction categories, whereas others are concentrated in the low interaction classes. This pattern suggests that the environmental effects of the traditional silvopastoral cattle production system are not homogeneously distributed across the study area, but instead vary in response to local environmental conditions, land-use configurations, and management practices.

Information regarding the $\pm 10\%$ and $\pm 20\%$ perturbation scenarios applied to the benefit score is presented in Table 9.

This finding indicates that the index exhibits low sensitivity to reasonable deviations from the equal-weighting assumption and that the results are structurally stable. Although the perturbation scenarios produced expected directional changes in CEII values, they did not alter the relative ranking of districts.

To assess ranking stability, Spearman's rank correlation analysis was performed, which demonstrated perfect agreement between all scenarios and the baseline ranking (Table 10).

Spearman's rank correlation coefficient was used not for inferential hypothesis testing, but as a robustness metric to assess the stability of ranking patterns under alternative scenarios. Given the limited number of spatial units after aggregation, the analysis does not aim to test statistical associations, but to evaluate whether the ordinal structure of observations is preserved across different model specifications. Accordingly, Spearman's ρ was computed to examine rank invariance under $\pm 10\%$ and $\pm 20\%$ perturbations.

As shown in Table 10, Spearman's ρ remained equal to 1.00 across all scenarios, indicating perfect rank stability. This result confirms that the relative ordering of spatial units is fully invariant to proportional changes in input values, thereby demonstrating the robustness of the proposed ranking framework.

The results indicate that the CEII exhibits a high degree of resistance to reasonable variations in weighting assumptions and consistently reflects spatial differentiation across the study area. In this context, the CEII can be considered a composite indicator that effectively represents socio-ecological interaction patterns and demonstrates structural robustness against methodological uncertainty.

Water provision in settlements where the traditional silvopastoral cattle production system is practiced relies predominantly on natural water sources (Table 11).

Water source usage patterns indicate that spring water constitutes the dominant form of water supply, while ponds serve as an important secondary and complementary source. In contrast, alternative supply modes such as piped water, streams, and tractor-based water transportation remain limited in use. These findings demonstrate that water accessibility within the silvopastoral production system is strongly shaped by the underlying natural hydrological structure.

SWAI results reveal pronounced spatial heterogeneity in water accessibility across settlements (Table 12).

In some settlements, very high water accessibility levels were observed, whereas others were predominantly concentrated in the moderate and high categories. This variation cannot be explained solely by differences in water source diversity; rather, it is also associated with the accessibility quality of resources and the operational dependency structure of the system.

The Resource Composition Score (RCS) indicates that natural and highly continuous water sources play a dominant role across the system. However, the primary driver of inter-settlement variation appears to be the Tractor Dependency Ratio (TDR). Settlements with higher reliance on tractor-based water transportation tend to exhibit lower SWAI values, whereas settlements without such dependency show higher levels of water accessibility. This pattern demonstrates that water accessibility is determined not only by resource availability but also by logistical sustainability and operational capacity.

Overall, these results suggest that in a substantial proportion of the study area, silvopastoral systems benefit from relatively advantageous access to natural water sources. However, tractor dependency observed in some settlements points to structural vulnerabilities in water provisioning systems. The SWAI findings highlight the need to jointly consider the spatial distribution of water resources and the management practices governing production systems.

When interpreted alongside CEII results, settlements with higher water accessibility levels tend to exhibit stronger socio-ecological interaction profiles. This indicates that SWAI, when used in conjunction with CEII, provides a complementary framework for the integrated assessment of both resource accessibility and environmental interaction dimensions in silvopastoral systems.

Discussion and Conclusions

This study demonstrates that the traditional silvopastoral cattle production system in the Beşparmak Mountains operates as a multidimensional socio-ecological system. The system is shaped by reciprocal interactions among vegetation structure, land-use patterns, animal behavior, and human management practices, indicating that grazing

is not merely a production-oriented activity but also a key mechanism actively structuring agro-silvopastoral system organization and ecosystem processes.

In particular, the heterogeneous floristic structure developed on gneissic bedrock influences the spatial mobility and foraging strategies of cattle, thereby promoting selective grazing behavior. This pattern is consistent with the behavioral grazing literature (Bailey et al. 1996; Bailey 2004; Launchbaugh and Howery 2005).

The findings indicate that grazing behavior is shaped not only by forage availability but also by microclimatic conditions and environmental comfort. The use of forested areas as low-grazing-pressure zones but high-intensity resting habitats suggests that these habitats primarily function as microclimatic regulators rather than forage production sites. In particular, the preference for shaded areas during periods of high summer temperatures is consistent with studies emphasizing the critical role of silvopastoral systems in thermal stress mitigation and animal welfare (Plieninger et al. 2014; Jose and Dollinger 2019; Pezzopane et al. 2019; Lemes et al. 2021; Goncherenko et al. 2024).

From a feeding behavior perspective, the preference of cattle for grasses and legumes, alongside the avoidance of toxic plant species, indicates that foraging decisions are not driven solely by nutritional content, but are also influenced by plant secondary metabolites and physiological feedback mechanisms. This pattern is consistent with studies demonstrating that feed selection in ruminants is shaped by learning processes and post-ingestive feedback mechanisms (Villalba and Provenza 2007, 2009), and suggests that selective grazing may function as a regulatory ecological filter influencing plant community composition (Provenza 1995).

The system also exhibits a substantial capacity for ecosystem service provision. Among the benefits reported by producers, fire risk reduction and natural fertilization were particularly prominent. Indeed, studies conducted in the Mediterranean basin have demonstrated that grazing reduces fire risk by decreasing flammable biomass (Oikonomou et al. ; Ribeiro et al. 2023; Lovreglio et al. 2024). Therefore, it can be argued that local perceptions reflect scientifically supported ecological processes. In addition, the recycling of nutrients through animal excreta (feces and urine) represents a critical mechanism for sustaining nutrient cycling in pasture ecosystem (Dubeux Jr et al. 2007; Lucci 2019; Teague and Kreuter 2020).

However, the limited number of reported negative impacts on olive groves indicates that potential land-use conflicts within agro-silvopastoral systems are not entirely eliminated. Therefore, controlled grazing practices, temporary fencing systems, and the protection of young trees during early developmental stages are considered critical management strategies for ensuring successful tree establishment and growth (Lopez-Sanchez et al. 2020;

Dimande et al. 2024). This highlights that the sustainability of the system depends not only on ecological processes but also on targeted management interventions.

The results obtained from the developed CEII index indicate that environmental performance is not spatially homogeneous, with pronounced differences observed among districts. This finding suggests that environmental performance cannot be explained solely by livestock presence, but is also determined by land-use patterns and management practices. The literature similarly supports the view that ecosystem services in silvopastoral systems exhibit marked spatial variability (Bagella et al. 2020; Amorim et al. 2023; de Macedo Carvalho et al. 2024).

In addition, the stability of CEII rankings across alternative weighting scenarios indicates that the index is methodologically robust and meets the sensitivity analysis criteria proposed by the OECD (2008) and Saisana et al. (2005).

SWAI analyses demonstrate that not only the presence of water sources but also their accessibility is a key determinant of system performance. The dominance of spring water and ponds indicates that the production system is strongly dependent on the natural hydrological infrastructure. In regions reliant on water transport, increased logistical costs emerge as a major constraint on system sustainability. Water accessibility is one of the primary variables shaping cattle movement patterns and grazing intensity across rangelands. In particular, recent GPS-based studies have shown that the location and accessibility of water sources are among the most influential factors determining cattle movement, grazing distribution, and pasture utilization intensity (Rivero et al. 2021; Maroto-Molina et al. 2023). In light of these findings, the most critical interventions for enhancing system sustainability include the rehabilitation of water sources, the development of small-scale ponds, the promotion of rainwater harvesting practices, and the implementation of rotational grazing systems. Such interventions are expected to support vegetation recovery and contribute to biodiversity conservation.

In conclusion, this study demonstrates that the traditional silvopastoral cattle production system in the Beşparmak Mountains extends beyond a conventional production practice and functions as a dynamic and adaptive socio-ecological system shaped by human–animal–environment interactions. The system is strongly associated with environmental variables such as vegetation structure, topographic heterogeneity, water accessibility, and land-use patterns, while simultaneously reshaping these environmental conditions through feedback mechanisms driven by animal behavior. This reciprocal interaction indicates that grazing is not merely a resource-extractive activity, but an active ecological process that regulates the structure and functioning of the foraging landscape.

Within this framework, access to water, the presence of shading habitats, and microhabitat availability emerge as key controlling factors that determine the spatial distribution of grazing pressure. The system also provides

important ecosystem services, including fire risk reduction, biomass control, and the maintenance of nutrient cycling processes; however, the sustainability of these benefits is constrained by structural thresholds related to water resource management, pasture integrity, and the spatial balance of grazing pressure.

In this context, the composite indicators developed in this study, namely CEII and SWAI, play a critical role in quantitatively representing the multidimensional structure of the socio-ecological system. While existing ecosystem service-based indices in the literature (Sullivan 2002; Garriga and Foguet 2010) are predominantly unidimensional or infrastructure-oriented, CEII explicitly captures benefit and damage interactions through an event-based framework grounded in participatory and field-derived data. SWAI, in turn, assesses water accessibility not only in terms of resource availability but also by incorporating structural vulnerability components such as tractor dependency. In this respect, both indices move beyond conventional sustainability indicators by jointly addressing the functional and structural dimensions of socio-ecological systems through an integrated analytical framework.

Overall, the traditional silvopastoral cattle production system can be regarded as a distinctive agro-silvopastoral production model characterized by a high capacity for ecological adaptation despite low external input use, while simultaneously supporting multiple ecosystem functions. Rather than being defined solely by production outputs, the system operates through multidimensional ecological processes, including the continuity of ecosystem services, the conservation of biodiversity, the regulation of fire regimes, and the maintenance of nutrient cycling. In this sense, unlike conventional intensive livestock systems, it represents a holistic land-use form that integrates resource-use efficiency with ecological integration within a unified structural framework.

In this regard, the system functions not only as an economic production activity in rural areas but also as a regulatory mechanism that supports ecosystem functions and ensures structural continuity within grazing systems.

In particular, its interaction with heterogeneous landscapes and natural vegetation composition enhances adaptive response capacity within the grazing-habitat matrix and strengthens system resilience to environmental variability.

This highlights the potential of traditional silvopastoral cattle production systems to act as multifunctional buffering mechanisms against both ecological dynamics and socio-economic shocks.

From this perspective, framing this system within a rural resilience approach helps to reveal not only its current production functions but also its long-term capacity for ecosystem service provision. Accordingly, traditional silvopastoral cattle production should not be regarded merely as a conventional practice in rural development policies, but rather as a strategic agro-silvopastoral system with adaptive management capacity. Integrating such

systems into agroecological planning processes offers important opportunities for both natural resource conservation and the diversification of rural livelihoods.

Acknowledgments

The authors would like to express their sincere gratitude to the General Directorate of Agricultural Research and Policies (TAGEM) for their financial and institutional support for the project (Project No: TAGEM-19/AR-GE/14), which made this study possible. We also gratefully acknowledge the livestock producers and local stakeholders who contributed to the fieldwork and generously shared their knowledge and time throughout the study.

Statement of Animal Rights

No animals were used, handled, or subjected to any experimental procedures in this study. The findings presented in this manuscript are based solely on data obtained through semi-structured interviews conducted with animal breeders. As the study involved only human participants providing information and did not include any intervention or experimentation involving animals, approval from an animal ethics committee was not required.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Funding

This research was financially supported by the General Directorate of Agricultural Research and Policies (TAGEM), Republic of Türkiye, under Project No. TAGEM-19/AR-GE/14.

Data Availability statement

The datasets generated and/or analysed during the current study are not publicly available due to institutional and project data governance policies. However, they can be made available from the supporting institution upon reasonable request and with appropriate authorization from the project coordinator.

Authors contributions

O.K. and I.C. contributed to conceptualization of the study. O.Y., N.A., and O.E. developed the methodology. O.Y. was responsible for index design. O.Y. and N.A. performed the formal analysis. N.A., O.K., and I.C. conducted the investigation. N.A., I.C., O.K., and O.Y. contributed to data curation. O.K., O.Y., and I.C. wrote the original draft of the manuscript. N.A., I.C., O.K., O.Y., and O.E. contributed to writing, reviewing, and editing the manuscript. N.A. and O.Y. prepared the visualizations. All authors reviewed and approved the final manuscript.

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