



A GIS-MCDA approach to map environmental suitability of *Posidonia oceanica* meadows as blue nature-based solutions in the Mediterranean eco-region

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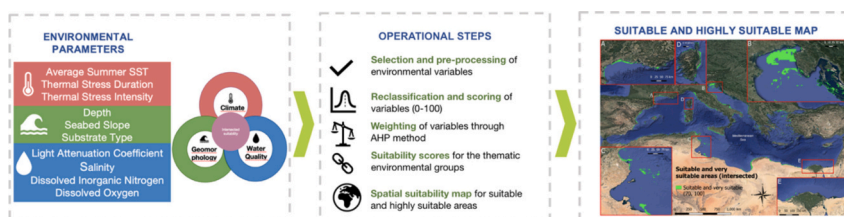
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HIGHLIGHTS

- Environmental Blue-NBS suitability modeling developed for seagrasses in the Mediterranean ecoregion using AHP and GIS methods.
- Multidimensional approach integrates geomorphological, water quality and climatic indicators considering expert opinions.
- Using GIS tools and MCDA to map marine coastal areas for prioritizing suitable areas for Blue NBS implementation.
- Very low WQ in Northern Adriatic, while southern Mediterranean has unsuitable climatic conditions for seagrasses growth.
- Results provide a baseline scenario for decision makers to implement blue NBS to recover ES and functions along marine-coastal areas.

GRAPHICAL ABSTRACT



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ABSTRACT

The growing environmental risks induced by interacting climate and human-induced pressures threaten the survival and growth of marine coastal ecosystems (MCEs) and the ecosystem services they provide. Nature-based solutions (NBS), consisting of ecosystem-based approaches, have emerged as vital tools for climate adaptation and mitigation facing biodiversity loss and societal challenges. Identifying suitable environmental conditions for implementing Blue-NBS in marine coastal areas is a key priority to drive robust and cost-effective nature-based adaptation pathways. This study developed a suitability model for Blue-NBS, with a specific focus on *Posidonia oceanica* meadows in the Mediterranean Sea under a baseline scenario. GIS-based Multiple Criteria Decision Analysis (MCDA) was applied for data integration and prioritization of different environmental variables in

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geomorphological (e.g., depth), water quality (WQ) (e.g., salinity), and climatic (e.g., thermal stress) sub-groups. Suitability classes and scores for each variable were determined using statistical distributions, ensuring a data-driven approach to defining environmental suitability. Variables' weights were derived from the Analytic Hierarchy Process (AHP) based on expert judgment and then combined with scores to generate suitability maps for managing Blue-NBS on seagrasses. Depth was found to be the most dominant environmental variable, with shallow areas (e.g., Northern Adriatic, Gulf of Gabés) showing higher suitability. The southern part of the Mediterranean (e.g., Egypt) reported relatively low scores for both climate and WQ, while the Northern Adriatic had the lowest WQ scores. This study represents the first attempt to evaluate Blue-NBS suitability for seagrass meadows at the eco-regional scale with geomorphologic, WQ, and climatic variables, providing decision support for the selection and allocation of Blue-NBS in different environmental settings. The resulting environmental suitability maps represent a basis for the integration of socio-economic and governance-related indicators into a more complex, multi-tier approach to support NBS mainstreaming.

1. Introduction

Marine and coastal ecosystems (MCEs) have become increasingly vulnerable to climate change (CC) impacts and anthropogenic activities (IPCC, 2022). MCEs provide many ecosystem services and functions, such as coastal protection, water purification, and carbon sequestration (Cohen-Shacham et al., 2016; EEA, 2021; UNEP-WCMC, 2011; IPCC, 2022). Nature-based Solutions (NBS), an umbrella concept consisting of various ecosystem-based approaches (e.g., ecosystem protection and ecosystem-based adaptation), are innovative, integrated, and sustainable solutions that protect and manage nature while providing comprehensive societal benefits (Cohen-Shacham et al., 2016). NBS can mitigate environmental degradation while improving ecosystem resilience and cover with various co-benefits by delivering multifaceted ecosystem services (Gómez Martín et al., 2020). They represent more flexible and adaptive solutions to changing environmental conditions compared to traditional/grey infrastructures, and are able to face societal challenges (EC, 2015; EEA, 2021).

The NBS have been mainly implemented in the terrestrial environment and urban systems, while there is still limited knowledge on how to implement NBS in marine coastal areas due to their complexity and dynamics, as well as the lack of long-term data and high uncertainty on their effectiveness (O' Leary et al., 2023). Although NBS have been implemented in some marine coastal contexts (e.g., seagrass restoration, mangrove restoration), the integration of this concept to large-scale interventions (i.e., upscaling processes) only received attention in the last two decades (Cohen-Shacham et al., 2019). Implementation of NBS in marine and coastal environments, so called Blue-NBS, is often aimed at reducing the physical impacts of CC (e.g., floods, erosion), in addition to improving water quality (WQ) by uptaking nutrients, trapping suspended particulate matter and sequestering carbon (CNDR and UNEP, 2019; Terrados and Williams, 1997).

However, for an effective and successful implementation of Blue-NBS, it is essential to identify suitable areas, where marine and/or coastal habitat restoration can be successful, while also providing the envisioned benefits for humankind. This requires understanding and consideration of the multiple dimensions (i.e., environmental, socio-economic and governance) related to implementation of the specific Blue-NBS (Mubeen et al., 2021). NBS suitability analysis is often performed at a local scale in urban and rural areas, considering the relationship between human-being and nature through integration of environmental, socio-economic, and governance dimensions in the assessment procedure (Antognelli and Vizzari, 2021; Bellamy et al., 2017).

To determine suitable areas for Blue-NBS (i.e., MCE's restoration), multiple studies (e.g., Bakirman and Gumusay, 2020; Catucci and Scardi, 2020; Syahid et al., 2020) often integrated diverse variables, applied different modelling methods considering variability over time and space, and investigated different timeframe scenarios. For example, Bakirman and Gumusay (2020) integrated geomorphologic variables (e.g., depth) within a GIS-based approach to evaluate seagrasses restoration suitability. Likewise, Syahid et al. (2020) included future CC

scenarios (i.e., different representative concentration pathways (RCPs)) and socio-economic variables when applying a GIS-based approach to mangrove restoration. In contrast, Catucci and Scardi (2020) identified the spatial distribution of seagrass species and the status of seagrass meadows (i.e., living, regressed, or mixed conditions) by assessing the vulnerability of *Posidonia oceanica* meadows through Machine Learning techniques. Overall, suitability assessments resulted to focus mainly on environmental variables able to frame growth and survival zone (comfort zone/safe operating space) of MCEs (Green et al., 2017; Scheffer et al., 2015).

While application of machine learning techniques, such as species presence/absence modelling, has proven to be very successful in NBS suitability mapping, GIS-based approaches that include expert and stakeholder opinions as important information sources allowed for the development of multi-dimensional analyses. This is especially crucial when considering the complexity of MCEs and NBS design and the data gaps in different components (i.e., both biotic and abiotic) in marine coastal areas. The integration of GIS and Multiple Criteria Decision Analysis (MCDA) techniques can provide powerful support to frame complex decision-making problems involving multiple decision dimensions and related variables. GIS-based MCDA is a multi-step process including setting up criteria, weighting, aggregation, and geoprocessing tasks (Greene et al., 2011), providing a valuable tool for identifying and evaluating criteria and enabling ranking and choice among alternatives. Combined scores and mapping are useful for decision-makers while developing conservation and management plans at different scales.

Drawing on previous studies, this study provides an essential first step in advancing a multi-tier NBS suitability framework by focusing on the critical environmental dimensions necessary for successful seagrass conservation and/or restoration. In this setting, this study proposes a GIS-based Analytic Hierarchy Process (AHP), a widely used MCDA technique, to identify areas with suitable environmental conditions for Blue-NBS design and implementation in the Mediterranean eco-region, with a specific focus on seagrass meadows (*Posidonia oceanica*). The methodology builds upon the identification and integration of optimum and threshold values for various environmental variables, crucial for seagrass survival and growth, into the AHP model, which allows for more accurate suitability mapping at an eco-regional scale. This approach uniquely combines statistical distribution analysis, expert knowledge, and existing literature to define these values, ensuring a robust and ecologically informed decision-making process. The developed approach aims to improve previous *P. oceanica* mapping efforts (e.g., Bakirman and Gumusay, 2020; Catucci and Scardi, 2020; Hounghan et al., 2020) by providing a structured method to prioritize environmental variables and assess their combined influence using AHP and GIS tools. This synergistic framework not only enhances decision-making in Blue-NBS design but also paves the way for integrating socio-economic and governance factors in future research, making it a critical tool for ecosystem-based management in climate adaptation strategies.

2. Materials and methods

2.1. Study area

The Mediterranean Sea, the largest enclosed sea (2.5 million km²) (Coll et al., 2010, 2012) with a total coastline length of 46,000 km (Telesca et al., 2015), connects to the Atlantic Ocean, Red Sea, and Black Sea (Fig. 1). It covers only 0.82 % of the global ocean surface but hosts 18 % of the global macroscopic marine biodiversity (Bianchi and Morri, 2000), making it one of the 25 biodiversity hotspots, and home to over 17,000 marine species, including *Posidonia oceanica* meadows (Coll et al., 2010; UNEP, 1999).

The Mediterranean seabed generally has a gentle slope and it consists of mostly sand and muddy sand along the coastal areas (Levin et al., 2014). Regarding the physicochemical characteristics of the water, the Mediterranean Sea is one of the most well-oxygenated and oligotrophic oceanic systems, with some areas experiencing higher nutrient inputs due to river discharges and upwelling (e.g., Northern Adriatic) (Zenetos et al., 2002). There is an eastward increase in salinity (i.e., average 37.5–39.5 Practical Salinity Unit (PSU)) (Coll et al., 2010), and average sea surface temperatures (SST) range from 15 to 21 °C with seasonal variability. During summer, identified marine heatwaves have an average duration of 15 days with a mean intensity of 0.6 °C, which can cause thermal stress pressure on *P. oceanica* meadows (Marbà and Duarte, 2010; García et al., 2012; Darmaraki et al., 2019).

The Mediterranean Sea is particularly vulnerable to climate change impacts due to its enclosed nature (i.e., limited water exchange with oceans) and its various climate-sensitive ecosystems (e.g., seagrass beds, coralligenous assemblages, and maërl beds) (Zenetos et al., 2002; European Commission, 2006; Coll et al., 2012; MedECC, 2020). Additionally, terrestrial and maritime (e.g., wastewater treatment, and

dredging) human activities also produce severe cumulative impacts (Furlan et al., 2019; Simeoni et al., 2023), contributing in concert to accelerate degradation of WQ (Aslan et al., 2022; UNEP/MAP, 2012) with cascading effects on its ecosystems.

This study is particularly relevant for *P. oceanica*, an endemic foundation species covering the largest area (12,247 km² despite the lack of data) among seven Mediterranean seagrasses species (Telesca et al., 2015). *P. oceanica* provides a full range of ecosystem services, such as food provision, water purification, coastal protection, recreation and tourism, hence supporting many organisms and human well-being. According to the European Red List of Habitat assessment, *P. oceanica* is considered in “Vulnerable” status in the Mediterranean Sea (EU, 2016) with a reduction of about 13–50 % of its extent since 1960 (Marbà et al., 2014) due to stressors such as runoffs, anchoring, trawling, and invasive species like *Caulerpa taxifolia* introduced by shipping activities (Pergent-Martini et al., 2016).

As *P. oceanica* requires light for photosynthesis, it prefers shallow waters with a maximum depth of about 50 m (Tursi et al., 2022). Considering this, the environmental suitability maps for *P. oceanica* were only developed for coastal areas with a depth range from 0 to 60 m (Fig. 1).

2.2. Available data for the case study area

The implementation of multi-criteria approaches for suitability mapping requires integrating a large amount of heterogeneous data from different fields. Therefore, information about various environmental variables (i.e., climatic, geomorphological, and water quality) was retrieved from publicly available data portals to spatially characterize the main suitability factors determining *P. oceanica* growth and survival. Specifically, data on geomorphology (e.g., bathymetry) and

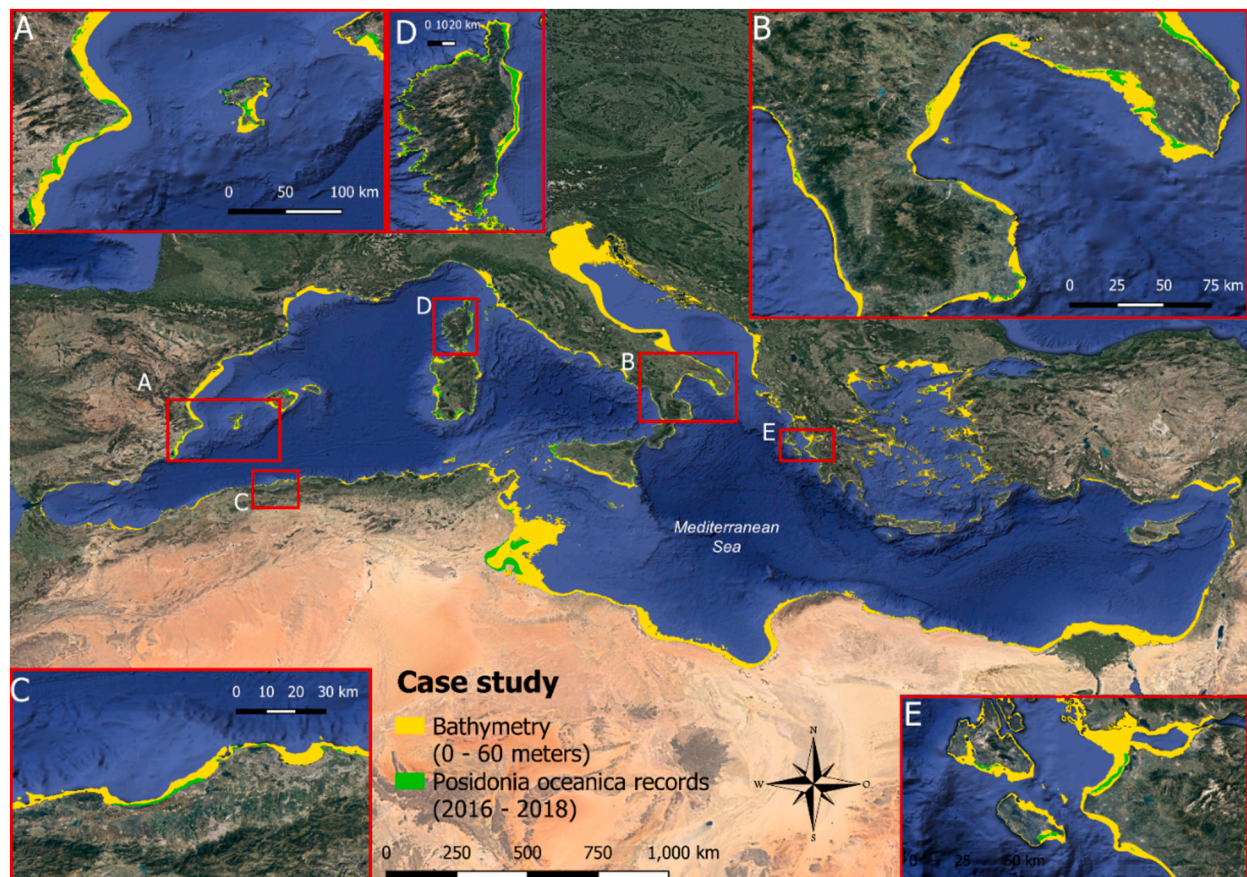


Fig. 1. Case study area for NBS suitability mapping (A: Spain coasts; B: Italian coasts; C: Algeria coasts; D: Corsica island; E: Greece coasts).

P. oceanica distribution and coverage were collected from EMODnet data portals (EMODnet seabed habitats, EMODnet bathymetry, and EMODnet geology), while the Copernicus Marine Environment Monitoring Service (CMEMS) was used to retrieve physical and biogeochemical data (e.g., SST, nitrogen compounds). In addition, some other relevant metrics and indicators were calculated from the abovementioned datasets to characterize the suitability of environmental conditions for seagrass. Specifically, the seabed slope was derived from the bathymetry dataset as a proxy representing past and present hydrodynamic effects (e.g., subtidal currents, wave forces) (Folmer et al., 2016). Thermal stress duration and intensity were computed from the SST dataset and used as a proxy for heat stress, a known threat to *P. oceanica* (Marbà and Duarte, 2010; García et al., 2012). Technical details on this data pre-processing phase were reported in Supplementary Material (SM) 1, leading to the visualization in Fig. S1.

The distribution of *P. oceanica* seagrass meadows in the Mediterranean Sea have been mainly recorded and reported between 2016 and 2018. As such, the suitability model of seagrass for Blue-NBS was trained using the abovementioned environmental data collected during this 2016–2018 timeframe. In Table S1 in SM1 we have reported the meta-data of the data collected for operationalization of the NBS suitability model developed for the Mediterranean eco-region.

2.3. NBS suitability modelling approach

The assessment of environmentally suitable areas for restoration of *P. oceanica* meadows was performed by developing a suitability model which builds on GIS-based and MCDA methods. Four main operational steps can be identified as follow: (i) selecting and preparing key variables able to represent environmental conditions for the survival and growth of *P. oceanica*, (ii) classifying and scoring selected variables considering literature review, expert opinions, and descriptive statistics of variables in the areas where *P. oceanica* populations exist, (iii) deriving weights using the AHP method including expert judgment and computing the overall suitability score for three thematic sub-groups (i.e., geomorphologic, WQ, and climate), (iv) overlay of suitable and very suitable areas for each sub-group to highlight highly suitable areas in the final suitability map. The following sections detail these methodological steps, as applied to the Mediterranean eco-region.

2.3.1. Selection and preparation of environmental indicators

The GIS-based AHP approach is based on the combination of individual weights and scores of different elements to assist decision-making process with aggregated scores (Chandio et al., 2013). In this study, ten environmental variables, which together represent the environmental conditions in the Mediterranean Sea, were selected and clustered into three sub-groups: climate, geomorphology, and WQ, respectively (Table S1 in SM1).

In particular, climate sub-group represents the suitability of *P. oceanica* growth to the variables relating to temperature values and changes (i.e., marine heatwaves or changes in SST due to climate change). Thus, summer SST (June–July–August), thermal stress duration, and intensity were selected as key variables for the climate sub-group. *P. oceanica* tolerates a wide range of SST (10–29 °C). However, prolonged exposure to temperatures higher than 28.4 °C forces the meadows to thermal stress conditions inhibiting their growth and functioning (Chefaoui et al., 2017; Marbà and Duarte, 2010).

Geomorphology represents the seabed characteristics linked to the natural coastal processes (e.g., storm surge). Geomorphologic variables can be considered as a proxy for light availability, root attachment, nutrient availability in sediment, and physical/hydrological factors. Therefore, depth, seabed slope, and substrate type were selected as key geomorphological variables for *P. oceanica* growth. In particular, seagrass meadows grow more efficiently in shallow water (i.e., mostly 1–30 m) with a soft substrate (e.g., sand) (Di Maida et al., 2013; Tursi et al., 2022). Moreover, they prefer gentle slope areas indicating reduced

hydrodynamic effects (e.g., waves, and currents). Lower wave energy and stable sediment with high *matte* accumulation is known to promote *P. oceanica* growth (Infantes et al., 2009).

WQ represents the influence of physical, chemical, and biological factors, and variations in the water column, on the growth and survival of *P. oceanica* meadows which need transparent, oligotrophic, and oxygenated water. Compared to other seagrass species (e.g., *Ruppia maritima*), *P. oceanica* is more sensitive to light limitation, while favouring stable and lower salinity (i.e., around 37–39 PSU) without a high tolerance to variability and increase of salinity (Effrosynidis et al., 2018). The relationship between seagrass and WQ has positive feedback (Ruiz and Romero, 2003). On the one hand, seagrasses contribute to increasing light availability by filtering particles in the water column, subsequently increasing seagrasses' growth rate and contribution to WQ improvement (van der Heide et al., 2011). On the other hand, if suitable WQ conditions are not provided for seagrass growth, the health condition of existing seagrass populations will be poor, and they will not be able to fulfill their water filtering functions such as nutrient uptake, with a resulting WQ degradation. Accordingly, light attenuation coefficient (K_d), dissolved inorganic nitrogen (DIN) concentration (i.e., N-NO_3 and N-NH_4), salinity and DO were selected as key WQ variables. Even though DIN concentration is the sum of the nitrogen concentration of NO_3 , NO_2 , and NH_4 , the data of NO_2 was not available from CMEMS; therefore, DIN was considered as the sum of the $\text{NO}_3\text{-N}$ and $\text{NH}_4\text{-N}$ in this study.

2.3.2. Classification and scoring of selected variables

In order to obtain an aggregated suitability score for each thematic sub-group, all variables were normalized using a common classification and scoring system, as indicated in Table 1. To assist the classification task of variables, descriptive statistics were developed taking into account values of the aforementioned variables (see Section 2.3.1) where *P. oceanica* populations are present in the Mediterranean Sea, examining locality, spread and skewness groups of all variables. This analysis, taking into account the limited state of knowledge on the ecosystem's comfort zone and tipping points (Trégarot et al., 2023), provided the basis for discussion with seagrass experts of the Mediterranean region, to understand and frame the favourable environmental conditions in which these ecosystems can grow and adapt.

In this analysis, for a given location, each variable was assigned a suitability score of either 10, 30, 60, 80 or 100, which were equivalent to the classes *least suitable*, *less suitable*, *moderately suitable*, *suitable*, and *very suitable*, respectively. As the values of environmental variables approach the threshold, pointing at the upper or lower ecological limits of species' tolerance, it is believed that the response of a certain species (i.e., *P. oceanica* presence and growth in this study) may change more abruptly (Munson et al., 2018; Spake et al., 2022). Therefore, a score of 30 was assigned to the *less suitable* class instead of applying a linear decrease with equal intervals across the entire range (Scheffer et al., 2001). Lastly, considering the adaptation capacity of seagrass meadows to changing and unsuitable conditions, 10 was assigned for the *least suitable* class (instead of 0).

Based on the characteristic of variables, the optimum conditions (i.e., *very suitable* class) were associated to those values located close to the median value (e.g., for salinity), or the lowest or the highest values depending on the analysed indicators (e.g., for summer SST and DO). While defining thresholds (i.e., *less suitable* class) underpinning variables classification in this study, both the outputs of existing studies in the literature were taken into account and the maximum and minimum values of the variables from the descriptive statistics were considered with seagrass experts.

For example, lower summer SST values represent more suitable conditions for *P. oceanica*. Histograms and boxplots belonging to the summer SST values in 2016–2018 were illustrated in Fig. 2. To define the interval of *very suitable* class, the value covering 50 % of the seagrass population, which corresponds to the median value (25.3 °C) of the average summer SST, was identified. Additionally, the *suitable* class

Table 1

Suitability classes and scores defined for each selected climate, geomorphological and water quality-related indicators.

Variable	Classes	Suitability class	Scores
Climate			
Summer SST (°C)	< 25.3	Very suitable	100
	25.3–26.8	Suitable	80
	26.8–28	Moderately suitable	60
Thermal stress duration (days)	28–28.4	Less suitable	30
	>28.4	Least suitable	10
	<5	Very suitable	100
	5–7	Suitable	80
	7–21	Moderately suitable	60
	21–45	Less suitable	30
Thermal stress intensity (°C)	>45	Least suitable	10
	0	Very suitable	100
	0–0.4	Suitable	80
	0.4–0.9	Moderately suitable	60
	0.9–1.6	Less suitable	30
	> 1.6	Least suitable	10
Geomorphology			
Depth (m)	0–1	Less suitable	30
	1–9	Suitable	80
	9–23	Very suitable	100
	23–30	Suitable	80
	30–40	Moderately suitable	60
	40–50	Less suitable	30
Seabed slope (%)	>50	Least suitable	10
	0–1	Very suitable	100
	1–5	Suitable	80
	5–10	Moderately suitable	60
	10–15	Less suitable	30
	>15	Least suitable	10
Substrate type	Sand and Dead Matte	Very suitable	100
	Muddy sand	Suitable	80
	Rock/hard and coarse	Moderately suitable	60
	Sandy mud and mixed	Less suitable	30
	Others (e.g., fine mud)	Least suitable	10
Water quality			
Light attenuation coefficient (m ⁻¹)	<0.06	Very suitable	100
	0.06–0.1	Suitable	80
	0.1–0.18	Moderately suitable	60
	0.18–0.27	Less suitable	30
Dissolved oxygen (mg/L)	>0.27	Least suitable	10
	>6.5	Very suitable	100
	6–6.5	Suitable	80
	4.6–6	Moderately suitable	60
Salinity (PSU)	<4.6	Least suitable	10
	<33	Least suitable	10
	33–36.8	Moderately suitable	60
	36.8–38	Suitable	80
	38–38.8	Very Suitable	100
	38.8–40	Suitable	80
Dissolved inorganic nitrogen (μmol/L)	40–40.5	Less suitable	30
	>40.5	Least suitable	10
	<3	Very suitable	100
	3–15	Moderately suitable	60
	>15	Least suitable	10

interval was determined as the values between the median and the third quartile (26.8 °C) of the average summer SST values, which covers 25 % of the seagrass population. Once the *suitable* and *very suitable* classes were defined, the intervals of lower suitability classes (from *moderately suitable* to *least suitable*) were defined based on non-structured discussions with seagrass experts, in line with the thresholds available in the literature (Marbà and Duarte, 2010; Mayot et al., 2005; Trégarot et al., 2023) and taking into account the maximum and minimum SST values to which *P. oceanica* are exposed. Specifically, the maximum average summer SST (28 °C) was given to the *moderately suitable* class, while 28.4 °C was assigned as the threshold of the *less suitable* class considering the literature (Chefaoui et al., 2017).

In the case of salinity, suitability classes were associated in two directions (i.e., considering both lower and upper limit). The first and third quartiles (38–38.8 PSU) of average salinity values (covering half of the seagrass population) were used to define the *very suitable* class. Next, considering the maximum and minimum average salinity values (i.e., 40 and 36.8 PSU), the intervals of the *suitable* classes were defined as 38.8–40 PSU for the upper part and 36.8–38 PSU for the lower part. Once the *suitable* and *very suitable* classes were decided, the intervals of lower suitability classes (from *moderately suitable* to *least suitable*) were defined by considering thresholds in current knowledge (Fernández-Torquemada and Sánchez-Lizaso, 2005; Ruíz et al., 2009; Sánchez-Lizaso et al., 2008), expert opinions, and maximum and minimum daily salinity values.

Note that for some variables (e.g., DIN) a reduced number of classes were assigned, due to the range of variability of indicators over seagrasses presence and the limited information available in the literature (i.e., optimum and threshold values). For instance, the maximum average DIN value to which almost all seagrasses are exposed is already quite low (i.e., around 3 μmole/L), resulting in the classification of values up to this concentration as *very suitable*. Moreover, the value of 15 μmol/L, reported by some countries (e.g., Greece, Croatia) as the DIN standards under the Marine Strategy Framework Directive (Poikane et al., 2019; Salas et al., 2022), was assigned to the *moderately suitable* class, and above this value was considered *least suitable*.

2.3.3. Derivation of weights

After the classification and scoring process, the AHP, one of the mostly applied MCDA methods for land suitability analysis (Chandio et al., 2013) and complex decision-making, was carried out to define the weights of variables. AHP uses pairwise comparisons to assess the relative importance of variables (Saaty, 1987), with expert scoring guiding this process. Seven seagrass experts provided scores (1–9) for the pairwise comparison matrices using the standard scale introduced by Saaty (1987) (Table S2–Table S6 in SM2). Next, the geometric mean of these matrices was used to form the final comparison matrix. This matrix was normalized by dividing each value (C_{ij}) by the sum of the values of its column (Eq. (1)). The final weight of each variable (W_{ij}), also known as priority vector, was obtained by calculating the arithmetic mean of the normalized values (X_{ij}) in rows (Eq. (2)).

$$X_{ij} = \frac{C_{ij}}{\sum_{i=1}^n C_{ij}} \quad (1)$$

$$W_{ij} = \frac{\sum_{j=1}^n X_{ij}}{n} \quad (2)$$

A crucial step in AHP is ensuring the consistency of expert scores, measured by the consistency ratio (CR), indicating the likelihood that the comparison matrix judgments were assigned randomly (Eq. (3)). The magnitude of the CR should be lower than 0.1 to provide a scoring with a reasonable level of consistency (Saaty, 1987). The intermediate steps of the consistency analysis for consistency vector (Cv), maximum eigenvalue (λ_{max}), consistency index (CI), and random index (RI) values are reported in SM2. ^{11max}.

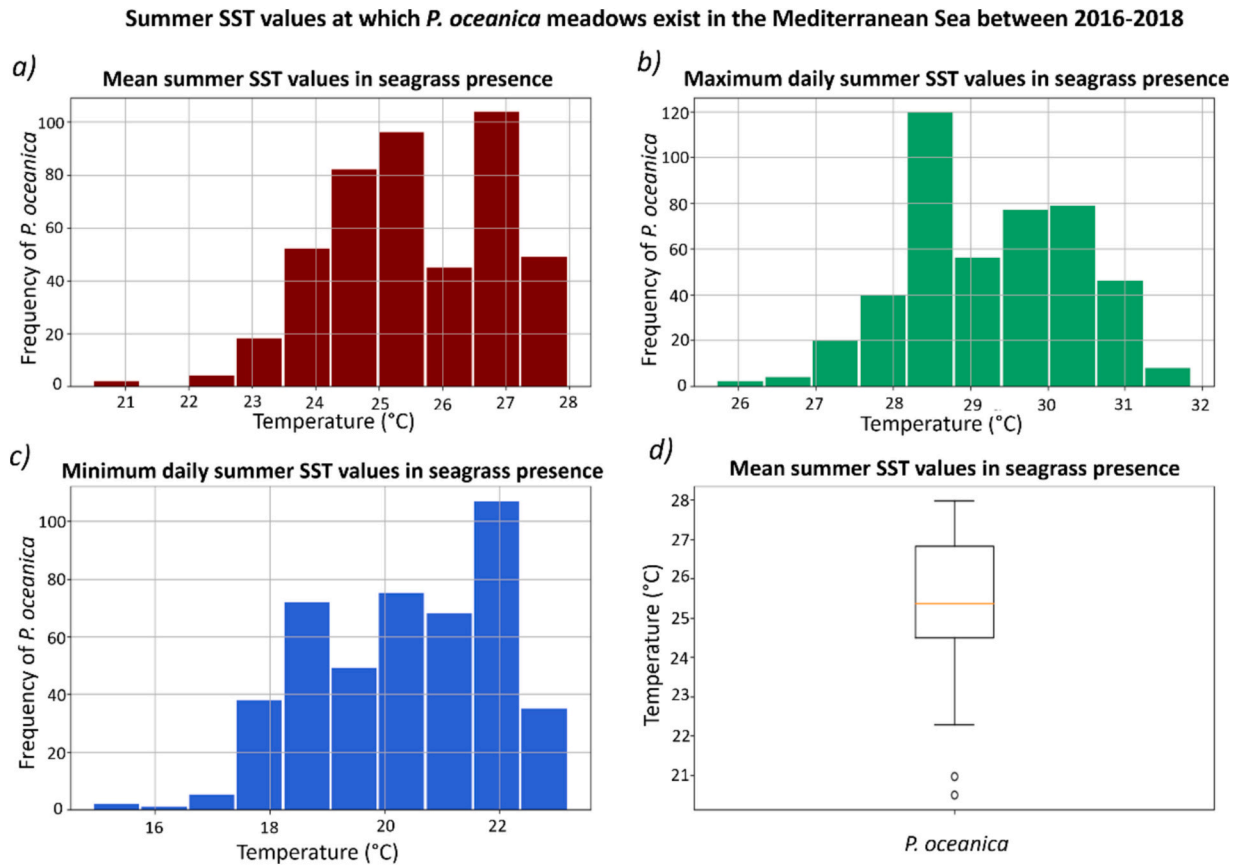


Fig. 2. Descriptive statistics of summer SST in *P. oceanica* presence: a) mean values; b) daily maximum values; c) daily minimum values d) boxplot of mean values in (a).

$$CR = CI/RI$$

(3)

2.3.4. Overlay analysis

The weighting process was performed for the variables belonging to each thematic sub-group separately. Once all the scores and weights for each variable were obtained, they were aggregated in a single suitability score using the weighted sum approach for each thematic sub-group (Eq. (4)).

$$\sum_{i=1}^n \text{Suitability score} = w_1x_1 + w_2x_2 + \dots + w_nx_n \quad (4)$$

where: x is the normalized score evaluated for each indicator; w is the weighting coefficient factor as defined through expert judgment for each indicator; n is the number of indicators belonging to each sub-group.

Once variables and weights were aggregated, final suitability scores were partitioned into five classes, from the lowest to the highest suitability scores. Values up to 30 were assigned as *least suitable*. 30–50 was identified as *less suitable*, 50–70 as *moderately suitable*, 70–90 as *suitable*, and 90–100 as *very suitable*. It is important to note that a narrower range was considered for the *very suitable* class to ensure perfect suitability conditions. This classification was applied to obtain the thematic suitability maps for geomorphology, WQ and climate sub-groups in $0.001^\circ \times 0.001^\circ$ grid cells.

The final suitability map was then created by selecting and overlaying *suitable* and *very suitable* areas from all sub-groups (i.e., geomorphology, WQ, and climate) to identify and explore the most suitable areas for the growth of *P. oceanica* and to support the decision-making of proper management and restoration actions. The regions not included in the final suitability map present lower scores (from *least* to *moderately suitable* class) in one or more of the thematic sub-groups.

2.4. Sensitivity analysis

GIS-MCDA applications involve various factors (e.g., criteria selection, thresholds, and variable weighting), introducing potential uncertainty (Chen et al., 2010). To assess the robustness and precision of the suitability model, a sensitivity analysis (SA) was performed using the Morris method, which analyzes variable contributions to the final suitability outcomes under different/random scenarios. Unlike traditional one-at-a-time (OAT) approaches, the Morris method, a global SA, perturbs variables repeatedly from different starting points to evaluate their importance and interactions (Morris et al., 1991). The effect of changes in the input variable on the output is called Elementary Effect (EE), which is observed thanks to randomized sampling matrices in the Morris one-at-a-time (MOAT) approach. The EE is then computed based on the following formula:

$$EE_i = \frac{y(x_1, \dots, x_i + \Delta, \dots, x_j) - y(x_1, \dots, x_i, \dots, x_j)}{\Delta} \quad (5)$$

where: x represents the given model parameters with j -dimensional vector $(x_1, \dots, x_i, \dots, x_j)$; $y(x)$ is the model output of Morris simulation; Δ is the step, defined as a multiple of $1/(p-1)$ and p is the number of levels.

Two measures (i.e., the mean (μ_i) and the standard deviation (σ_i)) are used to analyze the importance and interactions between variables based on the set of EEs (Morris et al., 1991). After numbers of independent EEs are computed with several trajectories (r) (i.e., distinct/elementary paths for sampling in the multi-dimensional space of parameters) for each input variable, the mean value representing the variable's overall influence is computed (Eq. (6)). A high μ_i value means that the variable has high strength and sensitivity on the output. Additionally, σ_i , which expresses the distribution of EE values, represents the high-order effect caused by the non-linear effect of the variable on the

output or its interactions with other variables (Eq. (7)). Moreover, Campolongo et al. (2007) proposed a third measure, μ^* representing the mean of the absolute values of the EEs to prevent negative and positive EE values from cancelling each other out, and to obtain an overall sensitivity (Eq. (8)). Within this study, the Morris method was applied using the open-source SALib library of Python (Herman and Usher, 2017).

$$\mu_i = \frac{\sum_{n=1}^r EE_n}{r} \quad (6)$$

$$\sigma_i = \sqrt{\frac{1}{r} \sum_{n=1}^r (EE_n - \mu_i)^2} \quad (7)$$

$$\mu_i^* = \frac{\sum_{n=1}^r |EE_n|}{r} \quad (8)$$

These sensitivity measures were computed for the variables of three sub-groups (i.e., geomorphology, WQ, and climate) separately. The outputs were illustrated by tabulating σ , μ , μ^* values and plotting σ versus μ^* for the weighting alternatives. In the graph, if the input variables are very close to the origin, they can be considered non-influential/unimportant. In the event that variables are located far from the origin in the x-axis (i.e., high μ^*), they have higher importance on the output than the other variables. In this case, if σ is low, the input shows a negligible non-linear effect. However, if both μ^* and σ are high, it points out an influential input with a strong degree of non-linear effects and/or interactions with other parameters.

3. Results

Following the approach presented in Section 2.3, variable weights were determined, and suitability scores and maps were obtained as primary outputs of the suitability assessment for restoration of *P. oceanica* meadows. Additionally, the results of the SA were investigated to understand the importance and non-linearity of the model input variables.

3.1. Weights of variables

While implementing the AHP method, the scores were assigned by experts in pairwise comparison matrices for the variables belonging to each sub-group. The CRs were computed as -0.01, 0 and 0.02 for geomorphology, WQ, and climate sub-groups, respectively, which showed good consistency levels of the final pairwise comparison matrices allowing the further analysis of suitability scores since they were smaller than 0.1.

The weights of geomorphological variables, which are depth, seabed slope, and substrate type, were 0.54, 0.20, and 0.26, respectively. The fact that the relative importance of depth is significantly higher than other variables aligns with the variable weights determined by Bakirman and Gumusay (2020), which focused specifically on geomorphological variables. Moreover, the weighting results of the WQ sub-group indicated that K_d had the highest weight as 0.51 showing obviously the strongest influence on the overall WQ suitability scores. It was followed by salinity, DIN and DO with the weights of 0.24, 0.16, 0.10 respectively.

The weight of thermal stress duration was obtained as 0.57, playing the most essential role for the climate suitability mapping as the third sub-group. Thermal stress intensity ranked second with the weight of 0.28 and summer SST got the lowest weight accounting for 0.15. These scores showed that the experts found the impact of the thermal stress variables on the seagrass growth and survival obviously greater than the mean summer SST values. Expert scores and CI, RI, and CR values were reported for geomorphology, WQ, and climate parameters in SM2.

3.2. Variables aggregation

3.2.1. Geomorphological suitability

Based on geomorphological scores only a very small *least suitable* area could be observed, while the distribution of geomorphological suitability scores from *less suitable* to *very suitable* classes was relatively homogeneous (Fig. 3). Almost half (i.e., 50.2 %) of the study area was classified as *suitable* and *very suitable*. In particular, relatively large *suitable* and *very suitable* areas were located along the Northern Adriatic coast of Italy and in the southeast of Tunisia (i.e., in the Gulf of Gabès) (boxes B and C in Fig. 3) due to a very gentle slope (i.e., 0–1 %) resulting in a large coastal area with shallow water (i.e., 0–35 m), and proper substrate types (i.e., sand and muddy sand) that characterized these locations. Moreover, the Gulf of Lion in France coasts, Gulf of Valencia in Spain coasts, Nile River Delta in Egypt coasts, and Greece's coasts and its islands also showed significant suitable areas.

Geomorphological suitability mainly decreased with increasing depth, which aligns with the historical distribution of *P. oceanica* meadows in the Mediterranean Sea (Telesca et al., 2015). *Moderately suitable* areas covered more than a quarter (i.e., 29.6 %) of the study area. Although these areas do not have very good conditions in terms of depth, they can still provide moderate geomorphologic conditions for *P. oceanica* growth as they generally have a gentle seabed slope and a suitable substrate type (e.g., sand or dead matte). The *less* and *least suitable* areas represented less than a quarter (i.e., 20.3 %) of the case study area. In addition to higher depth values characterizing these areas, the substrate type also contributed to decreasing the overall suitability score, since it generally changes from sand to muddy forms (e.g., the Italian coastline from Venice to the Apulian coastal areas). However, as the relative importance of substrate type was less than depth, the geomorphological score is still high in the very shallow part of this coastline.

Seabed slope generally showed gentle slope gradients (i.e., 0–5 %) on most of the Mediterranean coasts; hence it contributed to high suitability scores for most of the case study area. Relatively steep slopes, with sudden increases in depth, cause thinner and irregular suitable coastline surfaces, limiting the seagrass beds' expansion. For instance, suitable areas are patchier and thinner on the northern Mediterranean coasts of western Liguria and eastern Cote d'Azur (from Genoa to Nice), as well as in western Corsica, and Elba island, due to deep water and relatively steep slope conditions. Similarly, some parts of Algeria and Morocco's coasts in the southern Mediterranean showed irregular suitable patterns due to slope and depth effects. Hence, seagrass coverage would be lower compared to the overall length of the shoreline in these areas.

3.2.2. Water quality suitability

The WQ-related suitability scores showed that an extensive area in the Mediterranean Sea is *suitable* and even *very suitable* for *P. oceanica* (i.e., 89.9 %; Fig. 4). This result is tightly linked to the oxygenated, oligotrophic, and transparent water characteristics of the Mediterranean Sea. Although the total surface of areas belonging to *less suitable* and *least suitable* classes was very small (i.e., 1.0 %), 9.1 % of the study area was considered *moderately suitable*, suggesting that implementation of management measures to improve WQ status in these areas, most likely will support *P. oceanica* growth and persistence over there.

Less suitable and *moderately suitable* WQ-regions are primarily located in the Northern Adriatic and south/southeast Mediterranean (i.e., Egypt and Tunisia) (boxes B, C, and E in Fig. 4). More specifically, the main reason behind lower WQ scores in the Northern Adriatic (i.e., Veneto region) compared to the rest of the Mediterranean coasts, is the high eutrophic features characterizing this area, as reflected by excessively high DIN levels due to river discharges and influx of municipal sewage (Furlan et al., 2019). Moreover, the lower WQ score in Northern Adriatic, Egyptian coasts, and Tunisia coasts were mainly caused by relatively high values reported for K_d in these areas, which indicates lower light penetration in seawater. These phenomena can be linked to the

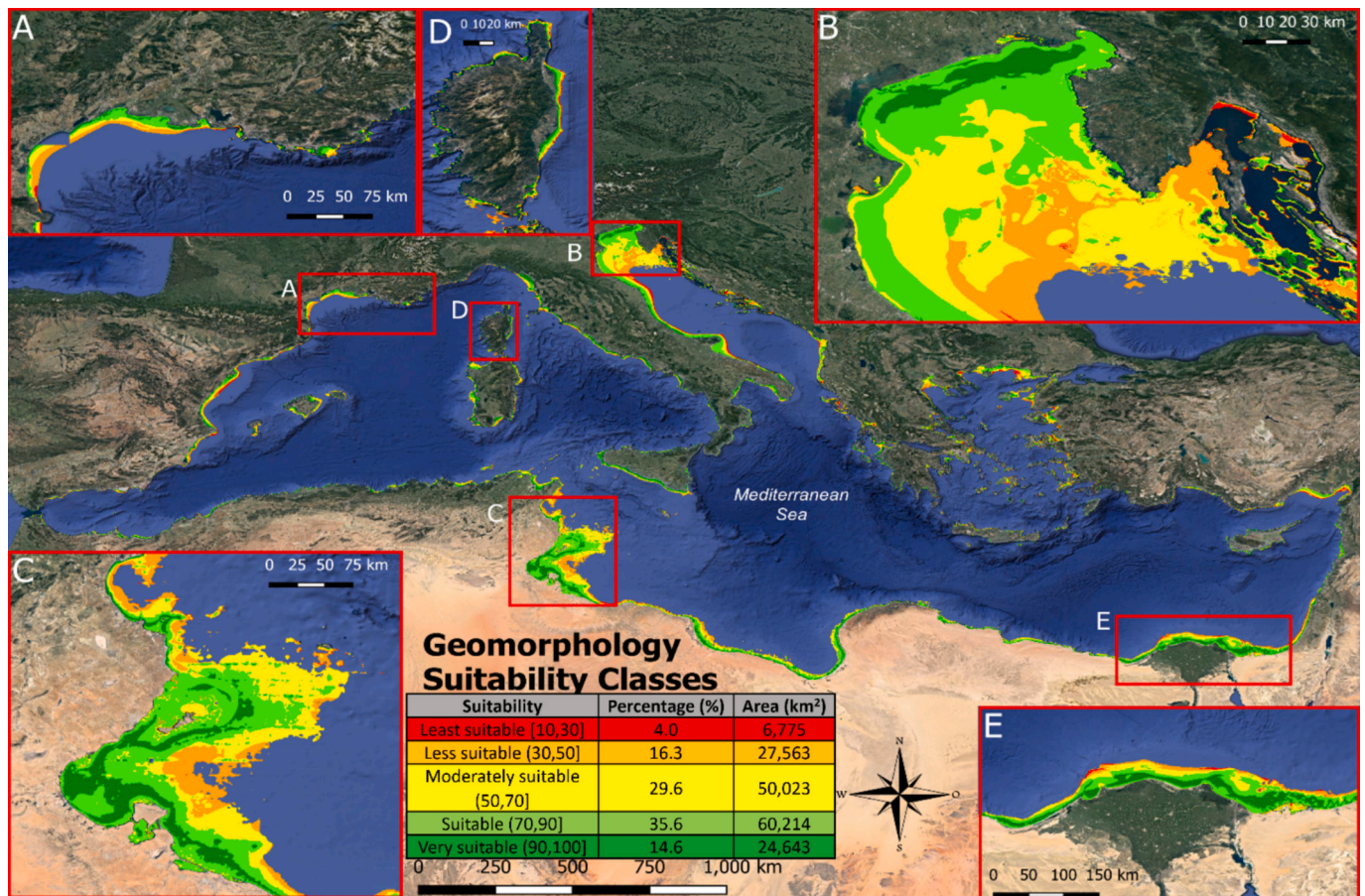


Fig. 3. Geomorphological suitability map and areas for *P. oceanica* (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès; D: Corsica; E: Egyptian coasts).

presence of the river mouth network of the Po River in the Northern Adriatic (Furlan et al., 2019) and Nile River in Egypt (Morsy et al., 2020), which threatens the WQ of the Mediterranean Sea. In addition, the observed *less suitable* and *moderately suitable* areas in the inner part of the Gulf of Gabès can also be linked to a high concentration of marine pollutants being discharged from the industrial areas in Gabès (box C in Fig. 4). Moreover, high chemical (e.g., trace metals) concentrations have been reported in *P. oceanica* plant tissues (i.e., roots, leaves, rhizomes) in this area, which induced a significant regression and disappearance of *P. oceanica* meadows, to which increased seawater turbidity (i.e., high K_d values) and acidity (El Zrelli et al., 2017) also contributed. Moreover, relatively high salinity values in the innermost parts of the Gulf of Gabès resulted in *moderately suitable* scores for WQ. In particular, rises in salinity with increased temperature and evaporation can negatively affect the suitability for *P. oceanica* restoration in this region. Likewise, there appeared to be a local negative effect of the Rhone River onto the WQ scores along the French Mediterranean coasts. In this area the WQ scores are generally considered *suitable*, but not for the site where the Rhone river flows into the Western Mediterranean, which is considered *moderately suitable*. In line with this finding, Houngnandan et al. (2020) did not consider the Rhone River area as a significant barrier to the spatial configuration of existing seagrasses. They suggested that environmental conditions might improve for seagrasses with the delay effect, indicating the continued poor development of *P. oceanica* even in favourable environmental conditions at early stage.

Overall, the Mediterranean Sea presented high WQ scores, but the influence of single WQ variables on the overall suitability can be different in terms of scales and causes. For example, on the one hand, aquaculture systems and wastewater inlets contribute to a high level of particulate matter, which has a significant environmental impact on a

small scale (Borum et al., 2004). On the other hand, high particulate matter concentration can cause over-sedimentation in shallow seagrasses, thus limiting the light availability of deep seagrass populations (Duarte et al., 2004). Moreover, seagrass meadows can adapt to the conditions of the environment where they grow, thus widening their tolerance limits and comfort zone. For example, seagrass meadows in the eastern Mediterranean can resist and grow efficiently at slightly higher salinities (i.e., around 40 PSU) than species in the western Mediterranean (i.e., around 39 PSU) (Sánchez-Lizaso et al., 2008). Although the outcome of this study showed high WQ values on average under baseline scenario, prolonged exposure to poor WQ values, exceeding environmental thresholds, may affect seagrass meadows' growth and survival in a longer timeframe.

3.2.3. Climate suitability

Climate scores generally reflected good conditions for *P. oceanica* growth, reaching an overall score of 69.6 % for both *very suitable* and *suitable* classes. These results are in line with the historical favourable conditions of the Mediterranean Sea (e.g., Sardinia, Corsica, Thyrrenian Sea) (Mayot et al., 2005), with mild average summer temperatures over the season, especially in the western Mediterranean (i.e., 24–25 °C). However, *moderately*, *less* and *least suitable* scores also cover substantial surfaces (32.4 %), especially in the southern and eastern parts of the Mediterranean Sea (Fig. 5).

From a climate perspective, the south (i.e., Tunisia and Libya) and especially the southeast part of the Mediterranean (i.e., Egypt, Lebanon, and south Turkey) seem less suitable for *P. oceanica*. More specifically, the areas on the eastern coasts of Egypt (box E in Fig. 5) have summer temperature higher than 30 °C for about two months (July–August), which had a negative impact on the suitability of this area for *P. oceanica*.

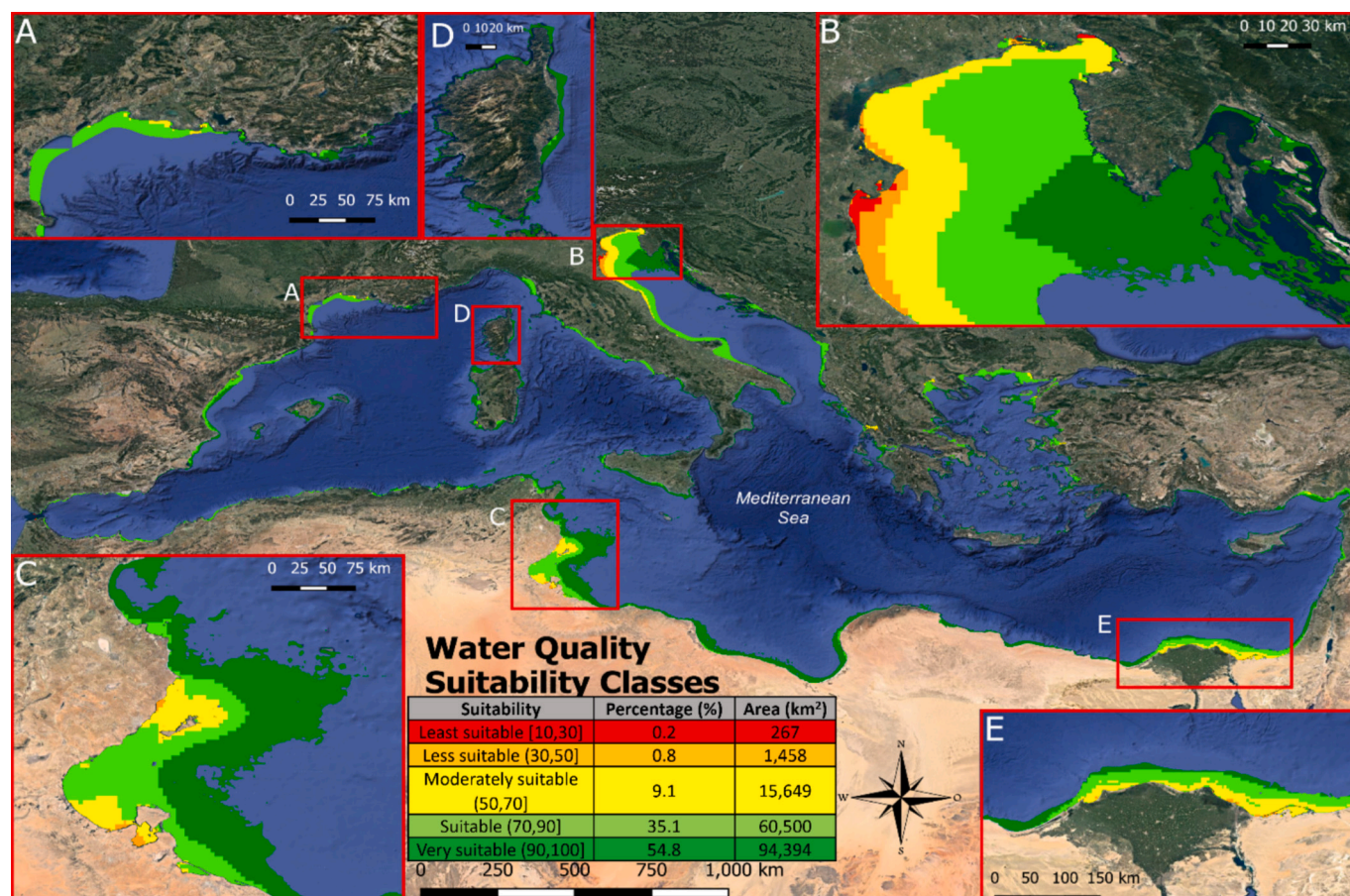


Fig. 4. Water quality suitability map and areas for *P. oceanica* (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès; D: Corsica; E: Egyptian coasts).

restoration. Moreover, although southeastern Tunisia (box C in Fig. 5) showed relatively more compatible climatic conditions compared to Egypt coasts, a large *moderately suitable* area was observed here due to long-term exposure (i.e., around 15 days) to SST around 28.5–29 °C. Exposure to thermal stress is higher in the southern Mediterranean, thus triggering a reduction in the coverage of meadows. In contrast, the average summer SST of the northern and western Mediterranean (i.e., 24–25 °C) is more favourable for *P. oceanica*. However, moderate values were occasionally observed on the Balearic Islands, the coasts of Spain, the island of Sardinia, and the coasts of Italy due to thermal stress variables. This indicates that heatwaves may also pose a threat on seagrass populations in these areas, especially under future CC scenarios. This threat was already highlighted in the models of Chefaoui et al. (2018) showing 70 % loss of *P. oceanica* under the best-case scenario (i.e., RCP2.6) in 2050 and species extinction under the worst-case scenario (i.e., RCP8.5) in 2100. Considering these results and the sensitivity of *P. oceanica* to temperature increases, future warming and heatwaves may cause an increase in *moderately* or *less* suitable classes in the northern Mediterranean, while it may cause the entire southern Mediterranean to become the *least* suitable class.

3.2.4. Final Blue-NBS suitability map for *P. oceanica*

Fig. 6 shows the overall Blue-NBS suitability map for *P. oceanica* seagrass meadows derived from the intersection of *suitable* and *very suitable* regions across all sub-groups (i.e., geomorphology, WQ, and climate assessment) (see Fig. S2 and Fig. S3 for the intermediate maps in SM3). Fig. 6 highlights a total area of 43,862 km² (around 25 % of the case study area) with high suitability for each sub-group. Western Italian coasts (Tuscany, Lazio), Apulia, southern Sicily, and Sardinia showed large suitable areas. Most of the Northern Adriatic is excluded in this

map due to low WQ scores (Fig. 6, box B). This emphasizes that even if regions with extensive shallow areas, such as lagoons, have high geomorphological suitability, other factors can govern suitability for seagrass meadows there (Boscutti et al., 2015). Moreover, the coastline of Spain (from Valencia to Barcelona), Gulf of Lion, and eastern Corsica (Fig. 6, box A and D) reported a considerable extent of suitable areas in the Western Mediterranean. The extent of suitable areas for restoration of *P. oceanica* meadows is high on the coasts of Libya and Tunisia in the Southern Mediterranean. However, the inner parts of the Gulf of Gabès were not included in this map due to the moderate climate (i.e., thermal stress) and WQ scores (i.e., salinity and light attenuation) (Fig. 6, box C). In the Eastern Mediterranean, a large suitable area for *P. oceanica* is located on the coasts and islands of Greece. Blue NBS like seagrass transplantation and/or restoration measures could be applied in these coastal areas, even if few or only degraded seagrass meadows exist. However, these activities may need to be jointly applied with conservation and management measures (i.e., MPAs with other area-based management measures) aimed at protecting *P. oceanica* from damages since it is a slower-growing seagrass species compared with other seagrass species (e.g., *Zostera marina*, *Cymodocea nodosa*) (Díaz-Almela and Duarte, 2008a, 2008b; Marbà et al., 1996). Moreover, transplanting projects require analysis of transplanting techniques (i.e., anchorage), implementation costs, estimation of *P. oceanica* growth rate for the expected colonization, regression reasons (e.g., economic activities), and investments in reducing pressures (e.g., water treatments) (Díaz-Almela and Duarte, 2008a, 2008b).

The regions not represented in the final suitability map have relatively lower scores (from *least suitable* to *moderately suitable*) for at least one of the sub-groups. In addition to geomorphological limitations of deeper waters, a significant amount of coastal area from the Northern

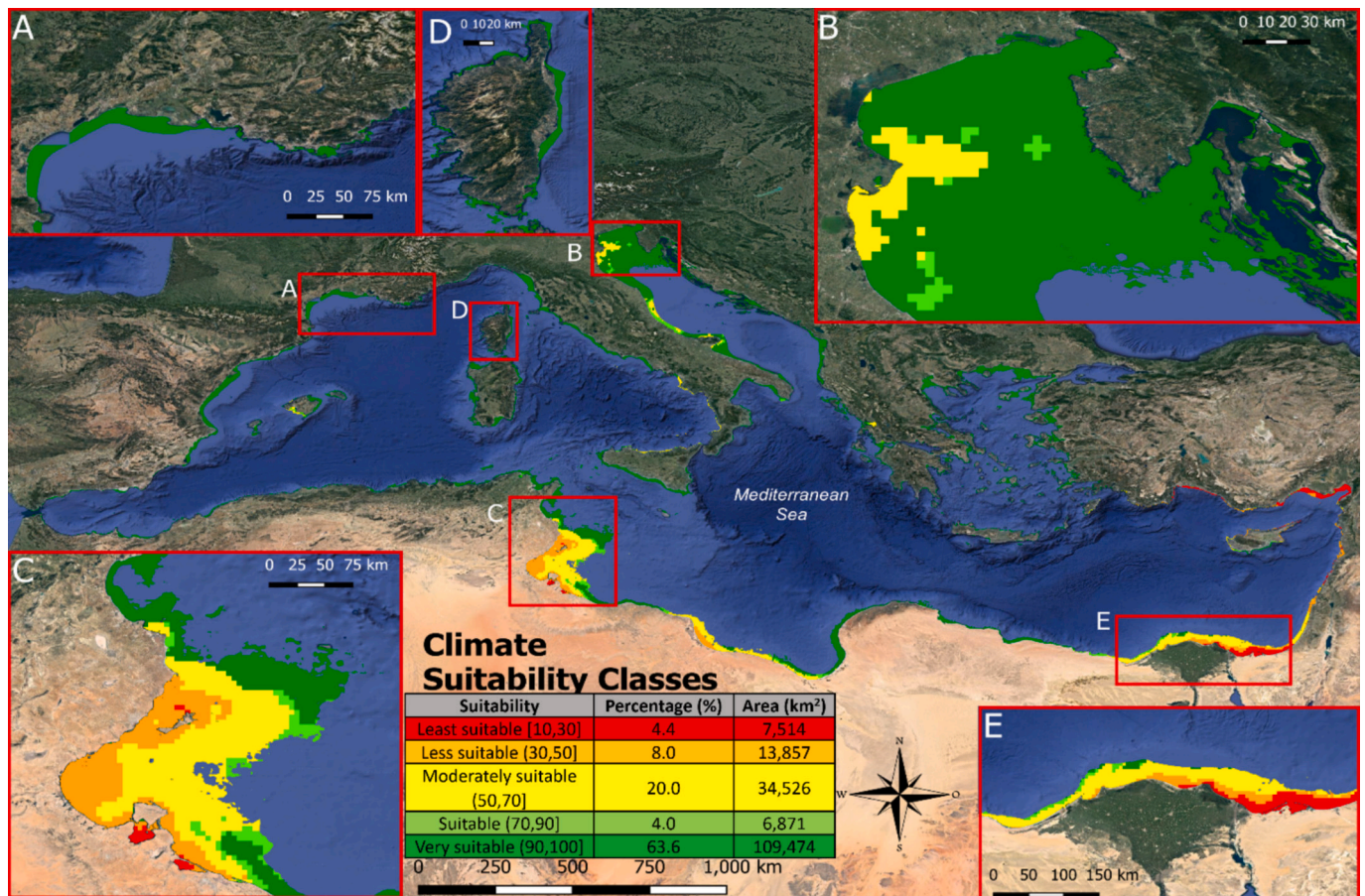


Fig. 5. Climate suitability map and areas for *P. oceanica* (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès; D: Corsica; E: Egyptian coasts).

Adriatic and the southern Mediterranean (i.e., Tunisia, Libya, and Egypt) is not included in the final suitability map due to both WQ and/or climate scores. Although WQ suitability scores are lower in the areas closest to the Northern Adriatic coasts, Egypt, and Tunisia, they increase when moving seawards. However, this pattern overlaps with a decreasing trend in the geomorphologic suitability as observed in Fig. 3 (Section 3.2.1). *P. oceanica* meadows can grow in clear seawater even if the geomorphological characteristics have relatively low suitability (Pergent-Martini et al., 2016). For example, despite moderately suitable geomorphological conditions in western Corsica, high WQ scores allowed existing *P. oceanica* populations to survive (box D in Fig. 4) as also observed in seagrass distribution layers, made available by EMODnet (<https://www.emodnet.eu/en>) and UNEP-WCMC (<https://data.unep-wcmc.org/>) data portals. However, WQ and climate changes can affect deep-sea meadows more severely.

If seagrass populations already exist in the regions outside the suitable areas (e.g., Gulf of Gabès), they may degrade due to poor WQ and climate conditions. It is important to ensure higher suitability scores by considering management actions to enhance poor WQ (e.g., reducing the nutrient and sediment loads from run-offs) for the growth of meadows in these regions. Moreover, improved WQ can increase the tolerance/resilience of seagrasses to higher SST values (Cullen-Unsworth and Unsworth, 2016) providing wider suitable intervals for climate variables. On the other hand, marine conservation activities (i.e., MPAs) can provide positive local effects on the health and environmental status of *P. oceanica* populations (Fraschetti et al., 2022) by contributing to proper water and sediment conditions and preventing siltation and erosion. However, a connectivity between land and sea measures (i.e., integrated land-sea planning) is necessary to support MPAs (Carlson et al., 2021). Complementary management actions

supporting MPAs (e.g., seagrass-friendly moorings, management of stranded seagrass litter, control of invasive species, and dredging recovery) could be implemented to integrate coastal zone management and marine spatial plans and reduce pressures on the land-sea interface.

3.3. Sensitivity analysis results

Building on the methodological approach as presented in Section 2.4, the outputs of the sensitivity analysis of weighting alternatives via Morris method were illustrated in Table 2 and Fig. 7. When the geomorphologic variables were examined in the weighting alternatives, all variables showed a strong non-monotonic relationship (i.e., relatively higher σ values compared to μ^*) with the output. Additionally, they demonstrated notably higher μ^* values compared to variables in WQ and climate sub-groups. Substrate type had the highest influence (i.e., σ as 24.4) on the geomorphologic suitability score with the strongest non-linearity and/or interactions (i.e., σ/μ^* ratio as 1.3) with other variables belonging to the same sub-group. Considering the SA applied for the WQ sub-group, K_d was the variable with the highest μ^* (i.e., 11.4). Even though the other inputs (i.e., DIN, DO, and salinity) showed similar influences on the output in the weighting alternatives of WQ, weight changes of DO had the weakest influence with the lowest μ^* (i.e., 8.9). Moreover, the μ^* ranking of WQ variables was consistent with the weights that were assigned by the seagrass experts within this study (e.g., K_d with the highest weight as 0.51 and the first rank in μ^*). Among SA results obtained for climate variables, summer SST had the highest μ^* (i.e., 7.3) and σ value (i.e., 14.2) in the weighting alternatives. Since average summer SST is generally very suitable for *P. oceanica* in the study area (see Section 3.2.3 for details), it may have a strong positive effect on the overall suitability score when it assumes a high variable

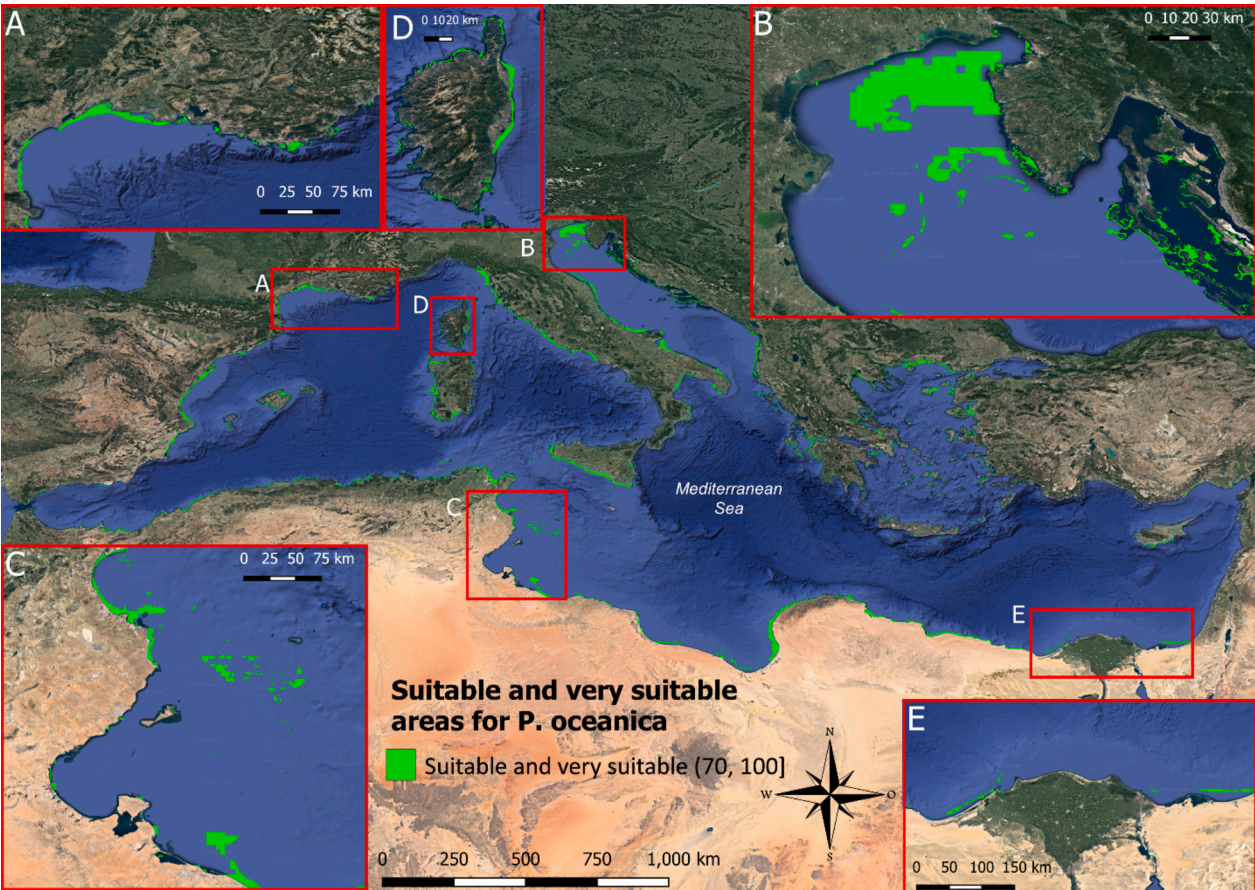


Fig. 6. Suitable and very suitable areas intersected for geomorphology, WQ, and climate (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès; D: western Corsica; E: Egyptian coasts).

Table 2
Morris sensitivity indices of the variables in each sub-group.

	μ^*	σ	σ / μ^*
Geomorphology			
Depth	17.5	23.3	1.3
Seabed slope	19.9	19.9	1.0
Substrate type	20.2	24.4	1.2
WQ			
K _d	11.4	15.7	1.4
DO	6.1	8.9	1.5
DIN	7.4	9.0	1.2
Salinity	7.6	10.4	1.4
Climate			
Summer SST	7.3	14.2	1.9
Thermal stress duration	4.0	9.6	2.4
Thermal stress intensity	4.2	9.9	2.4

weight. Furthermore, it should also be considered that the other climatic variables (i.e., thermal stress) were derived from the SST dataset. In summary, although the μ^* and σ values of the variables vary, it can be stated that since there is not a variable located very close to the origin, there is no variable having a negligible influence on the outputs of suitability scores.

4. Discussion

4.1. Data integration for mapping suitability of Blue-NBS

This study focused on assessing the environmental suitability of *P. oceanica* meadows by integrating input data representing different environmental variables at the eco-regional scale. The analysis was performed for sub-groups, such as water quality, to identify those factors mainly influencing suitability scores in different areas of the Mediterranean Sea. A reliable, feasible and replicable model was aimed at including 10 variables rather than using many more, which could make the model more complex, but also potentially increasing the number of parameters representing similar processes, leading to redundancy (e.g., suspended particulate matter and K_d are both used to represent water turbidity) (Pelegrina et al., 2022). However, to improve the performed suitability assessment, other significant environmental variables could be integrated into the analysis for those regions where data exist. For instance, under the geomorphology sub-group, hydrodynamic effects of current and waves on seagrass meadows, especially in shallow areas, could be explored with the integration of relevant parameters representing e.g., wave velocity and wave direction. Moreover, the temporal variability for WQ variables could be essential to be captured in the suitability evaluation. This would imply the integration of long-term data to understand the ecosystem responses to climate and human-induced pressures (Fraschetti et al., 2022), which requires defining critical thresholds associated with reliable exposure duration. In this study we utilized environmental data collected between 2016 and 2018, considering only one thermal stress event having the longest duration. However, variability in the frequency and intensity of thermal stress events could have impacted the survival and growth of seagrass

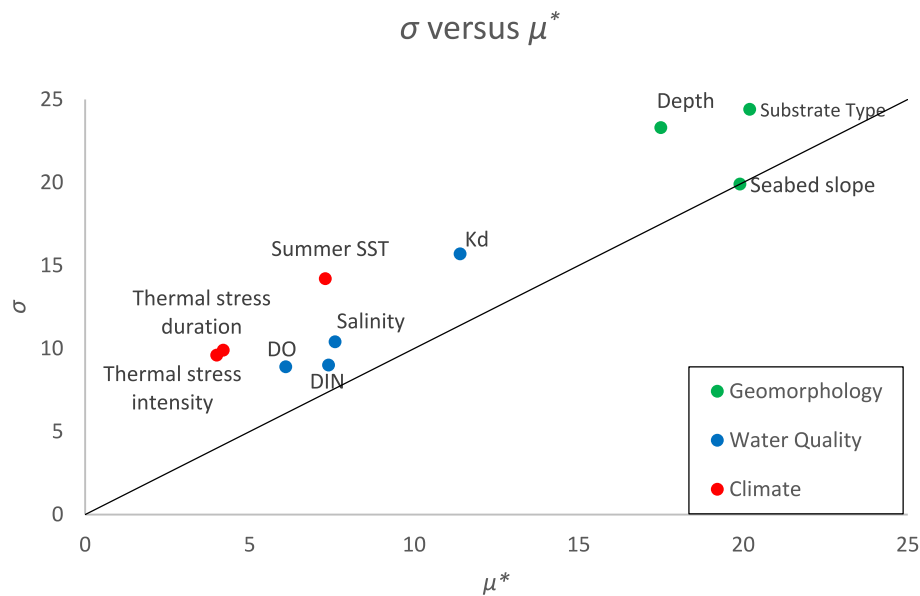


Fig. 7. Graphs of σ versus μ^* based on the results of sensitivity analysis for each sub-group in terms of weighting alternatives for geomorphologic, water quality, and climate variables.

meadows over the baseline period (Marín-Guirao et al., 2019). Therefore, integrating the effects (i.e., duration and intensity) of each thermal stress in the analysis may have provided more robust outcomes on climate suitability. Moreover, in addition to the mean values of variables, analysis of the exposure time of ecosystems to the identified threshold values could improve the model ability to capture and represent real-world ecosystems' suitability against certain environmental conditions. To achieve this, it would be necessary to analyze the duration of exposure against the identified threshold values for each variable, examining how the mortality of seagrass populations increases with respect to time. However, it should be noted that the Mediterranean Sea is a vast eco-regional basin, making it challenging to obtain high temporal resolution data covering such an extensive eco-region for shallow water ecosystems. In addition, data for ecosystem coverage is still poor in open-source data portals, which limits the timeframe to be investigated under the baseline scenario. For example, in the EMODnet data portal, data for Posidonia meadows presence were generally only recorded for the northern part of the Mediterranean Sea and without information on their health status. Finally, considering that ecosystems can adapt to their surrounding environmental conditions (i.e., seagrass populations with different comfort zones), suitability analysis in smaller sub-regions (e.g., Western Mediterranean) may give more robust results.

The environmental variables selected in this study are representative of seagrass growth and survival, and essential to make operative the first analytical-tier of a wider NBS suitability analysis. Even though environmental variables indirectly reflect the effects of anthropogenic activities (e.g., aquaculture, dredging, agriculture, road and port construction) and management measures that could be put in place to mitigate their connected pressures impacts (e.g., nutrient loading and run-off limitation measures, establishment of marine protected areas (MPAs)), socio-economic and governance dimensions should be assessed as well to get a more comprehensive NBS suitability evaluation (Gómez Martín et al., 2021; Guerrero et al., 2018), able to consider all those conditions enabling a real-world assessment and solutions implementation. However, for completing this more articulated multi-tier suitability analysis, stakeholder engagement is recommended, in order to achieve a sound evaluation and selection of different factors potentially affecting seagrass meadows social acceptance and willingness to pay for their e.g., restoration and transplantation.

4.2. Novelty and limitations of the study

The methodology developed for this study is practical and replicable across different locations and scales, while also considering the data limitations inherent to the eco-regional scale. 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 use of the Analytic Hierarchy Process (AHP) allowed experts' qualitative assessments to be converted into quantitative information by defining and integrating their weights in the Multiple Criteria Decision Analysis (MCDA). As such, the proposed weighted method provides more accurate outcomes for potentially suitable areas, compared to an unweighted approach that considers all variables equally. Although there is no strict limit on the number of experts in the AHP analysis, in this study we relied on the quality of the information provided by seven seagrass experts (T. L. Saaty and Ozdemir, 2014). This was supported by the satisfactory consistency ratio (CR) results, which were below 0.1. AHP allows for the variables' prioritization and consideration of their relative importance leading to a more consistent and reliable representation of decision factors. Moreover, the weighted sum approach and GIS techniques were used to aggregate variables' normalized scores and weights to obtain suitability scores and maps for each sub-group, and a final intersected/combined map, supporting decision-makers for proper measures to improve the environmental status of marine coastal ecosystems, while identifying proper areas for environmental restoration and protection.

The individual evaluation of variables based on pairwise comparisons is a limitation of AHP since it considers variables as independent. The developed model did not take into account interactions and relationships between the variables at stake, which may be crucial in decision-making processes. Therefore, future investigation applying decision-making methods able to consider and detect complex interactions between input variables is suggested (e.g., Analytic Network Process). For example, high mud ratio in the seabed not only contributes to smothering (burial) and changes in substrate physico-chemistry but also influences water turbidity (i.e., light availability). Furthermore, ecosystems can adapt to the environmental conditions at the site where they grow, which may result in site-specific threshold values for specific environmental variables. Considering this, suitability analysis in smaller

sub-regions/scales (e.g., Western Mediterranean or Adriatic Sea) may give more robust/precise results. Moreover, an analysis of the exposure time of ecosystems to the identified threshold values could improve the model predictability. However, to achieve this, further analysis would be necessary to define the classes for the exposure duration against the identified threshold values for each variable, to examine how the mortality of seagrass populations increases with respect to time.

5. Conclusion

This study provided environmental suitability assessment and mapping for seagrasses transplantation, restoration and protection as NBS to be applied in the Mediterranean eco-region. In particular, a GIS-based AHP method was developed integrating various environmental indicators under different sub-groups (i.e., geomorphology, WQ, and climate). Depth, seabed slope, and substrate type were chosen to fit with the geomorphology sub-group; salinity, DO, DIN, and K_d were then considered in the WQ sub-group; finally, summer SST and thermal stress duration and intensity were integrated into the climate sub-group. The environmental NBS suitability model was developed using GIS-based AHP, tailoring environmental variables' classes, scores, and weights based on available literature and expert knowledge. Suitability scores and maps were obtained from its application under the baseline timeframe 2016–2018.

The resulting suitability maps and metrics showed that while the *suitable* and *very suitable* areas for WQ and climate sub-groups are large in the case study area, the geomorphological one plays a more decisive and limiting role in defining overall suitable and very suitable areas resulting from the intersection among all sub-groups' suitability maps. Within each sub-group, the most dominant indicators were depth, K_d , and thermal stress duration, with weights of 0.54, 0.51, and 0.57, respectively. While the overall surface of *suitable* and *very suitable* areas in the geomorphological assessment was 50.2 % of the case study area, it was much higher for WQ and climate sub-groups, namely 89.9 % and 69.6 %. Large suitable areas under WQ and climate groups are expected for the baseline scenario, considering that *P. oceanica* is an endemic species in the Mediterranean basin. However, results for the Northern Adriatic and some other areas in the southern Mediterranean coasts showed lower WQ suitability scores. Moreover, the southern Mediterranean regions showed lower climate-related suitability scores due to prolonged exposure to high SST values in these areas over the investigated timeframe.

This study can be considered the first tier/phase of a wider multi-tier NBS suitability framework able to include multiple environmental factors for NBS suitability modelling (e.g., thermal stress, nutrients, bathymetry). To extend this analysis and provide a valuable support for forward looking management and NBS investments within adaptation planning, future CC scenarios could be integrated in the analysis, to be able to show the effects of changes in SST and WQ parameters on the overall NBS suitability. Moreover, for a more complete NBS suitability assessment, risk-prone seagrass areas should be detected thorough the design and operationalization at the Mediterranean scale of a multi-risk assessment framework. Accordingly, the integration of environmental suitability and multi-risk assessment maps that also consider future CC scenarios (e.g., SST, salinity) would assist the design of adaptive NBS pathways that are also able to show suitability and performance in the mid and long-run. Finally, under a multi-dimensional assessment perspective, NBS suitability appraisal should also consider socio-economic (e.g., population and fishing activities) and governance enablers (e.g., financial incentives and political will) that could influence the decision on a certain intervention, as well as its success and effectiveness. It should be noted that these types of variables require a more detailed scale of analysis (i.e., local scale) since related information/data is very site-specific. Drawing on this, future investigations and expansion of the proposed methodological approach can effectively address knowledge gaps in Blue-NBS implementations in marine coastal

areas by linking the suitability assessments with the strategic integration of climate adaptation actions into planning and policy frameworks. This comprehensive approach empowers the understanding of marine managers and policymakers and supports the decision-makers across different scenarios.

CRedit authorship contribution statement

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

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.176803>.

Data availability

The authors do not have permission to share data.

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