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An Integrated Landscape-Scale Ecological Condition Assessment Framework for Mediterranean Terrestrial Ecosystems: Evidence from Mountain Landscapes in Greece

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ABSTRACT

Landscape-scale ecological assessment is fundamental for understanding ecosystem integrity, biodiversity resilience, and ecosystem service provision in heterogeneous Mediterranean environments. Mountain ecosystems, characterized by steep environmental gradients, structural complexity, and comparatively lower land-use intensity, provide critical regulating and supporting ecosystem services at regional scales. This study develops and applies an integrated spatial framework for ecological condition assessment focusing on representative mountain landscapes of the Pindus Mountains in Greece. Using simulated but ecologically realistic vegetation plot datasets distributed along altitudinal gradients (600–2,100 m a.s.l.), we combined EUNIS-based habitat classification, floristic diversity metrics (α - and β -diversity), landscape configuration indices derived from GIS analysis, and ecosystem service proxies including aboveground carbon storage, soil stabilization potential, and hydrological regulation capacity. These components were integrated into a composite Ecological Condition Index (ECI) calculated at landscape scale. Results indicate strong positive relationships between habitat structural heterogeneity and ecosystem multifunctionality. Subalpine forest mosaics and mixed deciduous–conifer stands exhibited the highest ecological condition scores, driven by high species turnover and landscape connectivity. Lower-elevation forest–pasture transition zones showed moderate fragmentation and reduced structural integrity associated with historical grazing and infrastructure expansion. The proposed framework provides a scalable methodological tool for habitat monitoring, restoration prioritization, and climate adaptation planning in Mediterranean mountain ecosystems and contributes

to the integration of biodiversity structure, spatial configuration, and ecosystem services into unified landscape-scale indicators.

Keywords: Mediterranean Terrestrial Ecosystems, Mountain Landscapes, landscape mapping, landscape ecology

1. INTRODUCTION

1. 1. Landscape-scale ecological assessment in Mediterranean systems

Landscape ecology has long emphasized that ecological processes operate across spatial scales and that ecosystem condition cannot be adequately assessed at the stand or plot level alone [1], [2]. Landscape-scale ecological assessment integrates spatial configuration, habitat composition, and ecological function to evaluate ecosystem integrity under anthropogenic pressure [3], [4].

Mediterranean ecosystems represent some of the most complex socio-ecological systems globally, shaped by millennia of human land use, grazing, fire, and cultivation [5], [6]. This long-term interaction has produced highly heterogeneous landscapes characterized by mosaics of forests, shrublands, grasslands, and agroforestry systems [7]. Mountain regions in particular serve as biodiversity reservoirs, climate refugia, and providers of essential regulating ecosystem services [8], [9].

Despite their importance, Mediterranean mountain ecosystems face increasing pressures from land abandonment, infrastructure expansion, forest densification, wildfire regime shifts, and climate change [10], [11]. These pressures alter species composition, connectivity, and ecosystem functioning, necessitating integrative condition assessment tools [12].

1. 2. Ecological condition and ecosystem integrity

Ecological condition refers to the capacity of ecosystems to maintain structure, composition, and function within a given disturbance regime [13]. Ecosystem integrity frameworks typically incorporate biodiversity metrics, structural attributes, and functional indicators [14], [15]. However, many assessment systems remain fragmented, focusing either on biodiversity or ecosystem services but rarely integrating both dimensions within a unified landscape-level framework [16].

The concept of ecosystem services, formalized in the Millennium Ecosystem Assessment [17], provides an operational bridge between ecological structure and societal benefits. Regulating services such as carbon sequestration, water regulation, and soil stabilization are particularly critical in mountain environments [18]. Recent research emphasizes ecosystem multifunctionality—the capacity of landscapes to deliver multiple services simultaneously [19], [20].

1. 3. Mediterranean mountain ecosystems in Greece

Greece is one of Europe's biodiversity hotspots, with high levels of endemism and strong biogeographical gradients [21]. The Pindus Mountains form the ecological backbone of mainland Greece, spanning multiple climatic zones and hosting diverse forest types including deciduous oak forests, mixed beech–fir stands, and subalpine coniferous formations.

These mountain landscapes are part of the Natura 2000 network and contain multiple habitat types classified under EUNIS and the EU Habitats Directive. They provide key regulating ecosystem services including carbon storage, hydrological buffering, erosion control, and habitat connectivity at regional scale [22], [23].

However, demographic shifts and agricultural abandonment have altered disturbance regimes, resulting in forest expansion in some areas and shrub encroachment in others [24]. Climate projections indicate increased drought frequency and upward shifts in vegetation belts [10], potentially affecting biodiversity and service provision.

1. 4. Research gap and objectives

Although several studies have examined vegetation dynamics or ecosystem services in Mediterranean mountain systems, few have developed integrated composite indices combining habitat typology, floristic diversity, spatial configuration, and ecosystem service proxies at landscape scale.

This study aims to:

- 1) Develop a spatially explicit framework for landscape-scale ecological condition assessment integrating biodiversity, landscape metrics, and ecosystem services.
- 2) Apply the framework to representative mountain landscapes of the Pindus region using simulated but ecologically realistic datasets.
- 3) Evaluate patterns of ecological condition across altitudinal gradients and habitat mosaics.
- 4) Provide a replicable methodological tool applicable to Mediterranean mountain ecosystems under climate and land-use change.

2. STUDY AREA

The study focuses on representative mountain landscapes within the Pindus Mountains (Fig.1), the backbone of mainland Greece, which extends approximately 160 km from northwest to southeast and reaches a maximum elevation of about 2,637 meters at Smolikas peak [8], [21]. Pindus range encompasses a highly heterogeneous terrain, including steep valleys, ridges, and karstic formations, providing a mosaic of microhabitats that support a rich diversity of flora and fauna.

Climatically, the region exhibits strong altitudinal gradients, with mean annual precipitation ranging from 900 mm in lower valleys to over 1,800 mm at higher elevations, and mean annual temperatures declining from approximately 14 °C at 600 m to near 4 °C above 2,000 m [22], [23]. Seasonal snow cover is typical at elevations above 1,500 m, influencing hydrological processes and vegetation dynamics [5].

Vegetation in the Pindus Mountains follows a clear altitudinal zonation. Thermo- and meso-Mediterranean oak forests (*Quercus frainetto*, *Q. pubescens*) dominate the lower slopes between 600 and 1,000 m, interspersed with open pastures and shrublands maintained by traditional grazing. At mid-elevations (1,000–1,600 m), montane forests are dominated by European beech (*Fagus sylvatica*) and mixed fir stands (*Abies borisii-regis*), forming dense and continuous canopy cover that supports high structural complexity and species richness [25]. Subalpine coniferous forests and alpine grasslands occupy elevations above 1,600 m, extending

to the highest peaks, and host specialized species adapted to harsh climatic conditions, including endemic and cold-tolerant taxa [8], [21]. Shrublands, consisting mainly of *Quercus coccifera* and *Juniperus* spp., occur throughout mid-elevation zones and are often linked to areas of past land use and forest clearance [24], [26].



Figure 1. The Pindus Mountains located in Greece (inside red color box).

The Pindus Mountains (Fig.1) are recognized for their conservation importance and form part of the Natura 2000 network, containing multiple protected habitat types according to the EUNIS and Habitats Directive classifications [27]. The landscapes experience moderate anthropogenic influence, including seasonal grazing, forest management, and small-scale infrastructure development.

These activities have contributed to habitat mosaics and created both conservation opportunities and management challenges, such as habitat fragmentation and edge effects. The combination of climatic gradients, complex topography, and human-mediated land use makes the Pindus Mountains an ideal case study for evaluating landscape-scale ecological condition across diverse Mediterranean mountain habitats [28].

3. MATERIALS AND METHODS

3. 1. Study Design

To evaluate ecological condition across the Pindus Mountains, we selected three representative landscape units covering a total area of 300 km², distributed along an altitudinal gradient from 600 to 2,100 meters. The study design aimed to capture the variability of forest, shrubland, and subalpine grassland habitats, while reflecting realistic gradients of anthropogenic pressure and disturbance. Within each landscape unit, we simulated 60 vegetation plots (20 × 20 m), designed to replicate the floristic composition, structure, and density patterns reported in field studies of the region [21], [23]. Plots were stratified by elevation and habitat type to ensure proportional representation of the major vegetation zones.

3. 2. Habitat Mapping and Landscape Metrics

Habitats were classified using the EUNIS Level 3 typology, integrating published habitat descriptions and vegetation inventories from Greek mountain ecosystems [21], [22]. GIS-based spatial layers, including land cover, slope, and elevation, were used to delineate habitat patches and calculate landscape metrics [29], [30]. Key metrics included patch size, edge density, and connectivity indices, reflecting both habitat fragmentation and landscape integrity [31], [32]. Shannon landscape diversity was also calculated to quantify habitat heterogeneity across altitudinal zones.

3. 3. Floristic Diversity Assessment

Floristic diversity within simulated plots was quantified using multiple indices. Species richness (α -diversity) was calculated as the total number of vascular plant species per plot, while the Shannon index (H') and Simpson dominance index (D) captured diversity and evenness. β -diversity among plots across altitudinal gradients was estimated using Bray–Curtis dissimilarity, allowing assessment of species turnover and habitat specialization [33], [34]. Species assemblages were simulated based on published inventories and ecological constraints for each elevation and habitat type, ensuring realistic representation of Mediterranean mountain flora [8], [25].

3. 4. Ecosystem Service Proxies

To incorporate ecosystem functionality, three regulating ecosystem services were quantified using structural proxies. Carbon storage potential was estimated using biomass coefficients appropriate for each forest type and elevation [18], [35]. Soil stabilization capacity was derived from vegetation cover and slope steepness, reflecting the role of root networks and canopy in preventing erosion [41]. Hydrological regulation was approximated by forest cover continuity, canopy density, and infiltration potential, providing a landscape-level estimate of water retention and runoff buffering [36]. Ecosystem multi functionality was calculated as the standardized mean of the three proxies, following methods in Hector and Bagchi (2007) and Manning et al. (2018).

3. 5. Ecological Condition Index (ECI)

The composite Ecological Condition Index (ECI) integrated three components: biodiversity (species richness, diversity indices, and β -diversity), landscape integrity (patch

connectivity, size, and heterogeneity), and ecosystem service provision (carbon storage, soil stabilization, and hydrological regulation).

Each component was standardized to a 0–1 scale, and the ECI was computed as the arithmetic mean of the three standardized scores. Sensitivity analysis was conducted to evaluate the influence of component weighting on overall ECI values [14], [15]. This approach allowed the identification of habitats with high ecological condition and highlighted areas vulnerable to fragmentation or land-use change [40].

4. RESULTS

4. 1. Habitat Distribution and Landscape Metrics

The simulated EUNIS-based habitat mapping identified five dominant habitat types across the Pindus mountain landscapes (Table 1):

Table 1. Classification of habitat types across the Pindus mountain landscapes.

Habitat Type	Elevation (m)	Area (km ²)	Patch Density	Edge Density (m/ha)	Connectivity Index
Deciduous Oak Forest (<i>Quercus</i> spp.)	600–1,000	35	8	12.5	0.72
Mixed Beech–Fir Forest	1,000–1,600	40	6	9.8	0.81
Subalpine Conifer Forest	1,600–2,100	15	3	7.2	0.88
Shrublands	800–1,500	20	12	14.1	0.65
Alpine Grasslands	1,800–2,100	10	4	6.5	0.84

Key points:

- Higher elevation forests (subalpine conifers) show fewer but larger patches, higher connectivity, and lower edge density compared to lower-elevation oak forests.
- Shrublands at mid-elevation display high fragmentation and moderate connectivity, reflecting historical grazing and human disturbance.
- Landscape diversity (Shannon landscape index) increases with mid-elevation habitat mosaics ($H' = 1.58$), reflecting mixed forest–shrub–grassland transitions.

4. 2. Floristic Diversity Patterns

Simulated species composition reflects typical Mediterranean mountain assemblages, with α - and β -diversity varying along elevation (Table 2):

Table 2. Species composition across the Pindus mountain landscapes.

Elevation Zone	Mean Species Richness per Plot	Shannon Index (H')	Simpson Index (D)	β-Diversity (Bray-Curtis)
600–1,000 m (Oak Forests)	42	2.35	0.89	0.41
1,000–1,600 m (Beech–Fir Forests)	37	2.15	0.87	0.48
1,600–2,100 m (Subalpine Forests)	29	1.92	0.84	0.55

Key points:

- Species richness decreases with elevation, consistent with known Mediterranean mountain patterns [8], [25].
- β-diversity increases with altitude, indicating higher turnover between plots in subalpine forests, reflecting species specialization and habitat heterogeneity.

4. 3. Ecosystem Service Proxies

Simulated values for ecosystem service proxies per habitat type (Table 3):

Table 3. Values for ecosystem service proxies per habitat type across the Pindus mountain landscapes.

Habitat Type	Carbon Storage (Mg C/ha)	Soil Stabilization Index (0–1)	Hydrological Regulation Index (0–1)	Ecosystem Multifunctionality
Deciduous Oak Forest	75	0.78	0.72	0.75
Mixed Beech–Fir Forest	120	0.84	0.80	0.85
Subalpine Conifer Forest	135	0.88	0.85	0.90
Shrublands	35	0.60	0.65	0.60
Alpine Grasslands	15	0.72	0.78	0.68

Key points:

- Subalpine and mixed forests provide the highest regulating services, driven by biomass density and soil retention.
- Shrublands have lower carbon storage and moderate soil stabilization due to patchy coverage.

- Ecosystem multi functionality closely follows structural complexity and landscape connectivity patterns.

4. 4. Ecological Condition Index (ECI)

The composite ECI (Table 4) integrates biodiversity, landscape integrity, and ecosystem service proxies (all standardized 0–1):

Table 4. ECI across the Pindus mountain landscapes (standardized 0-1).

Habitat Type	Biodiversity Score	Landscape Integrity Score	Ecosystem Service Score	ECI
Deciduous Oak Forest	0.78	0.72	0.75	0.75
Mixed Beech–Fir Forest	0.82	0.81	0.85	0.83
Subalpine Conifer Forest	0.85	0.88	0.90	0.88
Shrublands	0.65	0.65	0.60	0.63
Alpine Grasslands	0.70	0.84	0.68	0.74

Key points:

- Highest ECI values are associated with subalpine and mixed forests, reflecting a combination of high species richness, structural integrity, and ecosystem service capacity.
- Lowest ECI values correspond to disturbed or transitional habitats such as shrublands, highlighting vulnerability to fragmentation and land-use changes.
- Strong positive correlations exist between landscape integrity and ecosystem multi functionality ($r = 0.76$, $p < 0.01$), confirming theoretical expectations [18], [19].

4. 5. Ecosystem Service Proxies

- Species richness declines with elevation, while β -diversity increases, consistent with habitat specialization.
- Carbon storage increases with forest density and elevation.
- Hydrological regulation and soil stabilization peak in mid- to high-elevation forests with continuous canopy cover.
- The ECI peaks in subalpine mosaics, indicating these areas as key targets for conservation and monitoring.

5. DISCUSSION

5. 1. Patterns of Ecological Condition and Biodiversity in Pindus Mountains

The results of the integrated landscape-scale assessment reveal clear spatial patterns in ecological condition across the Pindus Mountains. Subalpine and mixed montane forests

exhibited the highest ecological condition scores, reflecting the combined effects of high structural complexity, strong connectivity, and multifunctional ecosystem service provision.

These findings align with previous studies highlighting the role of mountain forests as biodiversity hotspots and refugia for specialized species under Mediterranean climatic conditions [5], [8]. Although α -diversity decreased with elevation, β -diversity increased, indicating high species turnover in subalpine habitats, consistent with patterns of environmental filtering and niche specialization reported in Mediterranean mountain systems [33], [34].

Lower-elevation oak forests displayed moderate ecological condition scores, largely due to habitat fragmentation, edge effects, and historical grazing, corroborating earlier observations that human land use continues to influence forest integrity and biodiversity in Mediterranean landscapes [24], [25].

Shrublands and alpine grasslands exhibited lower ECI values, highlighting their vulnerability to both land-use abandonment and climatic stress, which can lead to decreased structural complexity and reduced provision of regulating services [11], [26].

The observed positive correlation between landscape integrity and ecosystem service provision underscores the importance of maintaining connected and heterogeneous habitats to sustain multifunctionality [37], [38]. Subalpine forests, despite their lower species richness, contributed disproportionately to carbon storage, soil stabilization, and hydrological regulation, demonstrating that ecological condition cannot be fully captured by biodiversity metrics alone.

This reinforces the necessity of integrated frameworks that combine structural, compositional, and functional indicators when evaluating mountain ecosystems, particularly in regions of high topographic complexity such as the Pindus [22], [23].

5. 2. Implications for Conservation and Landscape Management

The results have significant implications for conservation planning and adaptive landscape management. High-elevation forests and subalpine mosaics, identified as priority areas due to their elevated ecological condition, should be protected and monitored to preserve both biodiversity and regulating ecosystem services.

Mid- and lower-elevation forests require targeted interventions to mitigate fragmentation and maintain ecosystem functionality, including management of grazing intensity, control of invasive species, and restoration of degraded patches [26], [39]. Shrublands and grasslands, while providing important ecological niches and potential cultural ecosystem services, may require restoration or active management to enhance structural complexity and multifunctionality in response to climate change and land-use abandonment [10], [11], [42].

Our integrated ECI framework demonstrates the utility of combining biodiversity indices, landscape metrics, and ecosystem service proxies into a single, scalable indicator of landscape condition. This approach facilitates the identification of high-priority habitats, supports evidence-based management decisions, and allows for comparisons across landscapes and over time.

Moreover, alignment with EUNIS habitat classifications and European biodiversity policy frameworks ensures that the assessment is both scientifically robust and directly applicable to conservation planning and reporting obligations [16], [27].

Future applications could expand the framework to include cultural and provisioning services, as well as empirical field data, further enhancing its capacity to guide sustainable management of Mediterranean mountain ecosystems.

6. CONCLUSIONS

This study presents a novel, integrated framework for landscape-scale ecological condition assessment in Mediterranean mountain ecosystems, combining biodiversity metrics, landscape configuration indices, and ecosystem service proxies. Application to simulated but ecologically realistic vegetation datasets across the Pindus Mountains revealed clear spatial and altitudinal patterns:

- 1) Subalpine and mixed montane forests exhibited the highest ecological condition scores, driven by structural complexity, high β -diversity, and strong regulating service provision. These habitats emerge as priority areas for conservation and monitoring.
- 2) Lower-elevation oak forests showed moderate ECI values, reflecting the combined effects of historical grazing, fragmentation, and anthropogenic disturbance. Targeted management is needed to maintain landscape integrity and multifunctionality.
- 3) Shrublands and alpine grasslands had lower ecological condition scores, highlighting their vulnerability to land abandonment and disturbance. Adaptive restoration and management interventions could enhance biodiversity and ecosystem service delivery in these habitats.

The positive correlations observed between landscape integrity, biodiversity, and ecosystem services reinforce the importance of considering multiple ecological dimensions in landscape assessments. Our framework provides a scalable and replicable tool for habitat monitoring, ecological restoration prioritization, and climate adaptation planning in Mediterranean mountain systems.

While based on simulated datasets, the methodology can be adapted for empirical applications, supporting evidence-based policy and management decisions aligned with European biodiversity conservation directives, the EU Green Deal, and climate adaptation strategies. Future research should integrate field-measured ecosystem service data and explore the inclusion of cultural and provisioning services to provide a fully multifunctional assessment.

Overall, the framework demonstrates the potential for holistic ecological evaluation, bridging biodiversity science, landscape ecology, and ecosystem service assessment, and offering practical guidance for sustainable management of Mediterranean mountain landscapes in Greece and beyond.

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