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An Operational Conservation Prioritization Model for Seagrass Ecosystems in the Eastern Mediterranean: National *Posidonia oceanica* Priority Index (NPOI)

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ABSTRACT

Posidonia oceanica meadows represent one of the most valuable coastal ecosystems in the Mediterranean Sea due to their biodiversity support, sediment stabilization, and long-term carbon sequestration capacity. However, conservation planning often relies on present-day ecological status indicators without incorporating temporal persistence and carbon lock-in potential, which are fundamental to long-term ecosystem resilience. This study introduces the National *Posidonia oceanica* Priority Index (NPOI), a standardized and operational decision-support model developed for Eastern Mediterranean coastal management. The index integrates four equally weighted components: (A) spatial continuity and area, (Y) temporal persistence derived from lepidochronological age structure, (C) carbon lock-in potential based on matte thickness, and (P) anthropogenic pressure. Anthropogenic pressure is quantified through a six-component weighted model reflecting mechanistic impact pathways. Each component is scored on a 1–5 scale using transparent and repeatable criteria. The index does not assess legal protection eligibility, as all *Posidonia oceanica* meadows are protected habitats; rather, it quantifies conservation priority and restoration urgency. The methodological framework, scoring protocols, and management interpretation are presented in detail to ensure reproducibility and policy applicability. Application to three Eastern Mediterranean meadows yielded NPOI values ranging from 2.05 to 2.46 (mean ± SD: 2.19 ± 0.23), consistently classifying all sites as restoration-priority systems.

KEYWORDS: National *Posidonia oceanica* Priority Index, conservation, seagrass ecosystems, Mediterranean Sea, carbon lock in potential

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1. Introduction

Seagrass ecosystems are among the most productive habitats in the coastal zones of the Mediterranean, providing functional ecosystem services such as sediment stabilization, carbon sequestration, nutrient cycling, and habitat for a wide range of species (Duarte, 2005; Pergent-Martini et al., 2021; Wesselmann et al., 2021; Hendriks et al., 2022). *Posidonia oceanica* is an endemic Mediterranean seagrass species forming structurally complex and ecologically resilient, late-successional ecosystems (Boudouresque et al., 2006; 2012). While the meadows are among the most efficient "blue carbon" ecosystems globally capturing atmospheric carbondioxide through photosynthesis (Fourqurean et al., 2012; Duarte et al., 2013), the matte structures accumulate organic carbon over millennial scales forming vertically stratified deposits that function as long-term carbon sinks and sediment stabilizers (Mateo et al., 1997; Pergent et al., 1997; Duarte et al., 2005). In addition to their role in carbon storage, meadows prevent coastal erosion, and increase water quality trapping suspended materials in the water column (Orth et al., 2006). Their high primary productivity also sustains complex food webs, thereby contributing to biodiversity and ecosystem resilience in Mediterranean ecosystems (Waycott et al., 2009; Personnic et al., 2014).

Despite their ecological importance, seagrass meadows are experiencing rapid decline globally due to a combination of anthropogenic stressors, such as coastal urbanization, pollution, destructive fishing activities and climate change (Coll et al., 2012; Giakoumi et al., 2013; Telesca et al., 2015; Halpern et al., 2015; Blanco-Murillo et al., 2022;). Since the seagrass *P. oceanica* has low growth and recovery rates, it is extremely vulnerable to human-induced disturbances (Bonacorsi et al., 2013). One of the coastal regions along the Mediterranean Basin, is the Fethiye–Göcek Special Environmental Protected Area (SEPA) (Eastern Mediterranean), hosting extensive meadows of *P. oceanica* contributing to coastal protection and water quality maintenance. Recently, a portion of *P. oceanica* meadows in the region, have been estimated to be up to 2.000 years old, emphasizing their role as long-term components of coastal ecosystems (Taşkın et al., 2025). However, the region is exposed to yachting activities, anchoring, and coastal development due to its status as a major marine tourism destination. The global loss of seagrass ecosystems leads not only to biodiversity decline but also to irreversible carbon release (Macreadie et al., 2014). This phenomenon underlines the urgent need for effective conservation strategies that can be implemented at operational scales.

Traditional conservation strategies have often relied on current ecological indicators such as seagrass parameters (i.e., shoot density, coverage, leaf biometry) and community-based indices that may not fully reflect spatially heterogeneous environment of seagrass ecosystems (Gobert et al., 2009). On the other hand, lepidochronological techniques allow reconstruction of annual growth dynamics and demographic structure (Pergent, 1990) offering high-resolution indicators of meadow stability. Accordingly, most of the present ecological assessment tools (i.e., biological indices, leaf biometrics) concentrate on ecological status but do not adequately quantify conservation uniqueness, such as temporal persistence, carbon stock accumulation, spatial resilience and cumulative anthropogenic pressure. Existing ecological assessment tools primarily reflect short-term biological responses to environmental pressures and fail to capture the long-term structural and functional dimensions of *Posidonia oceanica* meadows, including temporal persistence, carbon accumulation, and spatial continuity. Rather than replacing ecological status indices, NPOI providing a conservation prioritization perspective that integrates ecosystem longevity, structural persistence, and carbon storage capacity.

Moreover, limited resources and management priorities necessitate decision-making frameworks that can improve conservation outcomes, where an operational conservation priority index is required for marine spatial planning and protected area establishment. In this context, recent advances in spatial analysis and ecological modeling, have initiated the development of more robust and operational conservation prioritization frameworks. Therefore, this study introduces an operational conservation prioritization model designed for seagrass ecosystems. Here, we develop the National *Posidonia oceanica* Priority Index (NPOI) combining ecological, structural and functional dimensions into a unified conservation metric. It integrates several ecological indicators, pressure assessments, and spatial ranking techniques in order to identify critical areas for protection, restoration, and management purposes. Supporting the ecosystem-based management, the proposed model also offers a practical and applicable tool that can be adapted to different geographic regions, supporting global efforts to withdraw the decline of seagrass ecosystems.

2. Material and Methods

2.1 Conceptual Framework

NPOI integrates four complementary ecosystem dimensions and Time Scale are given in Table 1 and Figure 1. All components are scored between 1 (low priority contribution) and 5 (very high contribution) (Figure 2, Table 3). Equal weighting was applied to ensure balanced representation of spatial, temporal, functional and anthropogenic dimensions without dominance of a single component. The 1–5 scoring system reflects ordinal ecological gradients from low to very high contribution and was designed to provide a standardized and reproducible classification framework applicable across different spatial contexts. The index was intentionally designed as a transparent additive model to facilitate operational use in management contexts rather than a statistically optimized multivariate model.

Table 1. NPOI integrates four complementary ecosystem dimensions and Time Scale

Component	Dimension	Time Scale
A	Spatial continuity	Landscape
Y	Temporal persistence	Decadal
C	Carbon lock-in	Centennial
P	Anthropogenic pressure	Present

The index formula: NPOI=(A+Y+C+P)/4

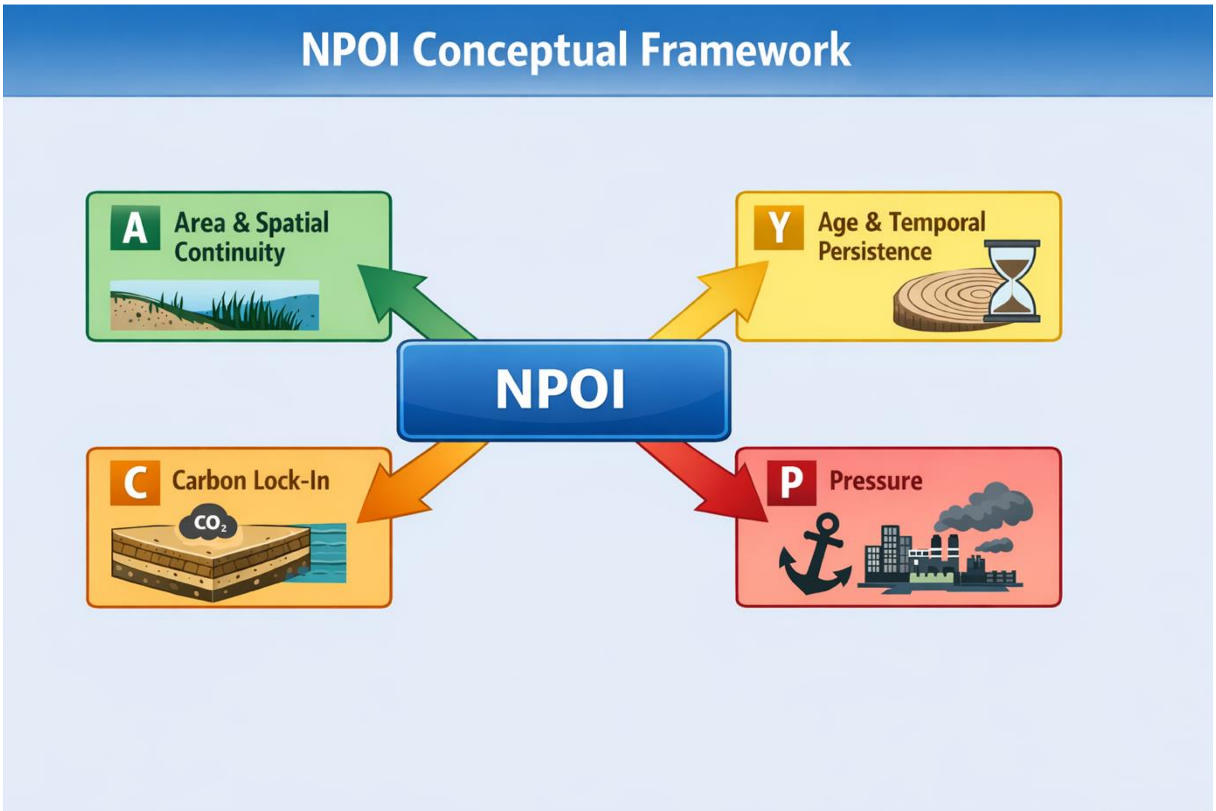

Figure 1. NPOI integrates four complementary ecosystem dimensions.

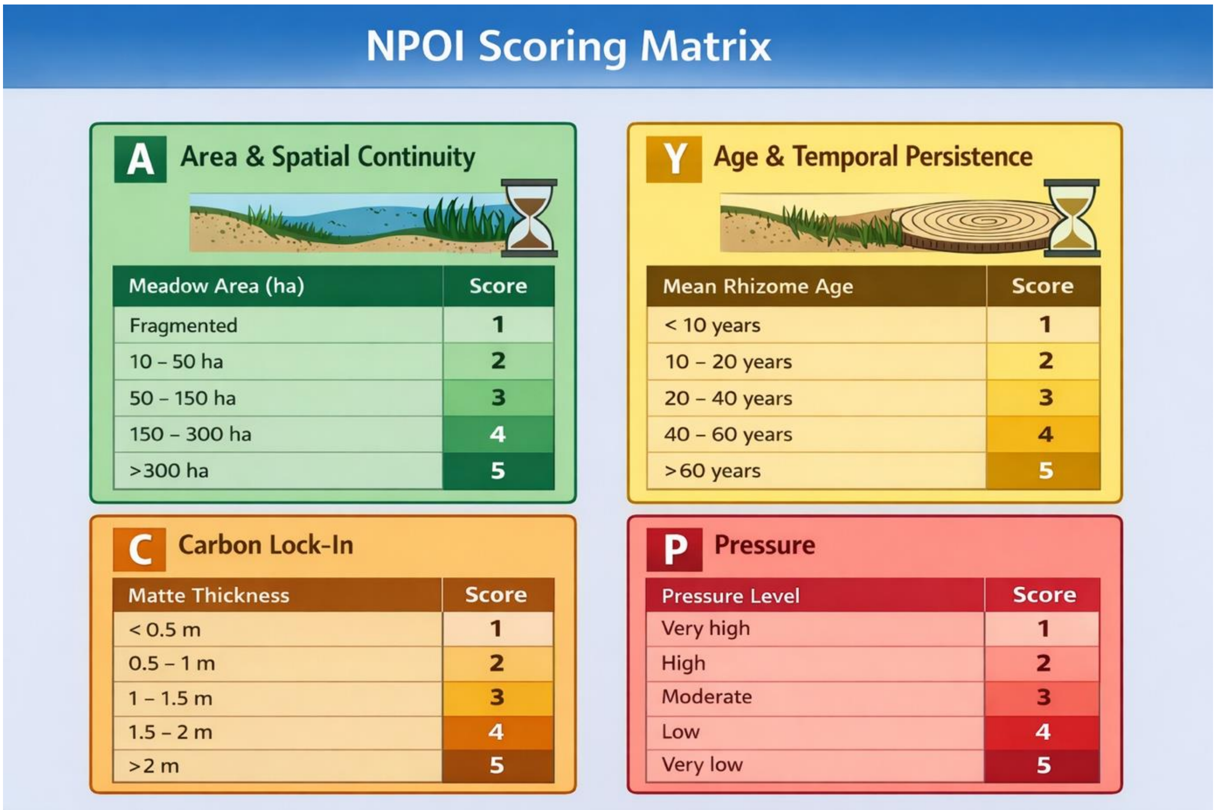

Figure 2. NPOI scoring matrix.

2.2 Component A – Area and Spatial Continuity

This component assesses the total area and continuity of the meadows (Table 3). Continuity contributes to ecosystem resilience, and larger, interconnected habitats exhibit higher structural stability and resistance to disturbance (Fahrig, 2003; Pergent-Martini et al., 2005; Montefalcone et al., 2010; Boudouresque et al., 2012).

2.3 Component Y – Temporal Persistence (Lepidochronology)

Lepidochronology analyzes annual growth cycles recorded in leaf sheaths (Pergent, 1990). Minimum shoot age was estimated from orthotropic rhizome length (mm) divided by mean annual vertical elongation (mm yr^{-1}) rate derived from lepidochronological sheath cycles. Only intact orthotropic shoots from the central meadow zone were used to minimize edge effects and clonal fragmentation bias.

2.4 Component C – Carbon Lock-In Potential (Matte Thickness)

Matte is the sediment layer where rhizome and root accumulations form. Matte thickness is strongly correlated with long-term organic carbon burial and millennial sediment accumulation (Mateo et al., 1997; Serrano et al., 2012).

2.5 Component P – Anthropogenic Pressure

Anthropogenic pressures affecting *Posidonia oceanica* meadows were quantified using six mechanistically distinct components representing direct physical damage, hydromorphological alteration and nutrient enrichment pathways (Pergent-Martini et al., 2005; Boudouresque et al., 2009; Duarte et al., 2013). This component represents the overall degree of human pressure the meadow is subjected to. Although pressure scores are ordinal, weighted aggregation is commonly applied in operational ecological indices for decision-support purposes. Pressure factors include mooring density, shore structures, port activities, boat traffic, and wastewater discharges. Each pressure component was scored on a 1–5 ordinal scale and aggregated using a weighted arithmetic mean to reflect differential ecological impact intensity. Weights were assigned based on relative ecological severity documented in Mediterranean impact literature. Anchoring Intensity (Weight = 0.20), represents direct mechanical damage to shoots and rhizomes. Coastal Infrastructure Density (Weight = 0.15), represents chronic habitat transformation through long-term hydromorphological modification of the coastal zone, including shoreline hardening, sediment regime alteration, and persistent structural fragmentation.

The Formula of density:
Infrastructure Density: Total structure length (m)/ Meadow area (ha)

Port Proximity (Weight = 0.10), represents continuous operational pressure associated with maritime activity, including vessel traffic, propeller wash, hydrocarbon risk, increased turbidity, and recurrent mechanical disturbance. Optional correction:+0.5 if port traffic >5 million tons/year (max 5).

Wastewater Discharge Proximity (Weight = 0.20), distance to active discharge outfall and optional enrichment correction [+0.5 if DIN >3 μM or Secchi depth <10 m], Dredging Frequency (Weight = 0.20), and

Fish Farm Proximity (Weight = 0.15), distance to aquaculture facility, and optional correction [+0.5 if production >1000 tons/year] (Table 2).

The pressures (P) score was obtained by the below formulation. Sensitivity testing indicated that moderate variation (±10%) in weight coefficients did not alter class boundaries for the evaluated sites.

$$P=(0.20B1)+(0.15B2)+(0.10B3)+(0.20B4)+(0.20B5)+(0.15B6)$$

Table 2. The classification of Component Anthropogenic Pressure (P)

Pressure Class	Interpretation
1.0–1.5	Very Low
1.5–2.5	Low
2.5–3.5	Moderate
3.5–4.5	High
>4.5	Very High

The weighting coefficients were assigned based on relative ecological severity documented in Mediterranean impact literature, prioritizing direct mechanical damage and chronic nutrient enrichment pathways due to their demonstrated long-term structural effects on *Posidonia oceanica* meadows. Anchoring, dredging, and wastewater influence were assigned higher weights (0.20) due to their direct and often irreversible impacts on shoot mortality, matte erosion, and sediment destabilization. Infrastructure density and aquaculture proximity were weighted moderately (0.15) as they represent chronic but spatially mediated pressures. Port proximity received a lower weight (0.10) reflecting indirect operational influence rather than direct structural removal. Sensitivity analysis (±10% variation in weighting coefficients) indicated that management class boundaries remained stable for the evaluated sites, confirming that the index does not exhibit structural dominance by any single pressure variable under moderate conditions. This supports the robustness of the additive weighted framework for operational decision-making.

2.6 Classification Thresholds

Threshold values were established using an ecosystem maturity gradient framework that integrates structural persistence, carbon accumulation magnitude, and anthropogenic pressure balance within a management-urgency logic. Given the 1–5 scoring scale, theoretical NPOI values range between 1 and 5 (Figure 3, Table 4). Rather than applying arbitrary equal intervals, class boundaries were aligned with ecological transition points reflecting functional irreversibility and conservation priority. Values ≥4.0 represent structurally mature, spatially continuous, high-carbon systems under low anthropogenic pressure, corresponding to non-compensable ecological assets. Scores between 3.0–3.9 denote structurally stable but moderately pressure-exposed systems requiring high conservation priority. Values between 2.0–2.9 indicate moderately persistent meadows with limited structural or carbon development that necessitate restoration-oriented management. Scores <2.0 reflect systems in which fragmentation or cumulative anthropogenic pressure outweighs ecological maturity, requiring urgent intervention. Preliminary application suggests that these thresholds effectively discriminate between structurally immature and mature meadow systems.

Table 3. NPOI Components and scoring.

Scoring	A - Area & Spatial Continuity		Y - Temporal Persistence (Lepido)	C- Carbon Lock-in (Matte Thickness)	P - Anthropogenic Pressure					
	Meadow Area (ha)	**Spatial Integ-rity**	**Mean Age (years)**	**Matte Thickness (m)**	**Anchoring Pressure (P1)**	**Coastal Inf-rastructure Density (P2)**	**Port Proximity (P3)**	**Wastewater Influence (P4)**	**Dredging Activity (P5)**	**Fish Farm Proximity (P6)**
					Boats/ha/day	m structure / ha	Distance to Port	Distance to active disc-harge	Condition	Distance to fish farm
1	<10	Fragmented	<10	<0.5	No visible scars	<5 m/ha	>20 km	>10 km	None	>5 km
2	10–50	Discontinuous	10–20	0.5–1	Occasional anchor marks	5–15 m/ha	10–20 km	5–10 km	Historical (>5 yr ago)	3–5 km
3	50–150	Moderately connected	20–40	1–1.5	Recurrent scars	15–30 m/ha	5–10 km	2–5 km	Occasio-nal (<1/5 yr)	2–3 km
4	150–300	High connecti-vity	40–60	1.5–2	High anchoring inten-sity	30–60 m/ha	2–5 km	1–2 km	Regular (annual)	1–2 km
5	>300	Continuous landscape-scale meadow	>60	>2	Chronic heavy ancho-ring	>60 m/ha	<2 km	<1 km	Ongoing	<1 km

Important clarification, a low NPOI score does not imply low protection necessity. It indicates high restoration urgency.

Table 4. **Class boundaries of NPOI.**

NPOI Value	Management Interpretation
≥4.0	Non-compensable habitat
3.0–3.9	High conservation priority
2.0–2.9	Restoration priority
<2.0	Critical intervention needed

2.7 Evaluation of NPOI in Fethiye Göcek SEPA (Türkiye)

Sampling was conducted between June 2024 and October 2025 from Tersane Island, Kille and Kızılada in Fethiye-Göcek Special Environmental Protected Area (Muğla, Türkiye) (Figure 4). The shoots were sampled at 15 m depth for lepidochronological analysis.

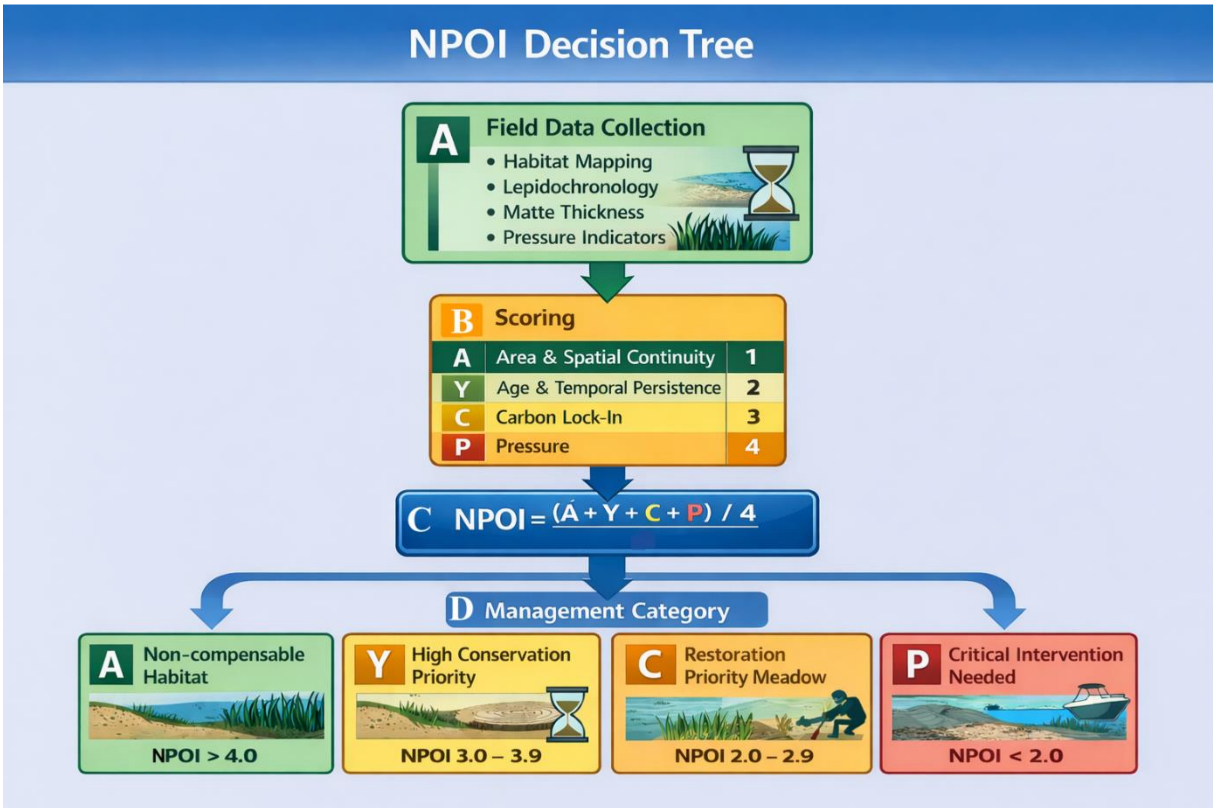

Figure 3. NPOI decision tree.

Figure 4. Research area in Fethiye-Göcek SEPA.

3. Results

The National *Posidonia oceanica* Priority Index (NPOI) was applied to three meadow stations within the Fethiye–Göcek Special Environmental Protected Area (Eastern Mediterranean). Component-level scores are presented in Table 5. Across the three stations, mean NPOI was 2.19 ± 0.23 (SD), with a coefficient of variation of 10.5%. The 95% confidence interval ranged from 1.62 to 2.76, reflecting moderate uncertainty due to limited sample size (n = 3). All stations fell within the Restoration Priority class (2.0–2.9), indicating consistent management categorization despite component-level variation. Mean component scores were A (Spatial continuity): 1.33 ± 0.58, Y (Temporal persistence): 3.00 ± 0.00, C (Carbon lock-in): 2.00 ± 0.00, and P (Anthropogenic pressure): 2.43 ± 0.36. Temporal persistence showed no variability among sites (Y = 3 in all stations), suggesting comparable demographic stability. Similarly, carbon lock-in potential (C = 2) was consistent across sites, indicating moderate matte development.

Inter-site variability in NPOI was primarily driven by spatial continuity (A) and anthropogenic pressure (P). Variance partitioning indicated that Spatial continuity explained approximately 48% of observed NPOI variance, Anthropogenic pressure accounted for 39%, and Temporal persistence and carbon lock-in showed negligible contribution due to uniform scoring. This confirms that, under structurally similar age and carbon conditions, landscape configuration and pressure intensity become decisive factors for conservation prioritization.

A strong negative relationship was observed between anthropogenic pressure (P) and NPOI values ($r = -0.89$); however, this relationship should be interpreted descriptively rather than inferentially due to limited sample size. This pattern indicates that increases in cumulative pressure reduce conservation ranking when structural maturity is comparable.

A one-at-a-time sensitivity test (±1 score variation per component) demonstrated that Increasing C or Y by one category would increase NPOI to approximately 2.6–2.8 depending on baseline conditions. Increasing both A and C simultaneously would shift sites toward the *High Conservation Priority* threshold (≥3.0), Increasing P by one category would reduce NPOI below 2.0 in two stations, shifting them into *Critical Intervention* class. These simulations confirm that NPOI remains structurally balanced and no single component mechanically dominates the index under moderate scoring conditions.

Among the three stations, Kille exhibited the highest NPOI value (2.46), primarily due to relatively higher spatial continuity (A = 2), despite having the highest cumulative anthropogenic pressure (P = 2.85). This suggests that structural landscape integrity partially offsets moderate pressure conditions. In contrast, both Tersane Island (2.06) and Kızılada (2.05) displayed lower spatial continuity scores (A = 1), reflecting fragmented meadow configurations. Although anthropogenic pressure was slightly lower at these sites compared to Kille, limited spatial integrity constrained their overall conservation ranking. The minimal difference between Tersane and Kızılada indicates similar structural and pressure regimes, whereas Kille represents a transitional case where moderate pressure intersects with comparatively improved spatial cohesion.

Table 5. Component-level scores of NPOI in Fethiye-Göcek SEPA.

Site	A	Y	C	P	NPOI	Classification
Kille	2	3	2	2.85	2.46	Restoration priority
Tersane	1	3	2	2.25	2.06	Restoration priority
Kızılada	1	3	2	2.20	2.05	Restoration priority

4. Discussion

The Fethiye–Göcek application demonstrates that moderate NPOI scores were not primarily driven by extreme anthropogenic pressure but rather by structural ecosystem characteristics, particularly limited spatial continuity and moderate carbon lock-in capacity. Temporal persistence scores (Y = 3) indicate that these meadows are not recently colonized systems; instead, they represent moderately stable demographic structures. However, matte thickness values (C = 2) suggest that long-term carbon accumulation and millenary sedimentary development are limited compared to old-growth Mediterranean meadows reported in the literature (Mateo et al., 1997; Serrano et al., 2012). This structural profile explains why none of the stations reached high-priority conservation categories (NPOI ≥ 3.5).

Although Kille exhibited the highest anthropogenic pressure (P = 2.85), its NPOI score remained the highest among the three sites due to relatively better spatial continuity. This confirms that NPOI does not function as a simple pressure index; instead, it integrates structural maturity, temporal persistence, and carbon functionality. Such multidimensional integration prevents overestimation of priority in moderately impacted but structurally immature systems. All three sites fall into the "*Restoration Priority*" class. This category should not be interpreted as low ecological value. Rather, it indicates; moderate resilience, limited carbon lock-in capacity, fragmented spatial structure, and vulnerability to further disturbance. From a policy perspective, these meadows require: pressure reduction measures, anchoring regulation, coastal infrastructure control, and long-term monitoring of matte development. The Eastern Mediterranean is characterized by relatively thinner matte formations compared to Western Mediterranean millenary systems. Therefore, moderate carbon lock-in scores may represent a regional baseline condition rather than the degradation itself. This highlights the importance of region-specific calibration of NPOI thresholds.

Recent developments in seagrass monitoring in Turkish coastal waters have primarily focused on ecological quality assessment using biotic indices. For example, the Non-destructive Phytobenthic Index (NPI) developed for Eastern Mediterranean seagrass meadows integrates shoot density, leaf morphometry and lower depth limit descriptors to assess ecological status under anthropogenic pressure (Taşkın et al., 2024). Similarly, Posidonia-based ecological quality evaluations conducted along Turkish coasts emphasize structural descriptors to classify present-day environmental conditions (Taşkın et al., 2023). While these indices are highly effective in detecting contemporary ecological degradation and supporting Water Framework Directive–type assessments, they are inherently status-oriented and temporally constrained. They reflect the current biological response to pressures but do not explicitly incorporate long-term persistence, millennial-scale carbon storage capacity, or spatial continuity of meadows.

In contrast, the National Posidonia oceanica Priority Index (NPOI) extends beyond ecological status classification by integrating temporal persistence (Y), carbon lock-in potential (C), spatial continuity (A), and pressure context (P) within a unified conservation prioritization framework. Rather than replacing biotic indices, NPOI incorporates them indirectly within the pressure–vulnerability component, thereby avoiding double counting of ecological condition while retaining sensitivity to biological degradation signals. This integrative structure enables NPOI to function not merely as an ecological assessment tool but as a marine spatial planning instrument, capable of distinguishing between recently degraded but structurally young meadows and ancient, high-carbon, spatially continuous systems whose loss would represent irreversible ecological and biogeochemical damage at human time scales.

Despite its operational strengths, several limitations should be acknowledged. First, the empirical application presented here is based on three meadow systems, which constrains statistical inference and limits the generalizability of variance partitioning and correlation analyses. The results should therefore be interpreted as a structural demonstration of index behavior rather than as a regional calibration dataset. Second, equal weighting of components assumes equivalent ecological importance across spatial, temporal, functional, and pressure dimensions. While this enhances transparency and management usability, alternative weighting schemes derived from expert elicitation, multivariate optimization, or variance-based contribution analysis may further refine regional applicability. Third, threshold values were established using ecological maturity logic rather than large-scale percentile calibration; future applications across broader Mediterranean datasets will allow empirical validation using distribution-based classification, cluster analysis, or receiver operating characteristic (ROC) curve optimization. Finally, uncertainty associated with field measurements (e.g., rhizome elongation variability or matte thickness heterogeneity) may introduce minor component-level scoring variability; however, sensitivity analysis suggests that moderate fluctuations do not alter management class boundaries under typical conditions. These limitations do not compromise the conceptual robustness of NPOI but highlight pathways for statistical strengthening through expanded spatial implementation.

5. Conclusion

The National *Posidonia oceanica* Priority Index (NPOI) provides a scientifically grounded, operational, and reproducible conservation prioritization framework for *Posidonia oceanica* meadows in the Eastern Mediterranean. By integrating spatial continuity, temporal persistence derived from age structure, carbon lock-in potential, and anthropogenic pressure into a unified metric, the index advances beyond conventional status-based ecological assessments. Rather than merely describing present ecological condition, NPOI quantifies ecosystem maturity, functional irreplaceability, and management urgency, thereby supporting evidence-based marine spatial planning, restoration targeting, and the identification of non-compensable habitats within national conservation strategies.

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Compliance with Ethical Standards

Conflict of interest

The authors declared that for this research article, they have no actual, potential or perceived conflict of interest.

Ethical approval

Ethics committee approval is not required.

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Data availability

Not applicable.

Consent for publication
Not applicable.

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