Ocean and Coastal Management 273 (2026) 108032

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Multi-criteria evaluation of blue nature-based solutions: Suitability of Posidonia oceanica in the Mediterranean Sea under climate scenarios

Ozan Ozkiper [a,b], Angelica Bianconi [a,b,c], Hung Vuong Pham [a,b], Jordan Bishop [a,b], Rémy Simide [d], Andrea Critto [a,b,*], Elisa Furlan [a,b]

[a] Department of Environmental Sciences, Informatics and Statistics, University Ca' Foscari Venice, I-30170, Venice, Italy
[b] Fondazione Centro-Euro-Mediterraneo Sui Cambiamenti Climatici, I-73100, Lecce, Italy
[c] University School for Advanced Studies Pavia, Piazza della Vittoria 15, Pavia, 27100, Italy
[d] Institut Océanographique Paul Ricard, île des Embiez, F 83140, Six-Fours-les-Plages, Italy

1. Introduction

In 2015, the UN member States identified 17 Sustainable Development Goals (SDGs) for our societies' prosperity and the planet's protection to the Horizon 2030. One of these goals, SDG 14 "Life below water", focuses on the conservation and sustainable management of the ocean. Beyond SDG 14, marine management can also contribute to other SDGs (Gissi et al., 2022) and to several IUCN societal challenges addressed through ecosystem-based approaches (Cohen-Shacham et al., 2016). The approach elaborated by the IUCN to cope with these challenges places nature at the core of the equation. Ecological processes and functions arise from biotic and abiotic interactions within ecosystems. These processes generate ecosystem services that people can benefit from, use, and value to contribute to human well-being. The materialization of ecosystem services produces societal benefits (Liquete et al., 2013; Rey et al., 2015), though their type, number, and intensity vary greatly depending on the presence and status of an ecosystem (Nicholson et al., 2021; Pérez et al., 2024).

Nature-based Solutions (NBS) is an umbrella term encompassing protection, restoration, and other sustainable management measures that address societal challenges while benefiting biodiversity (Cohen-Shacham et al., 2016; IUCN, 2020; SEEA, 2021; UNEP, 2022). With the need for climate change adaptation and mitigation, our societies require a panel of solutions. Marine and coastal (Blue) carbon ecosystems, such as seagrass, kelp forests, mangrove, and seaweeds, offer powerful opportunities to address societal challenges (O'Leary et al., 2023; Pérez et al., 2024; World Bank, 2023). However, NBS in marine ecosystems, or Blue-NBS, have been much less widely implemented than on land. This is partly due to a lack of information and understanding of marine biodiversity and the ecosystem services delivered in the field (O'Leary et al., 2023; Pérez et al., 2024). The systematic review (Martinez-Harms et al., 2015) reveals that only 14 % of the literature based on decision making for managing ecosystem services applied in marine systems, highlighting a gap that needs to be filled.

Considerable methods have been developed to assess the environmental suitability, from GIS-based approaches, such as multi-criteria decision analysis (MCDA) (Bakirman and Gumusay, 2020; Syahid et al., 2020) to machine learning techniques (e.g., random forest) (Catucci and Scardi, 2020). Among these, GIS-based approaches integrating expert and stakeholder opinions enable multi-dimensional analyses and help address data gaps in biotic and abiotic components (O'Leary et al., 2023). The combination of GIS and MCDA provides a structured framework for the complex decision-making process of NBS design involving multiple dimensions and related variables (Greene et al., 2011). Most suitability assessments of MCEs primarily focus on defining growth and survival (i.e., comfort zone/safe operating space) (Green et al., 2017; Scheffer et al., 2015), considering mainly environmental enablers. By integrating diverse criteria, GIS-based MCDA can identify habitat suitability while also supporting ecosystem-based management of marine natural capital and ecosystem services (Buonocore et al., 2020; Palumbi et al., 2009).

The Mediterranean Sea is considered one of the world's biodiversity hotspots, but also vulnerable to climate change impacts, considering its unique characteristics as the largest enclosed sea (2.5 million km^2) (e.g., limited water exchange with oceans) (Coll et al., 2010, 2012) and its endangered MCEs in both shallow and deep-water (e.g., seagrass beds, coralligenous assemblages, and maërl beds) (Coll et al., 2012; EC, 2006; MedECC et al., 2020; Zenetos et al., 2002). Additionally, terrestrial and maritime human activities (e.g., wastewater treatment, trawling, dredging, shipping activities) produce severe cumulative impacts (e.g., physical damages, invasive species) (Furlan et al., 2019; Simeoni et al., 2023). These impacts accelerate water quality degradation (e.g., an increase in turbidity) (Aslan et al., 2022; UNEP/MAP, 2012) with

* Corresponding author. Edificio Porta dell'Innovazione - Piano 2, via della Libertà 12, 30175, Venezia Marghera, VE, Italy.
E-mail address: critto@unive.it (A. Critto).

https://doi.org/10.1016/j.ocecoaman.2025.108032
Received 2 April 2025; Received in revised form 3 November 2025; Accepted 23 November 2025
Available online 29 November 2025
0964-5691/

cascading effects on MCEs, such as degrading the density and complexity of species' assemblages (Pergent-Martini et al., 2016). The Mediterranean basin shore is home to 150 million inhabitants who benefit from its ecosystem services. Because resilience and service delivery are driven by processes at the basin scale, yet implementation must align with local socio-economic contexts (IUCN, 2020; Nicholson et al., 2021; Seddon et al., 2020; SEEA, 2021), NBS planning requires mapping tools that link ecological and socio-economic dimensions.

Among the ecosystems contributing to Blue-NBS potential in the Mediterranean Sea, the most common is the *Posidonia* K.D. Koenig meadow. Endemic to the Mediterranean Sea, *Posidonia oceanica* (L.) Delile is a foundational species that forms a key habitat for many organisms. Their slow-growing, long-persisting (some aged up to 100,000 years) meadow ecosystem (Escandell-Westcott et al., 2023) provides a wide range of ecosystem services addressing six societal challenges: food security, economic and social development, disaster risk reduction, climate change adaptation, human health, and support to biodiversity. Globally, seagrasses have the capacity to store up to twice as much carbon per hectare as terrestrial forests (Fourqurean et al., 2012; World Bank, 2023). These underwater plants sequester carbon, most of which is retained in soils reaching depths of up to 4 m. Thus, seagrasses serve as a substantial carbon sink within the global carbon cycle, playing a crucial role in efforts to mitigate climate change. Although there are numerous studies on *P. oceanica* mapping (Catucci and Scardi, 2020; Houngnandan et al., 2020) the information is unevenly distributed and is rarely presented at the basin level scale (Telesca et al., 2015). Recent efforts have started to address this gap, such as the suitability mapping of *P. oceanica* in the Mediterranean basin developed in Ozkiper et al. (2024) under a baseline scenario. In addition, the relation between the presence of *P. oceanica* and the ecosystem services is largely assessed (Campagne et al., 2014; Nordlund et al., 2016; Zrelli et al., 2023) despite only local or regional information being available from mapping (Buonocore et al., 2020; Scanu et al., 2022; Vassallo et al., 2013).

This study proposes a GIS-based Multi-criteria Approach for Suitability of NBS (MAS-NBS) to indicate the environmental suitability of coastal areas in the Mediterranean eco-region for NBS implementation through *P. oceanica* seagrass meadows under different climate change (CC) scenarios. Building upon our previous baseline analysis of *P. oceanica* environmental suitability in the region (Ozkiper et al., 2024), this future scenario analysis aids in developing adaptive strategies by considering potential changes in the suitability of Blue-NBS over the long term under different scenarios (i.e., different RCPs). MAS-NBS is performed using the Analytic Hierarchy Process (AHP), a widely used MCDA technique in ecological and spatial decision-making contexts. Compared with alternative MCDA methods (e.g., TOPSIS, fuzzy logic), AHP allows explicit pairwise comparisons and integrates expert judgment transparently. The analysis builds upon the consideration of optimum and threshold values, as well as the prioritization of various environmental variables crucial for the survival and growth of seagrass meadows. The synergistic effect of AHP and GIS in the developed approach enhances the assessment of suitability for *P. oceanica* meadows and supports decision-makers in designing marine and coastal NBS. While previous assessments focused on local scales or baseline conditions, this study provides the first basin-scale Blue-NBS suitability analysis for the Mediterranean under climate scenarios, explicitly incorporating expert knowledge for forward-looking spatial planning. Ultimately, the proposed MAS-NBS model requires fewer input data and technical prerequisites compared to alternative machine learning methodologies and ecological niche models, while providing sufficient information for decision-makers in NBS spatial planning.

2. Case study area: The Mediterranean eco-region

The suitability assessment in this study was performed for *P. oceanica* meadows, a vulnerable-listed, endemic species (EU, 2016) in the Mediterranean Sea, which is one of the world's 25 biodiversity hotspot areas encompassing more than 17,000 marine species. Among seven seagrass species in the eco-region, *P. oceanica* populations have the largest and longest records, with a total area of 12,247 km^2 and a length of 11,907 km along the Mediterranean coastline. This is despite the lack of presence/absence data for 21,471 km—nearly half of the total coastline (∼46,000 km) (Telesca et al., 2015). It is estimated that *P. oceanica* has experienced a reduction of about 13–50 % in extent since 1960 (Marbà et al., 2014) due to climate change impacts and human pressures in the Mediterranean Sea.

The Mediterranean Sea basin's physicochemical characteristics show a well-oxygenated and oligotrophic oceanic system, with some exceptional coastal areas affected by river discharges, vertical mixing, and upwelling (e.g., Northern Adriatic, the Gulf of Lion) (Zenetos et al., 2002). Salinity increases eastward (i.e., average 37.5–39.5 Practical Salinity Unit (PSU)) (Coll et al., 2010) due to higher evaporation and reduced river runoff on the eastern side. The average annual sea surface temperature (SST) also shows spatial variability between 15 and 21 °C, with a higher trend in the eastern and southern parts. Moreover, it indicates significant seasonal variability, which may result in marine heatwaves during summer. Heatwaves in the Mediterranean Sea have an average duration of 15 days with a mean intensity of 0.6 °C, which can cause thermal stress on MCEs (Darmaraki et al., 2019). The Mediterranean seabed is primarily dominated by sand and muddy sand substrate with a gentle slope (Levin et al., 2014). Although the Mediterranean is the deepest enclosed sea (average 1460 m, maximum 5267 m) (Coll et al., 2010, 2012), the suitability maps were generated with a depth range between 0 and 60 m in this study (Fig. 1), reflecting the light-limitation threshold for seagrass growth, as meadows rarely extend beyond 50 m (Tursi et al., 2022).

3. Materials and methods: multi-criteria Approach for Suitability of NBS

The MAS-NBS model was developed for the assessment of environmentally suitable areas for *P. oceanica* growth. It is built on the GIS-based AHP approach, which aims to obtain a final aggregated score by combining individual weights and scores of different elements to assist decision-making processes (Chandio et al., 2013). The operational workflow and the key steps of the MAS-NBS model are summarized in Fig. 2.

3.1. Evaluation criteria and data collection

In this study, ten key environmental criteria for *P. oceanica* growth and survival representing environmental conditions in the Mediterranean coastal areas were selected. These criteria were then clustered into three thematic groups (TGs) where similar criteria were placed together: the *climate thematic group* (CTG), *geomorphology thematic group* (GTG), and *water quality thematic group* (WQTG).

The CTG represents the suitability of *P. oceanica* growth based on temperature values and their abrupt changes, such as marine heatwaves due to climate change. Thus, the evaluation criteria include average summer SST (i.e., June–July - August), thermal stress (TS) duration, and TS intensity. *P. oceanica* demonstrates tolerance to a broad range of SST (10–29 °C). Nevertheless, prolonged exposure to temperatures higher than 28.4 °C initiates TS conditions for meadows, inhibiting their growth and increasing shoot mortality (Chefaoui et al., 2017; Marbà and Duarte, 2010).

The GTG represents the NBS suitability for *P. oceanica* through the seabed characteristics. The criteria—depth, seabed slope, and substrate type—serve as essential proxies for natural coastal processes (i.e., hydrodynamic effects), light penetration, root attachment, and nutrient availability. Shallow waters (i.e., mostly 1–30 m) with soft substrates (e.g., sand) provide favorable conditions for the growth of seagrass meadows (Maida et al., 2013; Tursi et al., 2022) even if they can survive and adapt to deep water (up to 45–50 m) and other substrate types (e.g.,

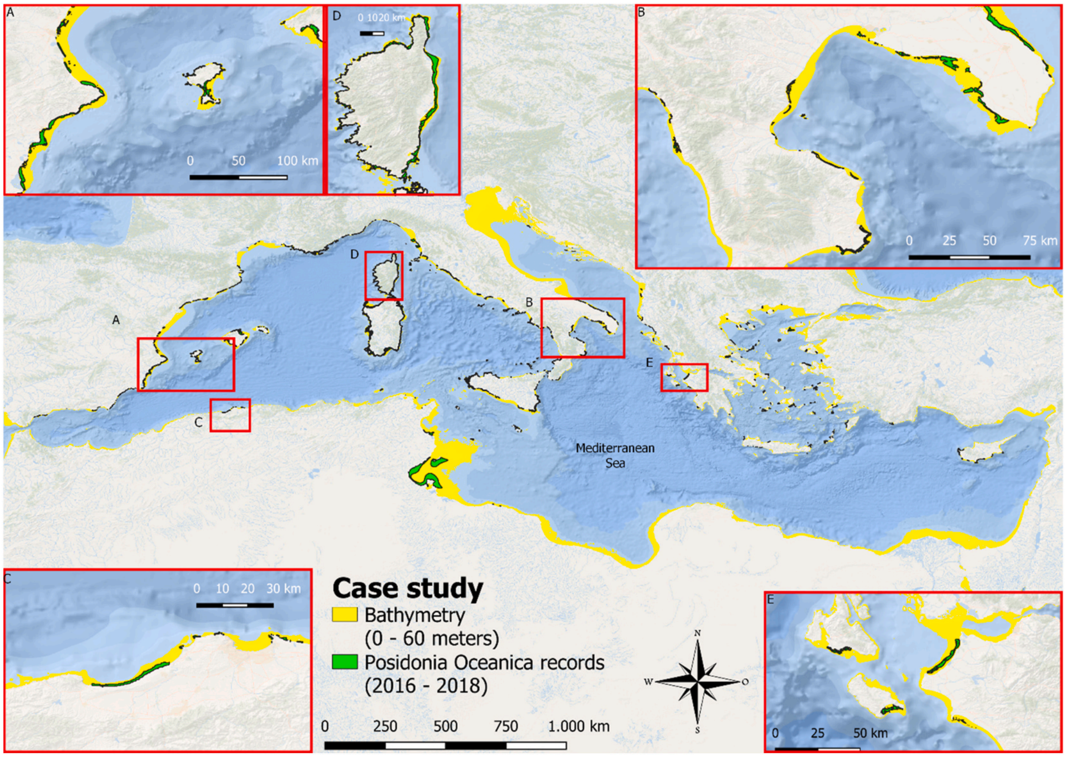

Fig. 1. Study area showing bathymetry (0–60m) with overlayed *Posidonia oceanica* records from 2016 to 2018. Specific case study areas are denoted as follows: A: Spain coasts; B: Italian coasts; C: Algeria coasts; D: Corsica island; E: Greece coasts. Adapted from Ozkiper et al. (2024).

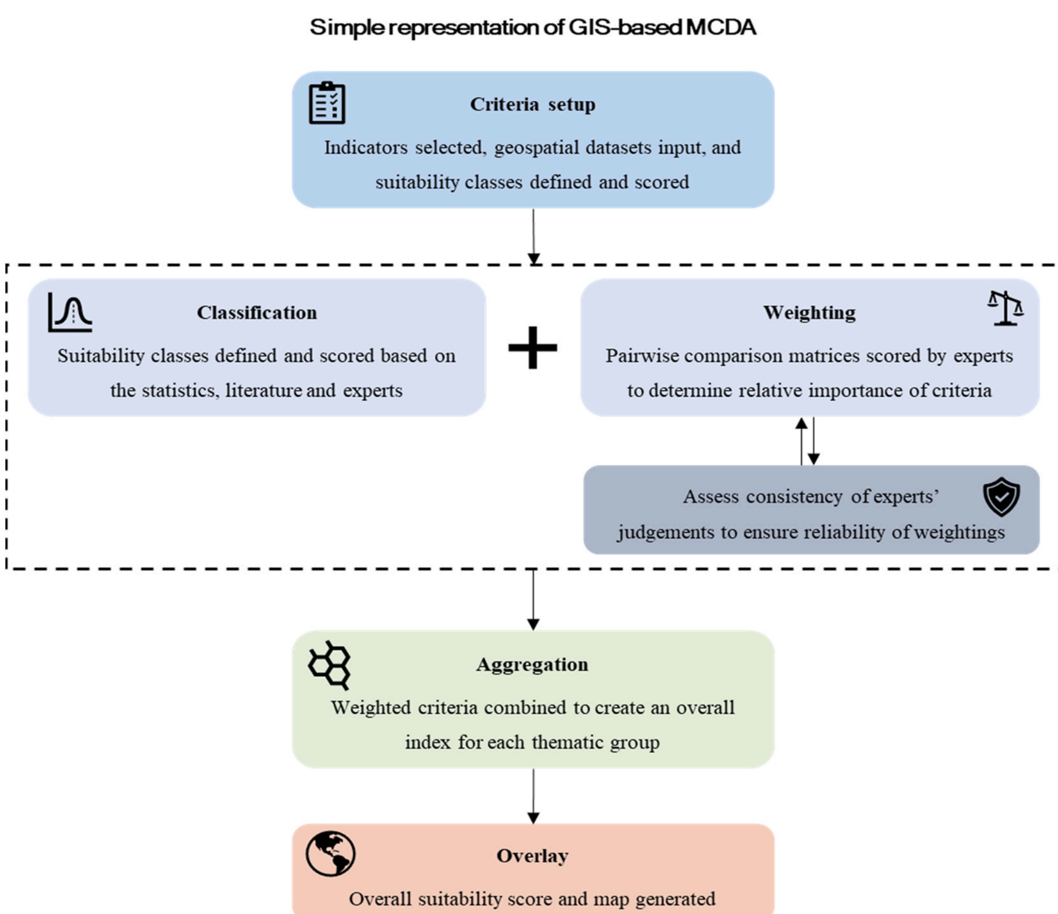

Fig. 2. Simple representation of the MAS-NBS model based on GIS-based MCDA for *P. oceanica* meadows. Adapted from Furlan et al. (2024).

rock). They prefer a gentle seabed slope as a proxy for reduced hydrodynamic effects (e.g., subtidal currents, wave forces), facilitating their regular and continuous expansion/distribution. Additionally, seagrass growth is favored by lower wave energy and stable sediment with high matte accumulation (Infantes et al., 2009).

The WQTG investigates the influence of water column characteristics on the growth and survival of *P. oceanica* meadows using the criteria diffuse attenuation coefficient (K_d), nitrate (NO_3) concentration, salinity, and dissolved oxygen (DO). Transparent, oligotrophic, and oxygenated waters provide ideal growth conditions for *P. oceanica,* whereas light limitation and extreme salinity (>40 PSU) negatively affect growth (Effrosynidis et al., 2018). It should be highlighted that the positive feedback between seagrass and WQ is an essential relationship (Ruiz and Romero, 2003). Poor water quality weakens seagrass health and limits their ability to improve it, whereas good water quality promotes both seagrass growth and the enhancement of physical, chemical, and biological conditions in the water column.

Baseline data (i.e., 2016–2018 timeframe) of the abovementioned criteria and seagrass distribution were retrieved from EMODnet data portals and the Copernicus Marine Environment Monitoring Service (CMEMS). For 2050 and 2100, SST (including derived TS duration/intensity) and salinity projections were retrieved from the CMCC Med-CORDEX RESM under RCP4.5/8.5 (Gualdi et al., 2013a, 2013b), validated within Med-CORDEX against ERA-Interim, satellite, and in-situ data. Consistency checks showed comparable spatial gradients and magnitudes between the Med-CORDEX historical period (2016–2018) and the CMEMS baseline. Future NO_3 and DO were sourced from POLCOMS–ERSEM (Copernicus Climate Data Store), which the Copernicus Marine Service has validated against long-term in-situ and satellite observations (Kay, 2020). The metadata of all datasets and further technical information are reported in Table S1 (SM1) and SM2.

To ensure methodological consistency, data collected from Med-CORDEX-CMCC were processed for integration into Copernicus datasets for future scenarios, given that the latter dataset was used under the baseline. For instance, in the case of RCP4.5 in 2050, the anomaly was computed by subtracting the values of Med-CORDEX-CMCC in 2017 from the corresponding values projected for 2050 under RCP4.5. Subsequently, these calculated anomalies were added to the CMEMS baseline data (Fig. S1 in SM2). Further technical information regarding data pre-processing is available in SM1 and SM2.

3.2. Descriptive statistics and classification

All the selected variables were normalized to obtain the final suitability scores and overlay maps for each TG in MAS-NBS. For this task, the descriptive statistics were developed by examining locality, spread, and skewness of evaluation criteria for the baseline (2016–2018), together with available knowledge of the ecosystem's comfort zone and tipping points from literature and national standards. This analysis was performed for the areas where *P. oceanica* populations are present in the Mediterranean Sea and provided a basis for expert discussions to define favorable environmental conditions for *P. oceanica*.

As shown in Table 1, a scale ranging from 1 to 10 was adapted from Ozkiper et al. (2024) and assigned to suitability classes. A score of 10 denotes the maximum score for the *very suitable* class. Scores of 8 and 6 were used to represent *suitable* and *moderately suitable* classes, respectively. As evaluation criteria approach the upper or lower limits of a species' ecological tolerance, the species' response (i.e., existence and growth in this study) is expected to become more abrupt. To address this, in alignment with seagrass expert opinions, a score of 3 was assigned to the *less suitable* class, deviating from a linear decrease in the score range (Scheffer et al., 2001). Lastly, due to the complexity of setting universal thresholds owing to seagrass meadows' adaptability to changing and unfavorable conditions, 1 was assigned for the *least suitable* class.

Depending on the nature of each criterion, the median (e.g., for

Table 1
Suitability classes defined for each selected evaluation criteria under the climate, geomorphology, and water quality thematic groups, respectively.

Thematic group	Criteria	Intervals	Suitability Class	Scores
Climate				
	Summer SST (°C)	<25.3	Very suitable	10
		25.3–26.8	Suitable	8
		26.8–28	Moderately suitable	6
		28–28.4	Less suitable	3
		>28.4	Least suitable	1
	TS duration (days)	<5	Very suitable	10
		5–7	Suitable	8
		7–21	Moderately suitable	6
		21–45	Less suitable	3
		>45	Least suitable	1
	TS intensity (°C)	0	Very suitable	10
		0–0.4	Suitable	8
		0.4–0.9	Moderately suitable	6
		0.9–1.6	Less suitable	3
		>1.6	Least suitable	1
Geomorphology				
	Depth (m)	0–1	Less suitable	3
		1–9	Suitable	8
		9–23	Very suitable	10
		23–30	Suitable	8
		30–40	Moderately suitable	6
		40–50	Less suitable	3
		>50	Least suitable	1
	Seabed slope (%)	0–1	Very suitable	10
		1–5	Suitable	8
		5–10	Moderately suitable	6
		10–15	Less suitable	3
		>15	Least suitable	1
	Substrate type	Sand and *Dead Matte*	Very suitable	10
		Muddy sand	Suitable	8
		Rock/hard and coarse	Moderately suitable	6
		Sandy mud and mixed	Less suitable	3
		Others (e.g., fine mud)	Least suitable	1
Water Quality				
	Diffuse attenuation coefficient (m^{-1})	<0.06	Very suitable	10
		0.06–0.1	Suitable	8
		0.1–0.18	Moderately suitable	6
		0.18–0.27	Less suitable	3
		>0.27	Least suitable	1
	Dissolved oxygen (mg/L)	>6.5	Very suitable	10
		6–6.5	Suitable	8
		4.6–6	Moderately suitable	6
		<4.6	Least suitable	1
	Salinity (PSU)	<33	Least suitable	1
		33–36.8	Moderately suitable	6
		36.8–38	Suitable	8
		38–38.8	Very suitable	10
		38.8–40	Suitable	8
		40–40.5	Less suitable	3
		>40.5	Least suitable	1
	Nitrate concentration (μmol/L)	<2.8	Very suitable	10
		2.8–5	Suitable	8
		5–15	Moderately suitable	6
		15–35	Less suitable	3
		>35	Least suitable	1

salinity) or the lowest/highest values (e.g., for summer SST and DO) were used to define the optimum conditions (i.e., *very suitable* class). For the threshold (i.e., *less suitable* class), the maximum or minimum values of the criteria from the descriptive statistics were discussed with seagrass experts, considering the knowledge from existing studies and reports (e.g., Marine Strategy Framework Directive) (Poikane et al., 2019; Salas et al., 2022). Figure S2 and Figure S3 in SM3 illustrate descriptive statistics of summer SST, salinity and TS variables according to the distribution of *P. oceanica* populations in the Mediterranean.

3.3. Weight derivation and aggregation

The weight derivation applied in this study follows the Analytical Hierarchy Process (AHP) methodology previously used in our baseline study (Ozkiper et al., 2024). This method utilizes expert-based pairwise comparisons, with scores assigned according to Saaty's standard scale (Tables S2–S6 in SM4) (Saaty, 1987). Seven experts specializing in seagrass ecology and NBS applications in marine environments participated in the weighting process.

The final weights were derived using normalized priority vectors calculated from the pairwise comparison matrices, as described in our baseline study (Ozkiper et al., 2024). Consistency ratios (CR) were calculated for each expert and TG to verify robustness, with CR values below the threshold of 0.1 considered acceptable, indicating a consistent and reliable weighting process. The weight calculations and consistency checks were performed for each thematic group (TG) separately. Once all the scores and final weights for each evaluation criterion were defined, a weighted sum approach was applied to generate thematic maps for each TG with aggregated suitability scores. The ranges for aggregated suitability scores of TGs were categorised into five classes as detailed in Table 2. Notably, a narrower range was applied to define the *very suitable* class, ensuring a representation of ideal suitability conditions. Details of the weight derivation and aggregation process are provided in Ozkiper et al. (2024).

3.4. Scenario and overlay analysis

Since the projection of geomorphology is not available, the scenario analysis was applied for CTG and WQTG by using future datasets of SST, salinity, NO_3, and DO. Since thermal stress variables were also derived from the SST values, only one output for each RCP scenario and year was computed by combining the future values of SST, TS duration, and TS intensity. SST values were projected daily, and both the average summer temperature and TS duration and TS intensity values for 2050 and 2100 were computed. This analysis was performed by keeping the threshold value constant for the TS event (i.e., 28.4 °C) as in the baseline scenario.

Since variables are not directly dependent on each other in the WQTG, an iterative analysis was followed for the future scenarios. Initially, only one variable was replaced using the future dataset, while keeping the other three as in the baseline, to assess its impact on the WQ suitability. This process was repeated for all the WQ variables one by one. Subsequently, various combinations of two (e.g., NO_3 + Salinity) and three criteria (i.e., NO_3 + Salinity + DO) were examined to assess their future effects on WQ suitability. Diffuse attenuation coefficient and all criteria weights were assumed to be constant (i.e., baseline values) in the scenario analysis. Then, suitability maps for CTG and WQTG were obtained for each scenario by applying the same weights in the baseline scenario.

Table 2
Suitability classes defined by their respective range.

Suitability Class	Range
Very suitable	>90
Suitable	70–90
Moderately suitable	50–70
Less suitable	30–50
Least suitable	<30

Final suitability maps were created by overlapping the TGs for each RCP and timeframe separately. In this analysis, a WQ scenario with a combination of three criteria was used. *Suitable* and *very suitable* areas from all TGs were extracted and intersected, as shown below.

$$\textit{Suitable \& Very suitable} = \textit{Suitable and very suitable areas} \; (GTG \cap WQTG \cap CTG)$$

Lastly, the obtained intersected maps were overlaid with the current distributions of *P. oceanica* to pinpoint and explore the changes in suitable areas. All maps were created using weighted sum approach with reclassification as in Table 2 within 0.001° x 0.001° grids for 2050 and 2100 under RCP4.5 and RCP8.5.

4. Results

4.1. Thematic maps under baseline and future scenarios

4.1.1. Geomorphology thematic group

Under the Geomorphology Thematic Group (GTG), depth was the most influential factor, with a weight of 0.54, emphasizing its critical role in *Posidonia oceanica* growth, as shallow areas are generally more suitable. Seabed slope and substrate type followed with weights of 0.20 and 0.26, respectively. It should be noted that no future scenarios were available for the GTG, as geomorphological characteristics are assumed to be constant. The baseline GTG suitability analysis is provided in Supplementary Information for reference (Fig. S2). Based on the baseline GTG suitability scores, approximately half of the study area was reported as *suitable* (35.6 %) or *very suitable* (14.6 %). The *moderately suitable* class, characterized by relatively higher depth values compared to *suitable* and *very suitable* areas, constituted a significant portion of the study area, encompassing more than a quarter (29.6 %). In contrast, the *less* and *least suitable* categories together accounted for less than a quarter (20.3 %) of the study area. Details for the suitability of specific regions for the GTG can be found in Ozkiper et al. (2024).

4.1.2. Water quality thematic group

In the Water Quality Thematic Group (WQTG), the diffuse attenuation coefficient, indicating the water clarity) was assigned the highest weight at 0.51, highlighting its critical influence on light availability for photosynthesis. Salinity showed the second-highest relative importance in WQTG with a weight of 0.24. Nitrate concentration and dissolved oxygen were weighted at 0.16 and 0.10, respectively. The distribution of WQTG suitability classes for the baseline scenario in the case study was previously detailed in our baseline study (Ozkiper et al., 2024) and presented in SM5 (Fig. S4). Future maps of WQTG were derived by integrating projected changes in salinity, NO_3, and DO concentrations under RCP4.5 and RCP8.5 scenarios in both 2050 and 2100 timeframes, respectively. Taken together, *very suitable* and *suitable* classes covered an extensive area across the Mediterranean in both the future and baseline scenarios, encompassing 90.4 % in the baseline and 89.7 % under RCP8.5 in 2100 with the combined projections of salinity, NO_3, and DO. Conversely, *less suitable* and *moderately suitable* areas were predominantly found in the Northern Adriatic and southern/southeastern Mediterranean regions (i.e., Egypt and Tunisia). WQ suitability scores under future scenarios exhibited only minor differences when compared to the baseline distribution. The most pronounced changes in WQTG suitability scores occurred under the RCP8.5 scenario in 2100 (Fig. 3), where still very slight shifts were observed in the distribution of suitability classes compared to the baseline. Future maps for other scenarios displaying the distribution of suitability classes were provided in SM5 (Fig. S4).

Fig. 3 also illustrates the percentage changes in surface area distribution of suitability classes under different combinations of variables in

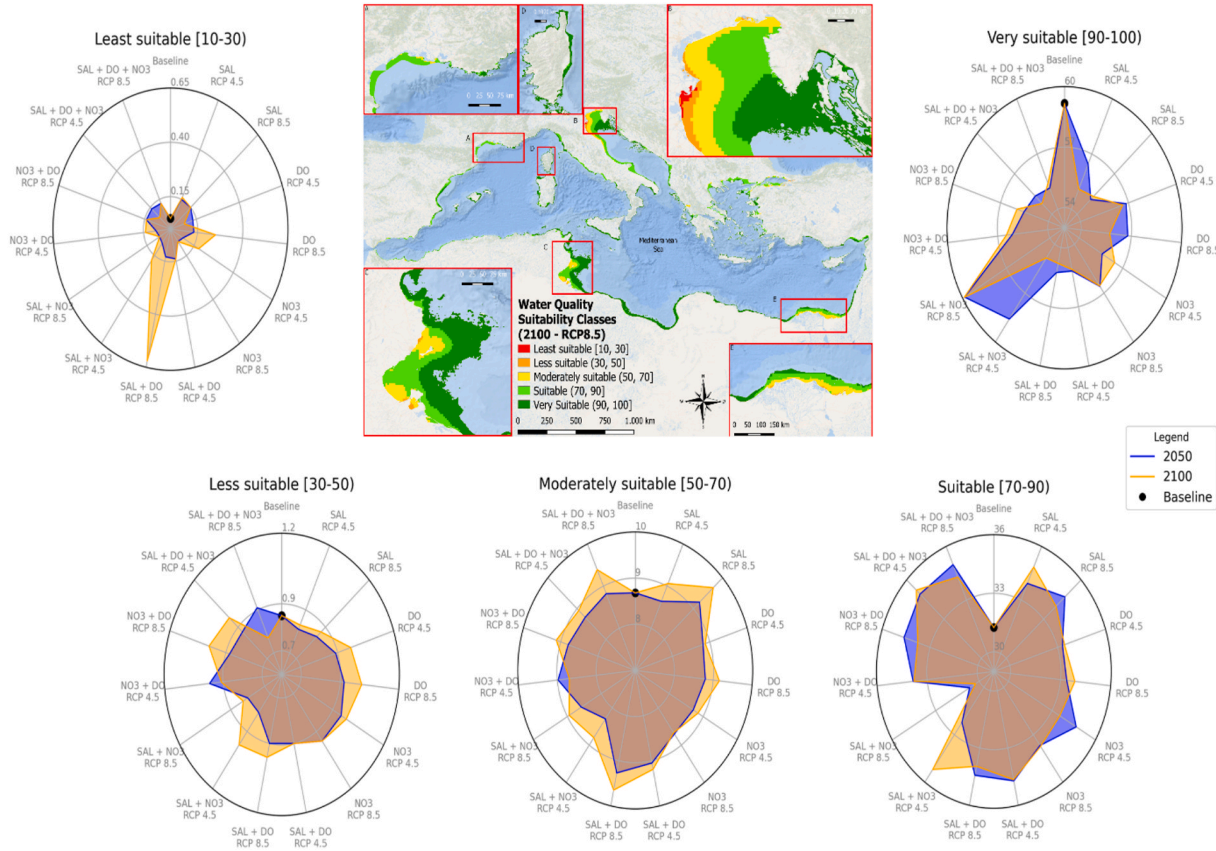

Fig. 3. Water quality thematic group map in 2100 under the RCP8.5 scenario displaying water quality suitability classes for *P. oceanica* (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès, Tunisia; D: Corsica, France; E: Egyptian coasts). Spider charts for the suitability classes under scenario analysis (RCP 4.5 and RCP 8.5) comparing baseline and future projections (2050 and 2100) with different combinations of salinity (SAL), dissolved oxygen (DO), and nitrate (NO_3). Unit of measurement: percentage (%).

scenario analysis comparing the baseline and future (2050 and 2100) scenarios. In general, the percentages of the *least suitable* class are relatively small and account for less than 1 % in both baseline and future scenarios. The highest surface area increase in the *least suitable* class compared to the baseline was observed for the combination of salinity and DO under RCP8.5 in 2100. For the *less* and *moderately suitable* classes, surface percentages varied very slightly, at around 1 % and 9 %, respectively. Overall, percentages for the *least*, *less*, and *moderately suitable* classes generally showed a slight increase for nearly all variable combinations, especially under the 2100 timeframe. Furthermore, the surface area of the *suitable* class typically showed a minor increase (e.g., 3 % increase from 31.3 % to 34.3 % in 2100 under RCP8.5 with all parameter combinations). Conversely, the surface area of the *very suitable* class decreased in each scenario (e.g., 3.8 % decrease from 59.2 % to 55.4 % in 2100 under RCP8.5 with all parameter combinations), except for the combination of salinity and NO_3 under the RCP8.5 scenario in 2050.

Fig. 4 presents boxplots for the single criteria of salinity and DO in Egypt to understand the drivers of changes in the specific hotspot. For salinity (Fig. 4a), three future scenarios (i.e., RCP4.5 in 2050, RCP4.5 in 2100, and RCP8.5 in 2050) have similar ranges to the baseline (i.e., quartiles usually placed on 39–39.3 PSU). However, the RCP8.5 scenario in 2100 showed an elevation up to 39.8 PSU (with quartiles on 39.4 and 39.6 PSU). The DO values in Egypt show a broader range in future scenarios compared to the baseline (6–6.8 mg/L), with a noticeable expansion towards lower values (Fig. 4b). The most extensive range is observed in the 2100 scenario under RCP8.5, with DO values decreasing to as low as 5.6 mg/L. Boxplots for all WQ criteria in additional hotspot areas (i.e., Northern Adriatic and Tunisia) are detailed in SM5 Figs. S5–S7.

4.1.3. Climate thematic group

The Climate Thematic Group (CTG) incorporated three criteria: Summer SST, TS duration, and TS intensity, weighted as 0.15, 0.57, and 0.28, respectively. TS duration was the most influential factor, as prolonged thermal stress significantly impacts *P. oceanica's* physiological performance. Baseline CTG suitability scores indicated favorable conditions for *P. oceanica* growth, reaching a value of 53.8 % of the area classified as *very suitable*. However, the southern and eastern Mediterranean Sea, as well as the Northern Adriatic, included significant proportions of the *moderately suitable* (28.7 %), *less suitable* (5.7 %), and *least suitable* (4.5 %) classes under the baseline scenario (Fig. 5). Future maps were obtained by considering SST projections under RCP4.5 and RCP8.5 scenarios in 2050 and 2100. Fig. 5 reports both the climate suitability map under the RCP8.5 scenario in 2050 and 2100, representing the worst-case climate scenario, and the percentage of surfaces of suitability classes under each scenario. Moreover, Fig. S8 in SM5 reports the distribution of suitability classes as maps for baseline and RCP4.5 scenarios in 2050 and 2100. Overall, while *very suitable* and *suitable* areas showed a sharp decrease in surface percentages in the whole Mediterranean, *less* and *least suitable* areas expanded significantly, especially under the RCP8.5 scenario in 2100 (Fig. 5). For instance, the surface percentages of the *least suitable* class increased from 4.5 % to 10.1 % and to 51.6 % under the RCP8.5 scenario in 2050 and 2100, respectively. Furthermore, under RCP8.5 in 2100, *very suitable* and *suitable* classes accounted for only 13.8 % and 7.3 % of the area, respectively. Despite an overall decline in climatic suitability across the Mediterranean, hotspot areas exhibited varying trends under different scenarios. For instance, under

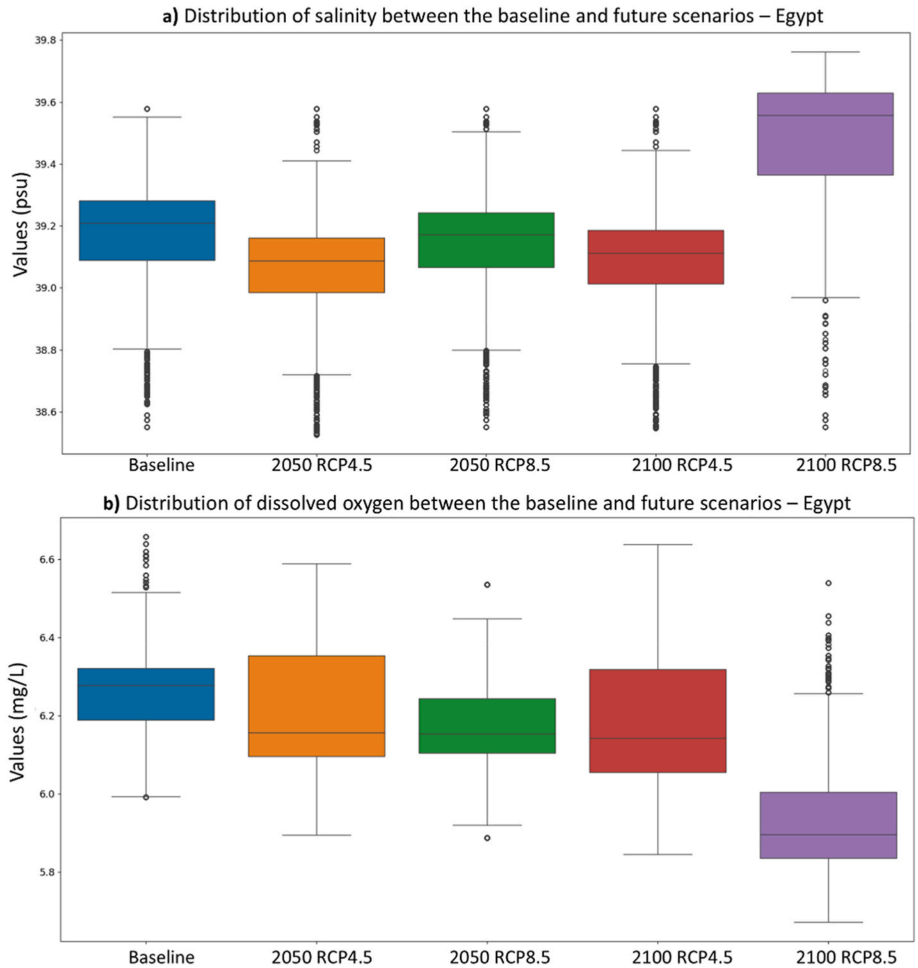

Fig. 4. Boxplots comparing a) Salinity and b) Dissolved oxygen across baseline and future scenarios (2050 RCP 4.5, 2050 RCP 8.5, 2100 RCP4.5, and 2100 RCP 8.5) in Egypt.

RCP8.5 in 2050, the *moderately*, *less*, and *least suitable* classes increased in the southern Mediterranean regions such as Tunisia and Egypt. However, the Northern Adriatic region observed an increase in the percentage of *very suitable* class surfaces under the same scenario.

In Fig. 6, the distribution of average SST and the cumulative number of thermal stress events (defined as temperature exceeding 28.4 °C for at least five consecutive days) within the Northern Adriatic hotspot were presented for all scenarios. While the average SST is projected to increase in 2050 compared to the baseline, the number of thermal stress events under both RCP4.5 and RCP8.5 in 2050 is lower than the baseline for the Northern Adriatic. On the contrary, both the average SST and the sum of the number of thermal stress events showed a substantial increase in 2100, especially under the RCP8.5 scenario.

4.2. Final suitability maps with P. oceanica distribution

In the last phase of the MAS-NBS model, final suitability maps were obtained by overlaying the *suitable* and *very suitable* areas of all three thematic groups (geomorphological, climatic, and water quality) and merging them with the current distribution of *P. oceanica* meadows. The intersection of the three TGs is performed to illustrate changes in the areas with the highest environmental quality for *P. oceanica* growth across the whole Mediterranean coastline in future scenarios. Fig. 7 indicates the intersected final suitability map in 2100 under RCP8.5 with the current *P. oceanica* distribution as well as the areal changes of this intersection under all scenarios. Maps of baseline and other future scenarios were reported in Fig. S9 in SM5. In the baseline scenario, the overall intersected suitable areas for seagrass growth covered 3910 km^2. This area slightly decreased to 3810 km^2 under the RCP8.5 scenario in 2050 and experienced a sharp decline to 1163 km^2 under the RCP8.5 scenario in 2100 (Fig. 7, bottom panel). When comparing across thematic groups, geomorphological suitability provided a relatively stable baseline, and water quality changes led only to minor shifts in suitable areas. In contrast, climate-driven factors were the dominant contributors to the sharp reduction of suitable habitat by 2100, which highlights climate change as the primary long-term threat to the persistence of *P. oceanica* meadows in the Mediterranean.

5. Discussion

5.1. Thematic suitability groups and their implications for ecosystem services of P. oceanica

5.1.1. Geomorphology thematic group

Geomorphological factors are critical for both the vertical and horizontal extension of these communities, influencing seabed stability and, consequently, seagrass anchorage and growth. The suitability of these areas for *P. oceanica* meadows directly impacts their ability to provide essential physical ecosystem services, such as coastal protection and habitat provision, which are particularly effective in shallow coastal zones where a stable seabed ensures robust seagrass anchorage, which in turn creates a buffer zone that protects coastal areas from erosion and storm surges (Heide et al., 2007). Blue-NBS actions such as seagrass restoration can further enhance these ecosystem services by dissipating

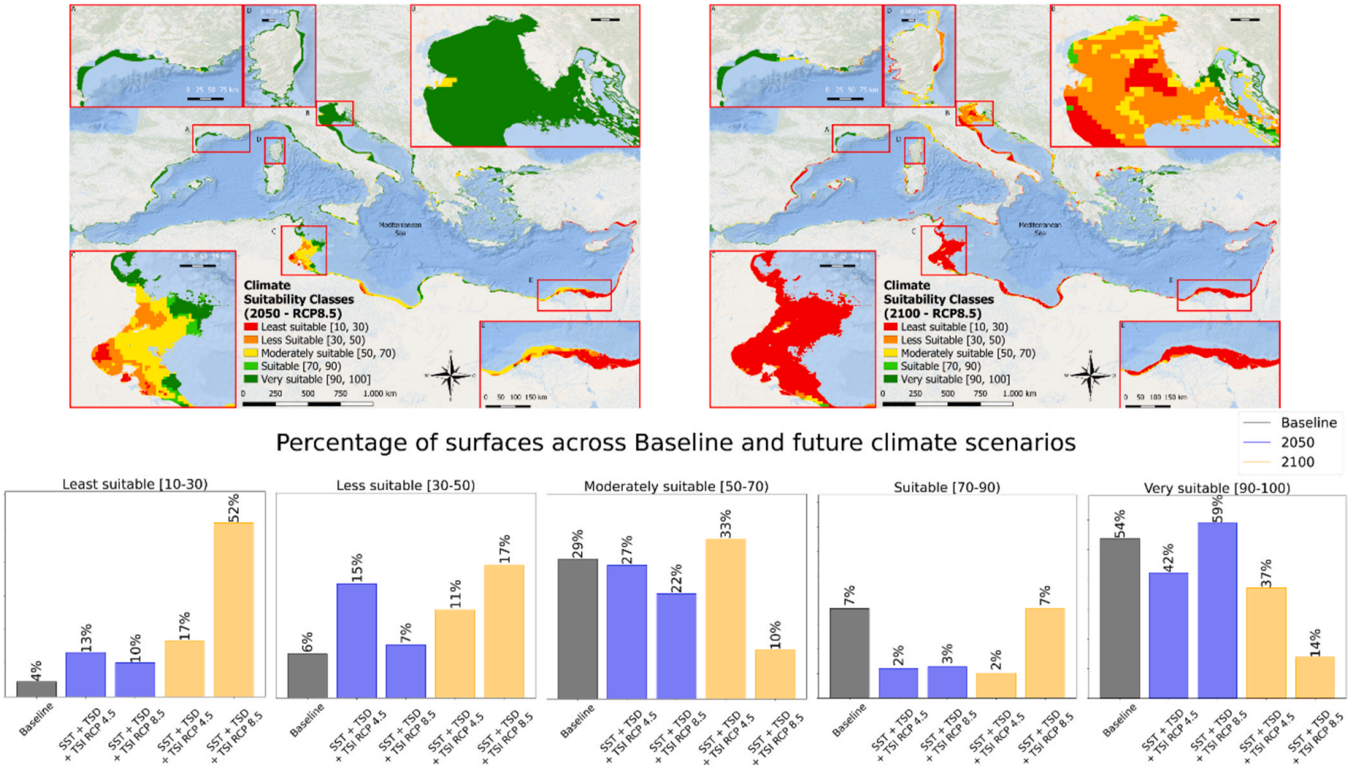

Fig. 5. Climate thematic map of 2050 and 2100 RCP8.5 (top panel) and bar plot (bottom panel) for suitability classes under baseline and future scenarios. Top panel shows *P. oceanica* distribution across the following: A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès, Tunisia; D: Corsica, France; E: Egyptian coasts.

wave energy and slowing currents, allowing suspended particulate matter to settle on the seabed and reducing sediment resuspension (CNRD& UNEP, 2019; Hynes et al., 2021; SEEA, 2021; Terrados and Williams, 1997).

In regions with steep slopes and abrupt depth increases, we observed more fragmented and narrower suitable zones for *P. oceanica*. These areas present challenges for seagrass expansion, limiting the effectiveness of meadows in stabilizing the coastline and protecting coastal communities, even if restoration efforts are implemented (Ondiviela et al., 2014). Steep slopes often lead to thinner seagrass coverage despite the long shoreline, as seen in regions like western Liguria, eastern Cote d'Azur, and parts of Algeria and Morocco's coasts. Substrate type also plays a critical role in successful anchorage and the expansion of seagrass meadows. The presence of *dead matte* offers favorable conditions for seagrass restoration (Escandell-Westcott et al., 2023), although transplanting efforts face challenges such as self-shading and uncertain long-term success (Terrados et al., 2013).

Geomorphological variables were assumed static through time, as coastal geomorphology typically changes very slowly from decades to centuries (even longer in rocky coastal areas) (Aucelli et al., 2018). Nevertheless, localized processes such as erosion, sediment transport, and sea-level rise may alter seabed conditions and affect future suitability. Future work should integrate dynamic coastal or sediment models to capture these changes better.

5.1.2. *Water quality thematic group*

Water quality suitability evaluation strengthens the analysis by focusing not only on physical features, discussed in the geomorphology thematic group, but also on chemical and biological characteristics of the water column. Seagrass health and water quality are mutually reinforcing—poor water quality suppresses meadow health, while favorable conditions support meadow expansion and water-column improvement (Heide et al., 2007; Orth et al., 2020). In regions with high water quality, *P. oceanica* meadows serve as natural biofilters, trapping sediments, reducing turbidity, and improving water clarity. This filtration process regulates marine life and supports denitrification, which manages phytoplankton levels and further mitigates stormwater runoff and improves water clarity, ultimately contributing to healthier marine ecosystems and cleaner coastal waters, which enhance human well-being and recreational opportunities (Ondiviela et al., 2014; Xu et al., 2021). Addressing water quality issues through Blue-NBS actions is therefore critical to maintaining and enhancing the ecosystem services provided by these meadows, ensuring they continue to play their role in sustaining healthy and productive marine environments (Connolly et al., 2016).

Even if regions with extensive shallow areas, such as lagoons, have high geomorphological suitability, other factors, such as WQ variables, can govern suitability for seagrass meadows there (Boscutti et al., 2015). As an example, a significant amount of coastal area from the Northern Adriatic is not included in the final suitability map due to WQ results. Although WQ suitability scores are relatively low in the areas closest to the coasts of Northern Adriatic, Egypt, and Tunisia, they increase as one moves away from the coasts with a decreasing trend in geomorphological suitability. Moreover, in Egypt, under RCP8.5 in 2100 (Fig. 4), even slight increases in salinity (~40 PSU) and decreases in dissolved oxygen (~5.5 mg/L) substantially reduced suitable areas as these criteria approached ecological thresholds. In particular, salinity levels around 40 PSU pose a serious risk of increased mortality for *P. oceanica* meadows (Sánchez-Lizaso et al., 2008).

The predominance of *very suitable* and *suitable* classes in both the future and baseline scenarios (90.1 % under the baseline) reflects generally favorable water quality of the Mediterranean, which is largely well oxygenated and oligotrophic with transparent water quality characteristics. The surface area of the *suitable* class showed slight increases with different variable combinations under future scenarios, but mainly due to the reduction of the *very suitable* areas, which stimulates a future need for Blue-NBS actions on WQ. In addition, the absence of future projections for diffuse attenuation coefficient, holding the highest

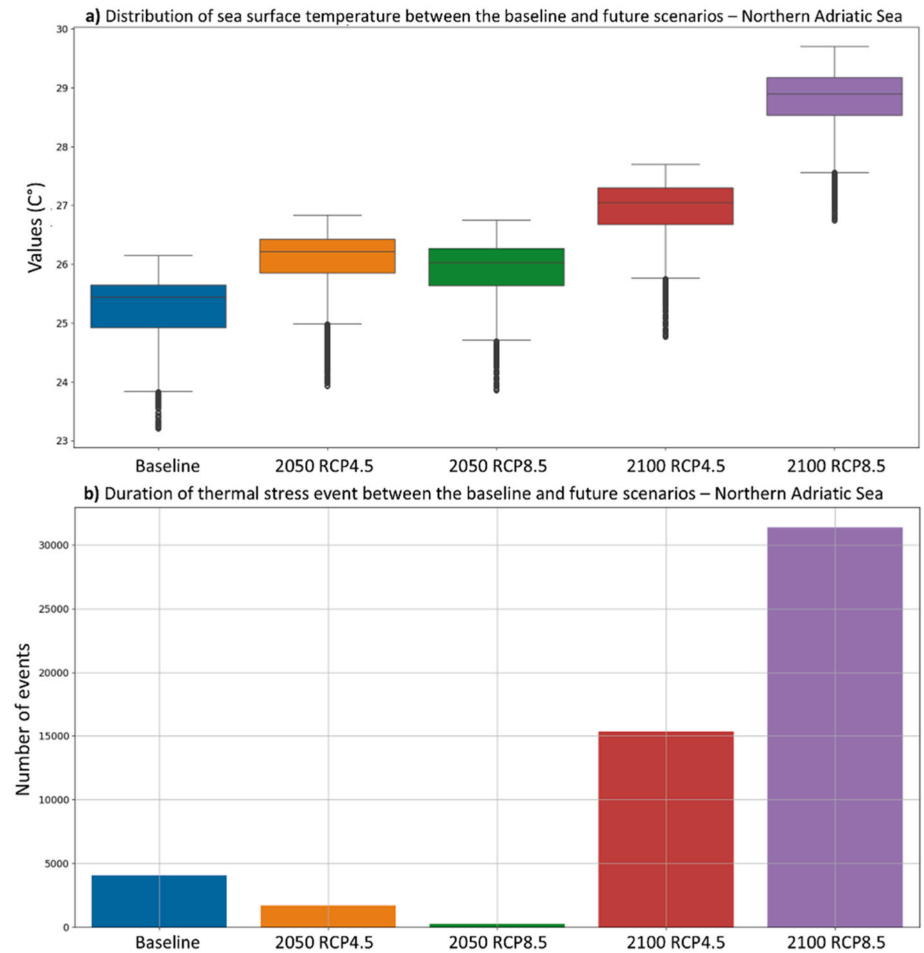

Fig. 6. Boxplots of average summer sea surface temperature (a) and the sum of thermal stress events (b) for the Northern Adriatic across the baseline and future scenarios (2050 RCP 4.5, 2050 RCP 8.5, 2100 RCP4.5, and 2100 RCP 8.5).

weight among the WQ criteria, potentially underestimates light-limitation risks in some areas.

5.1.3. *Climate thematic group*

Climate suitability showed potential effects of instant (i.e., marine heatwaves) and long-term (i.e., future scenarios) changes of temperature on *P. oceanica* growth and survival. Since thermal stress duration and intensity were also extracted from the SST dataset, all indicators under the climate sub-group affect the climate scores of the future timeframes. For this reason, contrary to WQ scores, future maps show very different results compared to the climate suitability of the reference timeframe. Even though *P. oceanica* is resistant to a wide range of average SST (10–29 °C), prolonged exposure to temperatures higher than 28.4 °C impacts their survival and ecosystem services (Chefaoui et al., 2017; Marbà and Duarte, 2010). Especially under the RCP8.5 projection in 2100, sharp decline in suitable areas (e.g., *very suitable* class from 54 % at baseline to 14 %) and expansion in *least suitable* areas (from 4 % to 52 %) indicates that sea surface temperature (SST) and thermal stress may become the primary limiting factors for seagrass growth, surpassing depth and other geomorphological indicators.

Meadows of *P. oceanica* are highly effective natural systems for carbon storage in the Mediterranean (Koopmans et al., 2020), sequestering significant amounts of CO_2 and mitigating the impacts of climate change. However, as climate models predict rising temperatures and more frequent heatwaves, the suitability of these meadows to thrive under such conditions is threatened. *P. oceanica* can shift from being highly autotrophic to becoming heterotrophic, reducing its ability to sequester carbon efficiently not only in the winter season (Koopmans et al., 2020) but even in late spring and summer, under prolonged thermal stress. A decline in meadow health due to such stress would not only lower their carbon storage capacity but also diminish other critical ecosystem services, such as local temperature regulation and biodiversity conservation. Protecting these meadows from the adverse effects of climate change, through adaptive management and targeted Blue-NBS interventions, is essential to preserve their role in climate regulation and to ensure that they continue to provide these critical ecosystem services in the future.

5.2. *Implications for Blue-NBS management through P. oceanica*

P. oceanica, despite its significant ecological role and potential as Blue-NBS (do Amaral Camara Lima et al., 2023), is listed as "*Vulnerable*" in the Mediterranean Sea (EU, 2016) with a reduction of about 13–50 % of its extent since 1960 (Marbà et al., 2014) with insufficient measures according to the European Red List of Habitat assessment (EU, 2016). Of particular interest to this study is the aim to protect and conserve biodiversity, restore degraded ecosystems, and strengthen governance structures. Our results indicate that *P. oceanica* meadows are particularly vulnerable under future climate scenarios—with marked declines in *suitable* and *very suitable* areas (especially under the RCP8.5 scenario in 2100)—highlighting the need to integrate their conservation into broader marine protection plans. This projected contraction in suitable habitat also implies measurable losses in ecosystem services, particularly carbon sequestration and denitrification potential (Simeoni et al., 2025), threatening the long-term provision of blue-carbon and food-security benefits that many Mediterranean communities rely on.

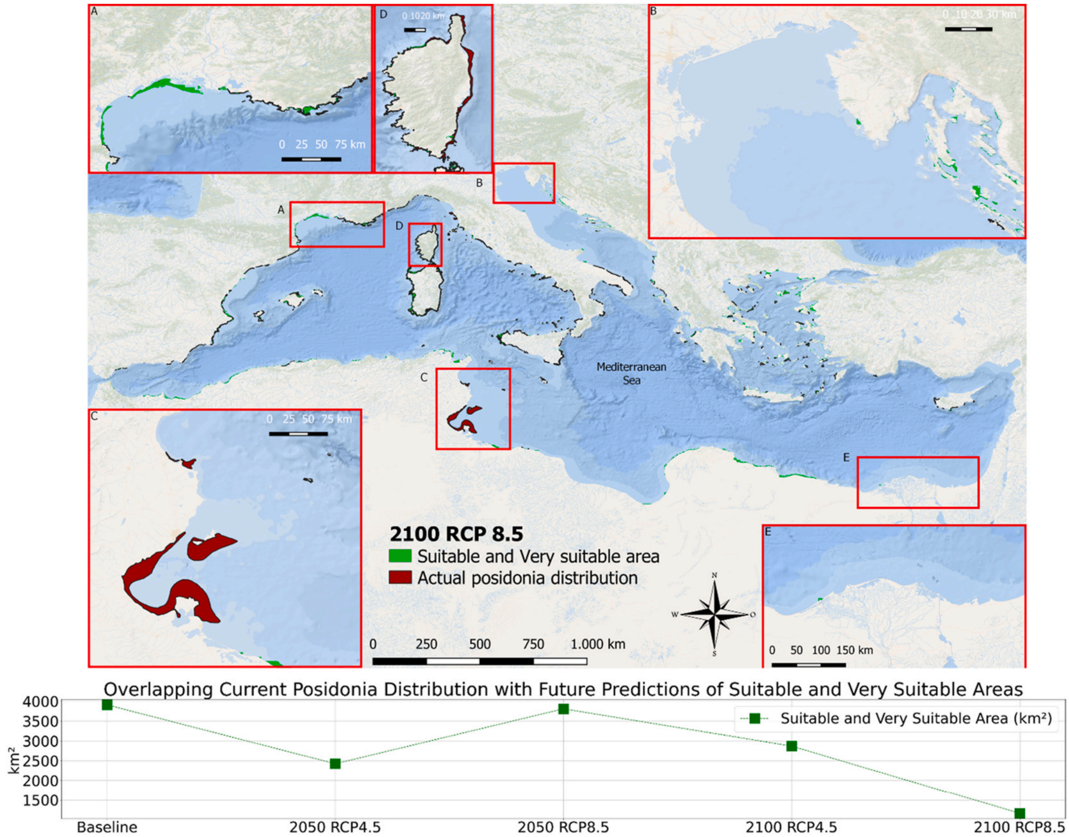

Fig. 7. Overlapped suitable and very suitable class map of 2100 RCP8.5 with the current distribution of *P. oceanica* (top panel) and line plot (bottom panel) very suitable and suitable area for 2050 RCP 4.5, 2050 RCP 8.5, 2100 RCP4.5, and 2100 RCP 8.5. Map inset boxes correspond to the following: A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès, Tunisia; D: Corsica, France; E: Egyptian coasts.

According to the study by Simeoni et al. (2025), a 20 % reduction in seagrass distribution under the RCP8.5 scenario could result in a decrease of approximately 3.5 %–6 % in carbon sequestration and up to 20 % in denitrification potential by the year 2100.

The projected loss of suitable habitat for *P. oceanica* under future scenarios also raises concerns about triggering a "blue carbon bomb", where degradation of these ecosystems could rapidly release stored carbon, intensifying climate change impacts. Seagrass meadows can act as either net sources or sinks of greenhouse gases in marine environments due to various interacting processes (Oreska et al., 2020; Unsworth et al., 2022). In healthy meadows, high net photosynthetic productivity and dense seagrass growth contribute to the rapid trapping and long-term storage of carbon within sediments. However, as our results demonstrate, increased thermal stress and eutrophication threaten the survival of these meadows, potentially leading to carbon remobilization and higher emissions of CH_4 and N_2O. Furthermore, the impact of calcification by associated fauna within productive meadows on the overall carbon balance is still not fully understood. The outcome of this analysis provides useful information on where to implement the conservation and restoration of *P. oceanica* meadows to enhance their extent and health and, in turn, improve their capability to offset greenhouse gases.

At the policy level, the EU Commission's Biodiversity Strategy for 2030, part of the European Green Deal, aims to legally protect a minimum of 30 % of both terrestrial and marine protected areas within the EU. Placing our results within the context of the ongoing "30 x 30" initiative has marked implications for preserving the vulnerable-listed *P. oceanica.* Complementing this, the Marine Strategy Framework Directive (MSFD) treats *P. oceanica* as key to Good Environmental Status, while the Water Framework Directive (WFD) governs ecological status in coastal waters (eutrophication, transparency). Accordingly, the EU Nature Restoration Regulation provides a legislative framework for large-scale restoration of degraded ecosystems, enhancing their resilience and ecosystem services that have been well documented to date, from carbon sequestration to habitat provision (Boudouresque et al., 2016; Campagne et al., 2014). Considering the projected declines in suitable habitats for *P. oceanica*, particularly in severely impacted hotspots, the outcome of this study serves as a robust tool in designing management practices that prioritize conservation of extant stands, which are crucial within various directives and frameworks.

Beyond biophysical stressors, socio-economic pressures such as coastal development, and unregulated anchoring (Bockel et al., 2024), further compromise meadow resilience and carbon storage potential. Sustaining these meadows also secures provisioning services such as small-scale fisheries and coastal livelihoods that are locally significant (Amone-Mabuto et al., 2023; Jones et al., 2022). Areas remaining biophysically suitable may nonetheless face socio-economic constraints to NBS, emphasizing the need for participatory governance to accompany ecological measures (Louarn et al., 2025). Targeted adaptive management, such as reducing local stressors (e.g., informed anchoring) and ensuring regular monitoring and evaluation of meadow conditions, can help prevent further meadow degradation, in line with the MSFD, WFD, and Nature Restoration Regulation.

Conservation presents a more favorable and cost-effective strategy for maintenance of biodiversity; this is especially true for climate-sensitive species already listed as vulnerable. Of particular interest to conservation efforts, *P. oceanica* meadows help to sustain diverse ecosystems ranging from epiphytes to organisms using the meadows cover habitat (Battisti et al., 2021). Furthermore, *P. oceanica* is slow growing and highly stress adverse, making restoration from seedlings difficult and time consuming (Escandell-Westcott et al., 2023). As mentioned by Castejón-Silvo and Terrados (2021), transplanted seedlings and fragments of *P. oceanica* tested in Majorca showed very poor survival due to the mechanical damage on the substrate previously (Castejón-Silvo and Terrados, 2021), showing that the protection of the *dead matte* is one of the most critical factors for the successful transplantation and growth (i.e., stability and resilience) of *P. oceanica* (Boudouresque et al., 2016). Furthermore, it assumes a static state where ongoing succession in the ecosystem best suited for *P. oceanica* has not already altered states, transitioning to substrates unable to support stands or water quality that prohibit re-establishment of stands. Indeed, there are multiple steps to establish if a site is still viable (Terrados et al., 2013). Water clarity and sea surface temperature changes are underway in the Mediterranean and while these may be buffered by extant stands, seedlings and transplants are especially sensitive to these changes and may increase mortality (Escandell-Westcott et al., 2023; Pansini et al., 2022). Hence, management practices focus on conserving existing meadows and maintaining suitable areas through 2050, prioritizing regions identified as hotspots (e.g., Egypt, Tunisia and Northern Adriatic).

5.3. Strengths and limitations of the study

The strength of the developed model hinges on the integration of statistical analysis of environmental variables, with expert opinions and information from the most updated literature to identify variables' thresholds (and comfort zone) for the growth and survival of *P. oceanica* in the Mediterranean basin. The AHP approach allowed experts' qualitative assessments to be converted into quantitative information and provided a structured and transparent weighting of criteria, enabling prioritization based on relative importance. Multi-criteria NBS suitability through GIS-based AHP represents an effective approach to identify suitable areas for ecosystem-based management and conservation actions on *P. oceanica* and support decision-makers for proper measures to improve the environmental status of areas before NBS implementations across the eco-regional scale. Compared with other MCDA techniques, the MAS-NBS framework provides clear expert reasoning, while future hybrid or machine-learning approaches could further enhance its ability to capture non-linear relationships. Importantly, the suitability analysis was conducted for different sub-groups, which aids the decision-making process for Blue-NBS by targeting specific issues.

The individual evaluation of variables based on pairwise comparisons is a limitation of AHP since it considers the variables as independent. The developed model did not take into account interactions and relationships between the variables, which may be crucial in decision-making processes, thus motivating future investigation using decision-making methods considering complex interactions (e.g., Analytic Network Process). Future work could also explore complementary approaches such as machine learning techniques (e.g., Random Forests) to better capture nonlinearities, or process-based ecological models to simulate temporal dynamics under climate stressors. Although the sensitivity and uncertainty analysis were not carried out in this study, the baseline study (Ozkiper et al., 2024) quantified the relative influence and non-linearity of the same variables. Geomorphological factors, especially substrate type, together with water clarity (K_d) and summer SST, were the most influential variables shaping suitability outcomes (Ozkiper et al., 2024). In addition, multiple time horizons (2050, 2100) and climate scenarios (RCP4.5, RCP8.5) provide a scenario-based exploration of the variability in projections.

Furthermore, ecosystems can adapt to the site-specific environmental conditions and can be resistant to different threshold values for different variables. Considering this, suitability analysis at the subregional scale (e.g., Western Mediterranean or Adriatic Sea) may provide more regionally accurate insights. In addition to the mean values of variables, analysis of the exposure time of ecosystems to the identified threshold values could improve the model. However, to achieve this, future analyses should define exposure-duration classes for each variable to evaluate how prolonged stress influences seagrass mortality.

A key limitation is the absence of socio-economic variables that condition the feasibility and uptake of Blue-NBS. The success of seagrass management measures often depends on local economic activities and governance capacity. Community perceptions influence management acceptance; likewise, boating and anchoring pressure can directly undermine restoration feasibility in high-use areas. Accordingly, future work should integrate socio-economic indicators—such as local livelihoods and governance capacity—to identify socio-ecological conflict zones and opportunity areas for NBS deployment. As highlighted by Geukes et al. (2024), embedding these indicators within iterative monitoring and evaluation frameworks would enhance adaptive management and ensure more informed, equitable decision-making.

6. Conclusion

This study presents a comprehensive environmental suitability assessment of Blue-NBS through *P. oceanica* meadows using a GIS-based Multi-criteria Approach for Suitability of NBS in the marine coastal areas of the Mediterranean eco-region under various future scenarios. Suitability analyses under different RCP scenarios enhance the understanding of possible effects of climate and water quality parameters on the suitability of Blue-NBS actions and support decision-makers for long-term adaptive strategies. The synergistic integration of GIS techniques and AHP enabled aggregation of different environmental criteria under separate sub-groups, with classes, scores, and weights tailored through literature and expert judgment.

The outcome of the analysis revealed substantial declines in suitable areas, particularly under RCP8.5 in 2100. It emphasizes the increasing dominance of climatic criteria, especially thermal stress, in driving suitability reductions. Under the baseline scenario, nearly one-quarter of the study area was *suitable* or *very suitable*, but this sharply decreased under future scenarios, indicating that seagrass meadows may face significant degradation and reduced capacity to provide critical ecosystem services such as water quality regulation and coastal protection, with direct consequences for coastal communities relying on these functions. The identification of environmentally suitable areas is therefore crucial to prioritize the areas for Blue-NBS measures. Future Blue-NBS suitability assessments should extend this framework with multi-risk assessment and socio-economic and governance factors that influence implementation and effectiveness at local scales. This multi-dimensional approach not only enhances the understanding of *P. oceanica* suitability under climate change but also provides actionable guidance for marine managers and policymakers across various scenarios.

CRediT authorship contribution statement

Ozan Ozkiper: Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Angelica Bianconi:** Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Hung Vuong Pham:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Jordan Bishop:** Writing – review & editing, Conceptualization. **Rémy Simide:** Writing – review & editing, Conceptualization. **Andrea Critto:** Validation, Supervision, Conceptualization. **Elisa Furlan:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that the "ChatGPT" tool was used to improve the readability and language of the manuscript during the preparation of this work. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research leading to these results has been implemented in the framework of the EU's Horizon 2020 research and innovation programme under Grant Agreement No 869710 (EU-MaCoBioS - https://macobios.eu/). This work is also funded by the project "DesirMED – Demonstration and mainstreaming of Nature-based Solutions for Climate Resilient transformation in the Mediterranean", a project funded under the Horizon Europe Programme, Grant Agreement No 101112972. This work is also funded by the European Union - NextGenerationEU, in the framework of the GRINS - Growing Resilient, INclusive and Sustainable project (GRINS PE00000018 - CUP H73C22000930001), National Recovery and Resilience Plan (NRRP) - PE9 - Mission 4, C2, Intervention 1.3. The views and opinions expressed are solely those of the authors and do not necessarily reflect those of the European Union, nor can the European Union be held responsible for them. The authors would like to thank Dr. Matthijs van der Geest, Dr. Jorge Terrados (IMEDEA), Dr. Silvia de Juan (IMEDEA), Dr. Chiara Silvestrini (Zoological Station "Anton Dohrn"), Dr. Claude Reveret (Creocean) and Dr. Dorian Guillemain (OSU Pythéas) for their support during the study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.108032.

Data availability

Data will be made available on request.

References

Amone-Mabuto, M., Mubai, M., Bandeira, S., Shalli, M.S., Adams, J.B., Lugendo, B.R., Hollander, J., 2023. Coastal community's perceptions on the role of seagrass ecosystems for coastal protection and implications for management. Ocean Coast Manag. 244. https://doi.org/10.1016/j.ocecoaman.2023.106811.

Aslan, S., Zennaro, F., Furlan, E., Critto, A., 2022. Recurrent neural networks for water quality assessment in complex coastal lagoon environments: a case study on the venice lagoon. Environ. Model. Software 154 (May). https://doi.org/10.1016/j.envsoft.2022.105403.

Aucelli, P.P.C., Matano, F., Salvini, R., Schiattarella, M., 2018. Editorial – coastal changes, from past records to future trends: proxy analysis, modelling, and monitoring. J. Coast Conserv. 22 (5), 821–825. https://doi.org/10.1007/s11852-018-0623-z.

Bakirman, T., Gumusay, M.U., 2020. A novel GIS-MCDA-based spatial habitat suitability model for Posidonia oceanica in the mediterranean. https://doi.org/10.1007/s10661-020-8198-1A.

Battisti, D.D., Balestri, E., Pardi, G., Menicagli, V., Lardicci, C., 2021. Substrate type influences the structure of epiphyte communities and the growth of Posidonia oceanica seedlings. Front. Plant Sci. 12. https://doi.org/10.3389/fpls.2021.660658.

Bockel, T., Bossut, N., Mouquet, N., Mouillot, D., Fontaine, Q., Deter, J., 2024. Quantifying the impact of small boats on posidonia seagrass meadows: methods and path for future efficient management of anchoring pressure. Ocean Coast Manag. 259. https://doi.org/10.1016/j.ocecoaman.2024.107454.

Boscutti, F., Marcorin, I., Sigura, M., Bressan, E., Tamberlich, F., Vianello, A., Casolo, V., 2015. Distribution modeling of seagrasses in brackish waters of grado-marano lagoon (Northern Adriatic Sea). Estuar. Coast Shelf Sci. 164, 183–193. https://doi.org/10.1016/j.ecss.2015.07.035.

Boudouresque, C.F., Pergent, G., Pergent-Martini, C., Ruitton, S., Thibaut, T., Verlaque, M., 2016. The necromass of the Posidonia oceanica seagrass meadow: fate, role, ecosystem services and vulnerability. In: Hydrobiologia, 781. Springer International Publishing, pp. 25–42.

Buonocore, E., Donnarumma, L., Appolloni, L., Miccio, A., Russo, G.F., Franzese, P.P., 2020. Marine natural capital and ecosystem services: an environmental accounting model. Ecol. Model. 424 (March). https://doi.org/10.1016/j.ecolmodel.2020.109029, 109029-109029.

Campagne, C.S., Salles, J.M., Boissery, P., Deter, J., 2014. The seagrass posidonia oceanica: ecosystem services identification and economic evaluation of goods and benefits. Mar. Pollut. Bull. 97 (1–2), 391–400. https://doi.org/10.1016/j.marpolbul.2015.05.061.

Castejón-Silvo, I., Terrados, J., 2021. Poor success of seagrass Posidonia oceanica transplanting in a meadow disturbed by power line burial. Mar. Environ. Res. 170. https://doi.org/10.1016/j.marenvres.2021.105406.

Catucci, E., Scardi, M., 2020. A machine learning approach to the assessment of the vulnerability of Posidonia oceanica meadows. Ecological Indicators 108. https://doi.org/10.1016/j.ecolind.2019.105744.

Chandio, I.A., Matori, A.N.B., WanYusof, K.B., Talpur, M.A.H., Balogun, A.L., Lawal, D. U., 2013. GIS-Based analytic hierarchy process as a multicriteria decision analysis instrument: a review. Arabian J. Geosci. 6 (8), 3059–3066. https://doi.org/10.1007/s12517-012-0568-8.

Chefaoui, R.M., Duarte, C.M., Serrão, E.A., 2017. Palaeoclimatic conditions in the Mediterranean explain genetic diversity of Posidonia oceanica seagrass meadows. Sci. Rep. 7 (1), 1–8. https://doi.org/10.1038/s41598-017-03006-2.

CNRD, & UNEP, 2019. Disasters and Ecosystems: Resilience in a Changing Climate Convention on Biological Diversity Sendai Framework for Disaster Risk Reduction United Nations Economic. Commission for Europe World Business Council for Sustainable Development.

Cohen-Shacham, E., Walters, G., Janzen, C., Maginnis, S., 2016. Nature-Based Solutions to Address Global Societal Challenges. IUCN, Gland, Switzerland. https://doi.org/10.2305/iucn.ch.2016.13.en xiii + 97pp.

Coll, M., Piroddi, C., Albouy, C., Lasram, F.B.R., Cheung, W.W.L., Christensen, V., Karpouzi, V.S., Guilhaumon, F., Mouillot, D., Paleczny, M., Palomares, M.L., Steenbeek, J., Trujillo, P., Watson, R., Pauly, D., 2012. The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves. Global Ecol. Biogeogr. 21 (4), 465–480. https://doi.org/10.1111/j.1466-8238.2011.00697.x.

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Lasram, F.B.R., Aguzzi, J., Ballesteros, E., Bianchi, C.N., Corbera, J., Dailianis, T., Danovaro, R., Estrada, M., Froglia, C., Galil, B.S., Gasol, J.M., Gertwage, R., Gil, J., Guilhaumon, F., Kesner-Reyes, K., et al., 2010. The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. PLoS One 5 (8). https://doi.org/10.1371/journal.pone.0011842.

Connolly, R., Dunn, R.J., Flindt, M.R., Jackson, E.L., Kristensen, E., 2016. Assessment of the effects of foreshore nourishment and mitigation projects on seagrass ecosystems. https://doi.org/10.13140/RG.2.2.20572.39044.

Darmaraki, S., Somot, S., Sevault, F., Nabat, P., 2019. Past variability of Mediterranean Sea marine heatwaves. https://doi.org/10.1029/2019GL082933.

do Amaral Camara Lima, M., Bergamo, T.F., Ward, R.D., Joyce, C.B., 2023. A review of seagrass ecosystem services: providing nature-based solutions for a changing world. In: Hydrobiologia, 850. Springer Science and Business Media Deutschland GmbH, pp. 2655–2670.

EC, 2006. Scientific, Technical and Economic Committee for Fisheries Opinion on 'Sensitive and Essential Fish Habitats in the Mediterranean Sea'.

Effrosynidis, D., Arampatzis, A., Sylaios, G., 2018. Seagrass detection in the mediterranean: a supervised learning approach. Ecol. Inform. 48 (August), 158–170. https://doi.org/10.1016/j.ecoinf.2018.09.004.

Escandell-Westcott, A., Riera, R., Hernández-Muñoz, N., 2023. Posidonia oceanica restoration review: factors affecting seedlings. In: Journal of Sea Research, 191. Elsevier B.V.

EU, 2016. European red list of habitats. https://doi.org/10.2779/032638.

Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M.A., Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., Serrano, O., 2012. Seagrass ecosystems as a globally significant carbon stock. Nat. Geosci. 5 (7), 505–509. https://doi.org/10.1038/ngeo1477.

Furlan, E., Cornet, C., Ozkiper, O., Allegri, E., Bianconi, A., Fonseca, C., Taylor, D., Trégarot, E., van der Geest, M., O'Leary, B., Roberts, C., Simide, R., Pérez, G., Espinoza-Cordova, F., Krause, T., Boyd, E., Gil, A., 2024. MAS-NBS: a multi-tiered approach to assess suitability for Nature-based solutions. https://doi.org/10.13140/RG.2.2.24908.01921.

Furlan, E., Torresan, S., Critto, A., Lovato, T., Solidoro, C., Lazzari, P., Marcomini, A., 2019. Cumulative impact index for the adriatic sea: accounting for interactions among climate and anthropogenic pressures. Sci. Total Environ. 670, 379–397. https://doi.org/10.1016/j.scitotenv.2019.03.021.

Geukes, H.H., van Bodegom, P.M., van Oudenhoven, A.P.E., 2024. Setting the stage for decision-making on nature-based solutions for coastal climate adaptation. Ocean Coast Manag. 247. https://doi.org/10.1016/j.ocecoaman.2023.106916.

Gissi, E., Maes, F., Kyriazi, Z., Ruiz-Frau, A., Santos, C.F., Neumann, B., Quintela, A., Alves, F.L., Borg, S., Chen, W., da Luz Fernandes, M., Hadjimichael, M., Manea, E., Marques, M., Platjouw, F.M., Portman, M.E., Sousa, L.P., Bolognini, L., Flannery, W., Unger, S., 2022. Contributions of marine area-based management tools to the UN sustainable development goals. J. Clean. Prod. 330 (October 2021). https://doi.org/10.1016/j.jclepro.2021.129910.

Green, A.J., Alcorlo, P., Peeters, E.T.H.M., Morris, E.P., Espinar, J.L., Bravo-Utrera, M.A., Bustamante, J., Díaz-Delgado, R., Koelmans, A.A., Mateo, R., Mooij, W.M., Rodríguez-Rodríguez, M., van Nes, E.H., Scheffer, M., 2017. Creating a safe operating space for wetlands in a changing climate. Front. Ecol. Environ. 15 (2), 99–107. https://doi.org/10.1002/fee.1459.

Greene, R., Devillers, R., Luther, J.E., Eddy, B.G., 2011. GIS-based multiple-criteria decision analysis. Geography Compass 5 (6), 412–432. https://doi.org/10.1111/j.1749-8198.2011.00431.x.

Gualdi, S., Somot, S., Li, L., Artale, V., Adani, M., Bellucci, A., Braun, A., Calmanti, S., Carillo, A., Dell'Aquila, A., Déqué, M., Dubois, C., Elizalde, A., Harzallah, A., Jacob, D., L'Hévéder, B., May, W., Oddo, P., Ruti, P., Navarra, A., 2013a. The CIRCE simulations: regional climate change projections with realistic representation of the Mediterranean Sea. Bull. Am. Meteorol. Soc. 94 (1), 65–81. https://doi.org/10.1175/bams-d-11-00136.1.

Gualdi, S., Somot, S., May, W., Castellari, S., Déqué, M., Adani, M., Artale, V., Bellucci, A., Breitgand, J.S., Carillo, A., Cornes, R., Dell'Aquila, A., Dubois, C., Efthymiadis, D., Elizalde, A., Gimeno, L., Goodess, C.M., Harzallah, A., Krichak, S.O., Xoplaki, E., 2013b. Future climate projections. In: Regional Assessment of Climate Change in the Mediterranean, pp. 53–118. https://doi.org/10.1007/978-94-007-5781-3_3.

Heide, T.V.D., Nes, E.H.V., Geerling, G.W., Smolders, A.J.P., Bouma, T.J., Katwijk, M.M. V., 2007. Positive feedbacks in seagrass ecosystems: implications for success in conservation and restoration. Ecosystems 10 (8), 1311–1322. https://doi.org/10.1007/s10021-007-9099-7.

Houngnandan, F., Kéfi, S., Deter, J., 2020. Identifying key-conservation areas for Posidonia oceanica seagrass beds. Biol. Conserv. 247 (February). https://doi.org/10.1016/j.biocon.2020.108546.

Hynes, S., Chen, W., Vondolia, K., Armstrong, C., O'Connor, E., 2021. Valuing the ecosystem service benefits from kelp forest restoration: a choice experiment from Norway. Ecol. Econ. 179. https://doi.org/10.1016/j.ecolecon.2020.106833.

Infantes, E., Terrados, J., Orfila, A., Cañellas, B., Álvarez-Ellacuria, A., 2009. Wave energy and the upper depth limit distribution of Posidonia oceanica. Bot. Mar. 52 (5), 419–427. https://doi.org/10.1515/BOT.2009.050.

IUCN, 2020. Guidance for using the IUCN Global Standard for Nature-based solutions: first editions. https://doi.org/10.2305/iucn.ch.2020.09.en.

Jones, B.L.H., Unsworth, R.K.F., Nordlund, L.M., Eklöf, J.S., Ambo-Rappe, R., Carly, F., Jiddawi, N.S., La Nafie, Y.A., Udagedara, S., Cullen-Unsworth, L.C., 2022. Dependence on seagrass fisheries governed by household income and adaptive capacity. Ocean Coast Manag. 225. https://doi.org/10.1016/j.ocecoaman.2022.106247.

Kay, S., 2020. Marine biogeochemistry data for the Northwest European shelf and Mediterranean Sea from 2006 up to 2100 derived from climate projections. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.dcc9295c. (Accessed 14 October 2025).

Koopmans, D., Holtappels, M., Chennu, A., Weber, M., de Beer, D., 2020. High net primary production of mediterranean seagrass (Posidonia oceanica) meadows determined with aquatic eddy covariance. Front. Mar. Sci. 7. https://doi.org/10.3389/fmars.2020.00118.

Levin, N., Coll, M., Fraschetti, S., Gal, G., Giakoumi, S., Göke, C., Heymans, J.J., Katsanevakis, S., Mazor, T., Öztürk, B., Rilov, G., Gajewski, J., Steenbeek, J., Kark, S., 2014. Biodiversity data requirements for systematic conservation planning in the Mediterranean Sea. Mar. Ecol. Prog. Ser. 508 (August), 261–281. https://doi.org/10.3354/meps10857.

Liquete, C., Zulian, G., Delgado, I., Stips, A., Maes, J., 2013. Assessment of coastal protection as an ecosystem service in Europe. Ecol. Indic. 30, 205–217. https://doi.org/10.1016/j.ecolind.2013.02.013.

Louarn, A., Meur-Ferec, C., Hervé-Fournereau, N., 2025. The concept of 'nature-based solutions' applied to urban coastal risks: a bibliometric and content analysis review. Ocean Coast Manag. 261. https://doi.org/10.1016/j.ocecoaman.2024.107530.

Maida, G.D., Tomasello, A., Sciandra, M., Pirrotta, M., Milazzo, M., Calvo, S., 2013. Effect of different substrata on rhizome growth, leaf biometry and shoot density of Posidonia oceanica. Mar. Environ. Res. 87–88, 96–102. https://doi.org/10.1016/j.marenvres.2013.04.001.

Marbà, N., Díaz-almela, E., Duarte, C.M., 2014. Mediterranean seagrass (Posidonia oceanica) loss between 1842 and 2009. Biological Conservation 176, 183–190. https://doi.org/10.1016/j.biocon.2014.05.024.

Marbà, N., Duarte, C.M., 2010. Mediterranean warming triggers seagrass (Posidonia oceanica) shoot mortality. Glob. Change Biol. 16 (8), 2366–2375. https://doi.org/10.1111/j.1365-2486.2009.02130.x.

Martinez-Harms, M.J., Bryan, B.A., Balvanera, P., Law, E.A., Rhodes, J.R., Possingham, H.P., Wilson, K.A., 2015. Making decisions for managing ecosystem services. Biol. Conserv. 184, 229–238. https://doi.org/10.1016/j.biocon.2015.01.024.

MedECC, 2020. Climate and environmental change in the Mediterranean Basin – current situation and risks for the future. In: Cramer, W., Guiot, J., Marini, K. (Eds.), First Mediterranean Assessment Report, Union for the Mediterranean, Plan Bleu. UNEP/MAP. https://doi.org/10.5281/zenodo.4768833.

Nicholson, E., Rowland, J.A., Sato, C.F., Stevenson, S., Watermeyer, K.E., Andrade, A., Brooks, T.M., Burgess, N.D., Grantham, H., Hill, S., Keith, D.A., 2021. Martine Maron 11 , Daniel Metzke 12, 9.

Nordlund, L.M., Koch, E.W., Barbier, E.B., Creed, J.C., 2016. Seagrass ecosystem services and their variability across genera and geographical regions. PLoS One 11 (10), 1–23. https://doi.org/10.1371/journal.pone.0163091.

O'Leary, B.C., Fonseca, C., Cornet, C.C., de Vries, M.B., Degia, A.K., Failler, P., Furlan, E., Garrabou, J., Gil, A., Hawkins, J.P., Krause-Jensen, D., Roux, X.L., Peck, M.A., Pérez, G., Queirós, A.M., Różyński, G., Sanchez-Arcilla, A., Simide, R., Pinto, I.S., Roberts, C.M., 2023. Embracing nature-based solutions to promote resilient marine and coastal ecosystems. Nature-Based Solutions 3 (December 2022). https://doi.org/10.1016/j.nbsj.2022.100044, 100044-100044.

Ondiviela, B., Losada, I.J., Lara, J.L., Maza, M., Galván, C., Bouma, T.J., van Belzen, J., 2014. The role of seagrasses in coastal protection in a changing climate. Coast. Eng. 87, 158–168. https://doi.org/10.1016/j.coastaleng.2013.11.005.

Oreska, M.P.J., McGlathery, K.J., Aoki, L.R., Berger, A.C., Berg, P., Mullins, L., 2020. The greenhouse gas offset potential from seagrass restoration. Sci. Rep. 10 (1), 7325. https://doi.org/10.1038/s41598-020-64094-1.

Orth, R.J., Lefcheck, J.S., McGlathery, K.S., Aoki, L., Luckenbach, M.W., Moore, K.A., Oreska, M.P.J., Snyder, R., Wilcox, D.J., Lusk, B., 2020. Restoration of seagrass habitat leads to rapid recovery of coastal ecosystem services. A P P L I E D E C O L O G Y Sci. Adv. 6.

Ozkiper, O., Allegri, E., Bianconi, A., Pham, H.V., Furlan, E., Simide, R., van der Geest, M., Critto, A., 2024. A GIS-MCDA approach to map environmental suitability of Posidonia oceanica meadows as blue nature-based solutions in the mediterranean eco-region. Sci. Total Environ. 955, 176803. https://doi.org/10.1016/j.scitotenv.2024.176803.

Palumbi, S.R., Sandifer, P.A., Allan, J.D., Beck, M.W., Fautin, D.G., Fogarty, M.J., Halpera, B.S., Incze, L.S., Leong, J.A., Norse, E., Stachowicz, J.J., Wall, D.H., 2009. Managing for ocean biodiversity to sustain marine ecosystem services. Front. Ecol. Environ. 7 (4), 204–211. https://doi.org/10.1890/070135.

Pansini, A., Bosch-Belmar, M., Berlino, M., Sarà, G., Ceccherelli, G., 2022. Collating evidence on the restoration efforts of the seagrass posidonia oceanica: current knowledge and gaps. In: Science of the Total Environment, 851. Elsevier B.V.

Pérez, G., O'Leary, B.C., Allegri, E., Casal, G., Cornet, C.C., de Juan, S., Failler, P., Fredriksen, S., Fonseca, C., Furlan, E., Gil, A., Hawkins, J.P., Maréchal, J.P., McCarthy, T., Roberts, C.M., Trégarot, E., van der Geest, M., Simide, R., 2024. A conceptual framework to help choose appropriate blue nature-based solutions. J. Environ. Manag. 352 (August 2023). https://doi.org/10.1016/j.jenvman.2023.119936.

Pergent-Martini, C., Otero, M.M., Numa, C., 2016. A5.535 posidonia beds in the mediterranean infralittoral zone. European Red List of Habitats, pp. 1–11.

Poikane, S., Kelly, M.G., Herrero, F.S., Pitt, J.A., Jarvie, H.P., Claussen, U., Leujak, W., Solheim, A.L., Teixeira, H., Phillips, G., 2019. Nutrient criteria for surface waters under the European water framework directive: current state-of-the-art, challenges and future outlook. Sci. Total Environ. 695. https://doi.org/10.1016/j.scitotenv.2019.133888, 133888-133888.

Rey, F., Cécillon, L., Cordonnier, T., Jaunatre, R., Loucougaray, G., 2015. Integrating ecological engineering and ecological intensification from management practices to ecosystem services into a generic framework: a review. Agron. Sustain. Dev. 35 (4), 1335–1345. https://doi.org/10.1007/s13593-015-0320-3.

Ruiz, J.M., Romero, J., 2003. Effects of disturbances caused by coastal constructions on spatial structure, growth dynamics and photosynthesis of the seagrass Posidonia oceanica. Mar. Pollut. Bull. 46 (12), 1523–1533. https://doi.org/10.1016/j.marpolbul.2003.08.021.

Salas, M.F., Araujo, R., Leujak, W., Poikane, S., 2022. Physico-chemical supporting elements in coastal waters: WFD-MSFD-RSC Links. https://doi.org/10.2760/58715.

Sánchez-Lizaso, J.L., Romero, J., Ruiz, J., Gacia, E., Buceta, J.L., Invers, O., Torquemada, Y.F., Mas, J., Ruiz-Mateo, A., Manzanera, M., 2008. Salinity tolerance of the Mediterranean seagrass posidonia oceanica: recommendations to minimize the impact of brine discharges from desalination plants. Desalination 221 (1–3), 602–607. https://doi.org/10.1016/j.desal.2007.01.119.

Scanu, S., Piazzolla, D., Bonamano, S., Penna, M., Piermattei, V., Madonia, A., Frattarelli, F.M., Mellini, S., Dolce, T., Valentini, R., Coppini, G., Fersini, G., Marcelli, M., 2022. Economic evaluation of Posidonia oceanica ecosystem services along the Italian Coast. Sustainability 14 (1). https://doi.org/10.3390/su14010489.

Scheffer, M., Barrett, S., Carpenter, S.R., Folke, C., Green, A.J., Holmgren, M., Hughes, T. P., Kosten, S., van de Leemput, I.A., Nepstad, D.C., van Nes, E.H., Peeters, E.T.H.M., Walker, B., 2015. Creating a safe operating space for iconic ecosystems. Science 347 (6228), 1317–1319. https://doi.org/10.1126/science.aaa3769.

Scheffer, M., Carpenter, S., Foley, J.A., Folke, C., Walker, B., 2001. Catastrophic shifts in ecosystems. Nature 413 (6856), 591–596. https://doi.org/10.1038/35098000.

Seddon, N., Chausson, A., Berry, P., Girardin, C.A.J., Smith, A., Turner, B., 2020. Understanding the value and limits of nature-based solutions to climate change and other global challenges. Philos. Trans. R. Soc. Lond. B Biol. Sci. 375 (1794), 20190120. https://doi.org/10.1098/rstb.2019.0120.

SEEA, 2021. System of environmental-economic accounting — ecosystem accounting final draft. SEEA 5 (Marzo), 362-362. https://unstats.un.org/unsd/statcom/52nd-session/documents/BG-3f-SEEA-EA_Final_draft-E.pdf.

Simeoni, C., Furlan, E., Bianconi, A., Pham, V.H., Vascon, S., Simide, R., Marcomini, A., Critto, A., 2025. The big picture: appraising the risk of cumulative impacts on seagrass meadows in the Mediterranean Sea. Ecol. Inform. https://doi.org/10.1016/j.ecoinf.2025.103461.

Simeoni, C., Furlan, E., Pham, H.V., Critto, A., de Juan, S., Trégarot, E., Cornet, C.C., Meesters, E., Fonseca, C., Botelho, A.Z., Krause, T., N'Guetta, A., Cordova, F.E., Failler, P., Marcomini, A., 2023. Evaluating the combined effect of climate and anthropogenic stressors on marine coastal ecosystems: insights from a systematic review of cumulative impact assessment approaches. Sci. Total Environ. 861 (November 2022). https://doi.org/10.1016/j.scitotenv.2022.160687.

Syahid, L.N., Sakti, A.D., Virtriana, R., Wikantika, K., 2020. Determining optimal location for mangrove planting using remote sensing and climate model projection in Southeast Asia. Remote Sens. https://doi.org/10.3390/rs12223734.

Saaty, R.W., 1987. The analytic hierarchy process-what it is and how it is used. Math. Model. 9 (3–5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8.

Telesca, L., Belluscio, A., Criscoli, A., Ardizzone, G., Apostolaki, E.T., Fraschetti, S., Gristina, M., Knittweis, L., Martin, C.S., Pergent, G., Alagna, A., Badalamenti, F., Garofalo, G., Gerakaris, V., Pace, M.L., Pergent-Martini, C., Salomidi, M., 2015. Seagrass meadows (Posidonia oceanica) distribution and trajectories of change. Sci. Rep. 5, 1–14. https://doi.org/10.1038/srep12505.

Terrados, J., Marín, A., Celdrán, D., 2013. Use of Posidonia oceanica seedlings from beach-cast fruits for seagrass planting. Bot. Mar. 56 (2), 185–195. https://doi.org/10.1515/bot-2012-0200.
Terrados, J., Williams, S.L., 1997. Leaf versus root nitrogen uptake by the surfgrass Phyllospadix torreyi. Mar. Ecol. Prog. Ser. 149 (1–3), 267–277. https://doi.org/10.3354/meps149267.
Tursi, A., Mastrototaro, F., Montesanto, F., Giosa, F.D., Lisco, A., Bottalico, A., Chimienti, G., 2022. The Status of Posidonia oceanica at Tremiti Islands Marine Protected Area (Adriatic Sea), pp. 1–17.
UNEP, 2022. Nature-Based Solutions: Opportunities and Challenges for Scaling up.
UNEP/MAP, 2012. UNEP/MAP: State of the Mediterranean Marine and Coastal Envir Onment. UNEP/MAP – Barcelona Convention, Athens, p. 2012.
Unsworth, R.K.F., Cullen-Unsworth, L.C., Jones, B.L.H., Lilley, R.J., 2022. The planetary role of seagrass conservation. Science 377 (6606), 609–613. https://doi.org/10.1126/science.abq6923.
Vassallo, P., Paoli, C., Rovere, A., Montefalcone, M., Morri, C., Bianchi, C.N., 2013. The value of the seagrass posidonia oceanica: a natural capital assessment. Mar. Pollut. Bull. 75 (1–2), 157–167. https://doi.org/10.1016/j.marpolbul.2013.07.044.
World Bank, 2023. Unlocking Blue Carbon Development: Investment Readiness Framework for Governments.
Xu, S., Qiao, Y., Xu, S., Yue, S., Zhang, Y., Liu, M., Zhang, X., Zhou, Y., 2021. Diversity, distribution and conservation of seagrass in coastal waters of the Liaodong Peninsula, North Yellow Sea, northern China: implications for seagrass conservation. Mar. Pollut. Bull. 167. https://doi.org/10.1016/j.marpolbul.2021.112261.
Zenetos, A., Siokou-Frangou, I., Gotsis-Skretas, O., Groom, S., 2002. European Environment Agency Europe ' S Biodiversity – Biogeographical Regions and Seas Seas Around Europe the Mediterranean Sea. *Main*(June 2014).
Zrelli, R.E., Hcine, A., Yacoubi, L., Roa-Ureta, R.H., Gallai, N., Castet, S., Grégoire, M., Courjault-Radé, P., Rabaoui, L.J., 2023. Economic losses related to the reduction of Posidonia ecosystem services in the Gulf of Gabes (Southern Mediterranean Sea). Mar. Pollut. Bull. 186 (June 2022). https://doi.org/10.1016/j.marpolbul.2022.114418.