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Looking for the surviving optimal areas for the threatened species *Pinna nobilis* in a highly anthropized coastal lagoon (Mar Menor, SE Spain)

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ABSTRACT

Pinna nobilis, an endemic bivalve species in the Mediterranean Sea, is critically endangered mainly due to the devastating impact of the protozoan parasite *Haplosporidium pinnae*. The population within the Mar Menor lagoon (Murcia, Spain) represents one of only two surviving populations along the Spanish coast. This relict population has witnessed a significant decline since 2016, primarily due to eutrophication episodes and other anthropogenic impacts affecting the lagoon. It is imperative to identify the most suitable zones for the survival of this species, where adult individuals could be translocated from affected areas to enhance their chances of survival. In the present study, we identify these zones through a Multi-Criteria Evaluation considering several factors that pose a threat to the species. This evaluation was complemented using Geographic Information Systems based multi-criteria decision analysis (GIS-MCDA). A total of 18 factors were weighted and combined, resulting in a surface area of 307.92 hectares (2.28% of the lagoon) with over 70% high suitability for species survival.

1. Introduction

The fan mussel, *Pinna nobilis* Linnaeus, 1758, is a critically endangered bivalve species that suffers a drastic reduction in its populations since 2016 (Katsanevakis et al., 2022) because of a mass mortality event primarily caused by the infection of the protozoan *Haplosporidium pinnae*, with the possible synergy with other pathogens (Carella et al., 2019; Catanese et al., 2018). Nearly the entire population has disappeared, although certain Mediterranean areas with specific water conditions preventing the spread of *H. pinnae* maintain surviving populations (Katsanevakis et al., 2022). In Spain, there are only two confined areas surviving populations of *P. nobilis*: the Ebro delta in Catalonia and the Mar Menor coastal lagoon in the Region of Murcia (Fig. 1). Salinity is considered to be the factor that prevents the spread of the pathogen in both areas. Mar Menor salinity is higher than the survival threshold of the pathogen, whereas in the Ebro delta is lower (Prado et al., 2020, 2022). However, infected individuals have been punctually detected in both locations (Cortés-Melendreras et al., 2022; Prado et al., 2022), as temporary fluctuations in salinity facilitate the ingress of the protozoan. These *P. nobilis* reservoirs are also affected by various anthropogenic activities affecting their survival. Since the 1990s, the Mar Menor has suffered a process of eutrophication, which led to several crises and environmental collapses since 2016 (Pérez-Ruzafa et al., 2019). These events have led to the development of conditions such as hypoxia, anoxia, and even euxinia, affecting both the water column and sediment (Giménez-Casalduero and Martínez-Fernández, 2020; Ruiz et al., 2021). Other negative factors include, among others, boat anchoring, illegal harvesting, and the effects of fishing nets (Conesa and Jiménez-Cárceles, 2007; Cortés-Melendreras et al., 2022; Hendriks et al., 2013; Ruiz et al., 2021). More than one and a half million individuals of *P. nobilis* were estimated in 2014 (Giménez-Casalduero et al., 2020), while currently there are barely a thousand individuals relegated to depths lower than 3 meters because of the severity of eutrophication episodes (Cortés-Melendreras et al., 2022;

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Giménez-Casalduero et al., 2020). Being in these shallow depths, they are exposed to dangers of anthropogenic origin. It is therefore important to take conservation measures to guarantee the survival of the species in the short, medium, and long term. One critical measure to consider is the translocation of individuals from risk areas to optimal zones, or the reintroduction of individuals maintained or bred in laboratory.

Several studies have explored the successful transplantation of *Pinna bicolor* (Wu and Shin, 1998), *P. rugosa* (Arizpe, 1995) or *P. nobilis* (Bottari et al., 2017; Katsanevakis, 2016; Tursi et al., 2018). However, none of them conducted a comprehensive study on the best zone to relocate the individuals. Katsanevakis (2016) emphasises the need to study which sites are most likely to succeed. This can inform future translocation and reintroduction protocols, and guide for the search for surviving specimens within the lagoon.

Because of the multiple factors and threats in the lagoon, a multi-criteria evaluation (MCE) may be the most accurate approach for identifying areas with lower impact. MCE is defined as “an explicit decision-making process related to the structuring and resolution of spatial problems involving multiple criteria and provides a system of relative weighting” (Bagdanavičiūtė et al., 2015). In combination with GIS, it is a powerful tool for complex spatial decision-making (Dapueto et al., 2015), the so-called GIS-based multi-criteria decision making analysis (GIS-MCDA) (Malczewski, 2006; Malczewski and Rinner, 2015, de Oliveira et al., 2023. GIS-MCDA has been employed for various aspects of marine environment management and conservation, such as obtaining coastal vulnerability indices for shoreline management (Bagdanavičiūtė et al., 2019, 2015), determining coastal risk in the face of threats like climate change (Félix et al., 2012), Integrated Coastal Zone Management (Garmendia et al., 2010), selecting suitable offshore locations for establishing aquaculture facilities (Buitrago et al., 2005; Dapueto et al., 2015; Shunmugapriya et al., 2021), or identifying priority areas for marine protection (Nelson and Burnside, 2019; Wood and

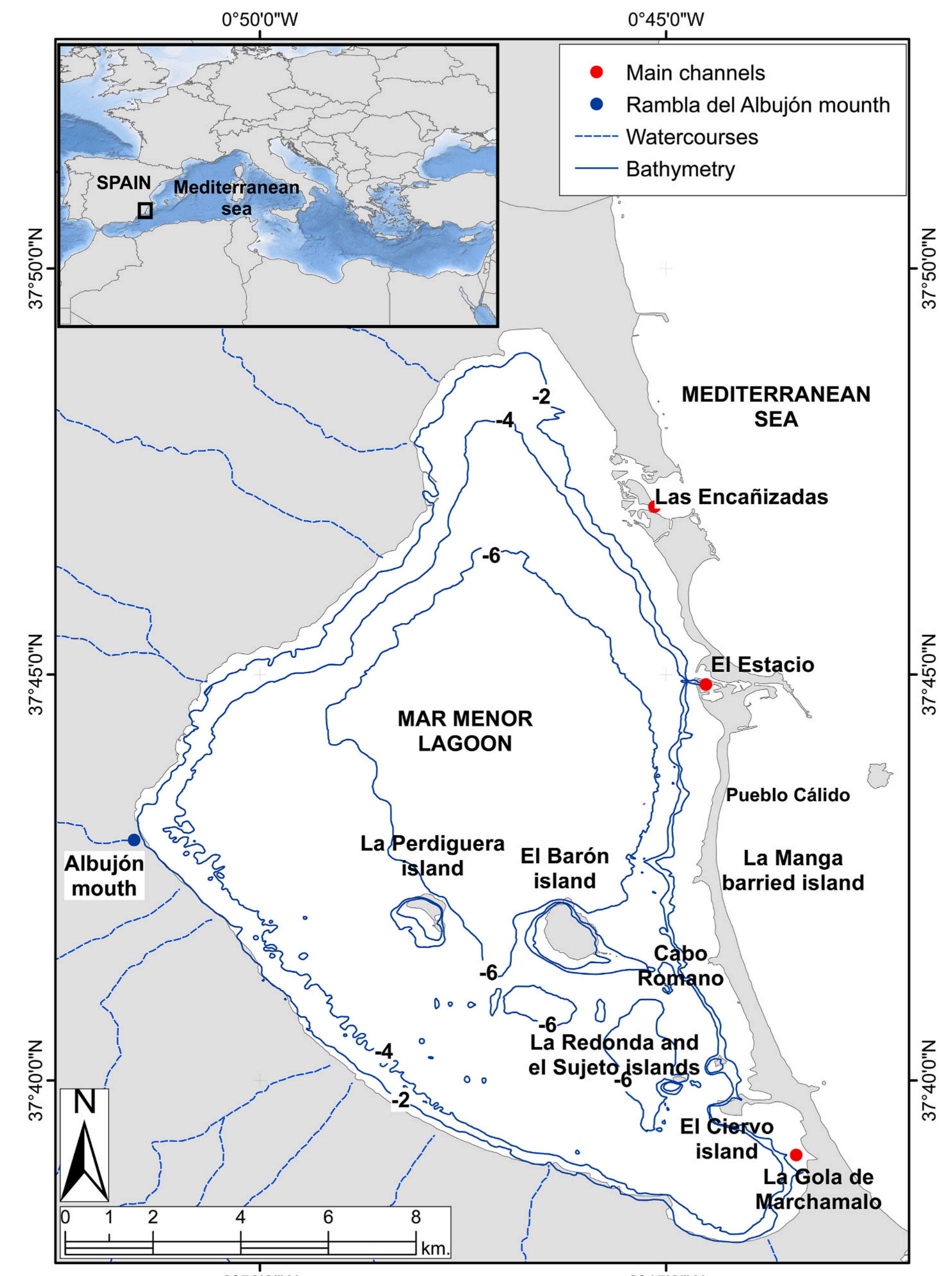

Fig. 1. Location of the Mar Menor lagoon in south-eastern Spain (Western Mediterranean Sea). Source: BTN25 2006–2019 CC-BY 4.0 ign.es (administrative data); Derived data from MDT25 2015 CC-BY 4.0 ign.es; MITECO (2009) (bathymetry).

Dragicevic, 2007); Therefore, it is a very useful framework for processes of marine spatial planning (MSP) and integrated coastal zone management (ICZM) (Tammi and Kalliola, 2014). In this way, the present study aims to identify potential zones for the survival of *P. nobilis* within the Mar Menor lagoon, through the combination of MCDA techniques and GIS.

2. Materials and methods

2.1. Study area

The Mar Menor, located in the southeast of the Region of Murcia (Spain) (Fig. 1), is a semi-enclosed hypersaline coastal lagoon with an area of approximately 135 km^2. It is separated from the Mediterranean Sea by a 21 km-long strip of land known as *La Manga*. Along *La Manga*, there are three main channels that connect the waters of the Mediterranean with the lagoon, from north to south: *Las Encañizadas*, *El Estacio*, and *La Gola de Marchamalo* (Fig. 1). The lagoon receives water from the sedimentary basin of *Campo de Cartagena*, with numerous watercourses flowing into it, of which the *Rambla del Albujón* mouth is the principal contributor (Fig. 1). The deepest part of the lagoon reaches a depth of 7 meters, with salinity ranging between 38 and 47 psμ, while temperature exhibits notable seasonal fluctuations, ranging from 10 °C in winter to over 30 °C in summer (Conesa and Jiménez-Cárceles, 2007). The bottom of the lagoon is predominantly covered by macrophyte meadows, mainly *Caulerpa prolifera* and *Cymodocea nodosa*, which coexisted in the lagoon for decades (Belando et al., 2021). Regarding its fauna, it is noteworthy for hosting eurythermal and euryhaline species (Mas et al., 2017).

The Mar Menor boasts numerous protected designations due to its high ecological, historical, and scenic value. It is declared as a protected area in several lists, such as the RAMSAR Convention on Wetlands of International Importance, the Specially Protected Areas of Mediterranean Importance, the European Union Birds Directive (Council Directive 79/409/EEC) (European Communities, 1979) and the Natura 2000 Network (Conesa and Jiménez-Cárceles, 2007). Despite the regulatory efforts to mitigate it, the lagoon has witnessed a eutrophication process since the 1990s, exacerbated in 2016, driven by the continuous influx of nutrients mainly from agriculture. Notably, three severe episodes of Harmful Algal Blooms (HABs) have occurred: the first began towards the end of 2015, reaching its peak in 2016; the second in 2019, followed by the most recent one in the summer months of 2021 (Aguilar-Escribano et al., 2016; Ouaissa et al., 2023; Ruiz et al., 2020, 2021; Soria et al., 2020).

Between 2016 and 2018, following the initial eutrophic crisis, a slight recovery of vegetation in the shallow areas of the lagoon and an initial recolonization of invertebrates in the sediment were observed (Ruiz et al., 2020). However, in 2019 an extreme rainfall event caused by a deep cut-off low produced a massive input of water and sediments into the lagoon, causing water stratification and a euxinic process. As a result, anoxic conditions appeared and toxic compounds, such as sulphides and methane, were produced in the water column due to the decomposition of organic matter by anaerobic bacteria (Giménez-Casalduero and Martínez-Fernández, 2020; Ruiz et al., 2020; Sandonnini et al., 2021a). All these ecological events, parallel to the mortality that the species suffered in the Mediterranean since 2016, had a detrimental impact on the population of *P. nobilis*, resulting in a reduction of over 99% (Giménez-Casalduero et al., 2020).

2.2. GIS-MCDA approach

To identify the optimal zones in the lagoon for the survival of *P. nobilis*, a multi-criteria analysis, based on extensive literature and the knowledge and experience of the authors, was conducted. The process unfolded as follows: i) Identification of environmental variables or factors which may affect the survival of fan mussels in the lagoon; ii) Acquisition of cartography and base layers for each of these factors, sourced from various platforms or created by the authors themselves; iii) Conversion of each factor into a criterion score ranging from 0 (indicating very poor suitability for fan mussels) to 1 (representing optimal suitability); iv) Creation of maps for each criterion, with a resolution of 10 m; v) Determination of the importance and weight for each factor; vi) Linear combination of the criteria using the assigned factor weights; vii) Generation of a final suitability map.

For the development of the base cartography, the criterion maps for the factors, and the final suitability maps, we utilized the GRASS GIS software (GRASS Development Team, 2022), QGIS (QGIS Development Team, 2023), and some Python scripts.

2.2.1. Data used, selected factors and criteria standardisation

The selected factors, according to expert knowledge and the review of the results of previous work (Cortés-Melendreras et al., 2022; Giménez-Casalduero et al., 2020; Supplementary Material Table S1, Appendix A) were (Supplementary Material Figs. S1–S3, Appendix A): i) Depth; ii) Distance to the Albujón mouth; iii-v) Distance to the connection points with the Mediterranean; vi) Distance to urban centres; vii-ix) Distance to beaches, nets, and anchorages zones; x) Type of habitat; xi-xiv) Water salinity and temperature and xv-xviii) Water deficiency of oxygen.

i) Depth

It is a key factor for the distribution of *P. nobilis* individuals within the lagoon. Due to the severity of eutrophication episodes, there are no living individuals beyond 3 meters since 2017 (Cortés-Melendreras et al., 2022; Giménez-Casalduero et al., 2020). Most individuals are located between 1.1 and 2 m deep (Cortés-Melendreras et al., 2022). Therefore, it is considered that at a depth of 1.5 meters the suitability of the depth criterion is maximum, so it is assigned a score of 1, and it decreases linearly to 0 at depths up to a threshold of 3 m and to the surface at 0 m. This criterion stands as the sole restrictive factor; if its score is zero, the final suitability will be zero, regardless of the other factors. The bathymetry used derives from the coastal ecocartography provided by MITECO (2009).

ii) Distance to the Albujón mouth

The Albujón watercourse represents the primary source of water, sediment, organic matter, and nutrients discharges into the lagoon that trigger eutrophication events (Álvarez-Rogel et al., 2020). Excessive increases in suspended solids and organic matter has caused the mortality of individuals in the Ebro Delta in 2020 (Prado et al., 2021). The impact of these inputs intensifies the closer they are to the Albujón mouth (Fig. 1). However, it is crucial to account for lagoon currents and water circulation. Therefore, a criterion has been devised based on the distance to the Albujón mouth, calculated taking into consideration water circulation patterns within the lagoon obtained from a current direction and speed map (Fraile-Nuez et al., 2017). Velocity values in the X and Y components were interpolated, yielding raster layers for current direction and velocity modulus. These layers enable the calculation of the cost associated with traversing each cell, which, when accumulated from the mouth of the Albujón, approximate the distance to it following the currents. To translate this value into a criterion, it is considered that the criterion increases linearly from 0 (indicating proximity to the mouth) to 1, up to an accumulated cost equivalent to that calculated at La Perdiguera Island (Fig. 1). This assumption considers that the distance to La Perdiguera island is sufficient to mitigate the impact of the inputs on the environment. Beyond this value, the criterion remains fixed at 1.

iii-v) Distance to the connection points with the Mediterranean Sea

The channels connecting to the Mediterranean Sea are the entrance of the protozoan *H. pinnae* (Cortés-Melendreras et al., 2022). In 2017, a temporary reduction in salinity, following a large influx of Mediterranean water into the lagoon, allowed the protozoan to enter, resulting in the mortality of several individuals near the channels (Cortés-Melendreras et al., 2022); Similarly, in 2019, a reduction in water salinity following a torrential rainfall event lead to another infection and mortality episode. Therefore, individuals closer to the connection zones are at higher risk of infection, as these channels serve as entry points for the protozoan and are more susceptible to salinity reductions. A factor calculated based on lagoon currents has been used, as these currents can influence salinity decreases and the spread of the parasite in a specific directions. Consequently, three criteria were derived, each corresponding to one of the channels (Fig. 1): iii) Encañizadas; iv) Estacio, and v) Gola de Marchamalo, with scores ranging from 0 to 1. However, the threshold at which suitability is considered 1 is now the distance between Las Encañizadas and an area in La Manga known as Pueblo Cálido (Fig. 1).

vi) Distance to urban centres

The coastline of the Mar Menor is highly urbanized and experiences a high influx of tourists during the summer months. Snorkelling, nautical activities, litter, and wastewater treatment systems pose a risk to the lagoon, being the risk larger the closer to urban centres. The locations of these urban centres, obtained from the urban centres layer of the National Centre for Geographic Information (CNIG) (CNIG, 2023), updated to 2022 are used to establish this criterion. In this context, suitability is at a minimum when 0 m distance from urban centres, and it linearly increases until reaching a suitability score of 1 at 50 m, considering this distance sufficient to mitigate the potential impact of urbanization.

vii-ix) Distance to beaches, nets, and anchorage zones

The beaches (vii) lining the entire lagoon witness a high influx of visitors during the summer months that may potentially pose risks to the fan mussel populations (García-Ayllón and Miralles, 2014). Utilising high-resolution orthophotos, the shorelines around the lagoon wee digitised. As a criterion score, it is considered that suitability is minimal at a distance of 0 m and reaches maximum suitability beyond 50 m.

These orthophotos have also been utilized for the digitalization of nets throughout the lagoon (viii), whether they are designated for fishing, bathing areas, or anti-jellyfish purposes. Their presence poses a potential risk to *P. nobilis*. The net lines from three different years and seasons (2012, 2017 and 2020, encompassing both winter and summer periods) have been digitised to obtain the most detailed information possible. Based on these data, the criterion score is set at 0 for the minimum distance to the net and progressively increases to 1 when situated at 50 m or more, with this threshold being considered sufficient to prevent the entanglement of the net from affecting the individuals.

Likewise, the polygons of anchorage zones for boats (ix) were digitize, as the direct impact of an anchor strike can be significant. Both permanent and temporary anchorage zones, particularly during the peak summer season, have been considered for determining this criterion score. The criterion score ranges from 0 to 1, commencing at 50 m from the polygon, and reflects the assumed distance required to mitigate the potential impact of anchor strike.

x) Type of habitat

P. nobilis prefers seafloors covered by marine seagrasses (Katsanevakis and Thessalou-Legaki, 2009; MAAMA, 2012), *Cymodocea nodosa* in Mar Menor. Unfortunately, *C. nodosa* has experienced a significant decline in the lagoon after the eutrophication episodes, with a rapid growth of *C. prolifera* (Belando et al., 2021). Fan mussels within the lagoon are also found in areas with mixed beds of these two species, and even within specific *C. prolifera* beds. However, *Caulerpa* beds are not ideal for the species, as they have been associated with anoxia conditions in the ecosystem (Aldeguer-Riquelme et al., 2022). Individuals in unvegetated and exposed seafloors are more vulnerable to other threats like poaching.

An eight classes (Table 1) seabed map was generated classifying Sentinel-2 satellite images using Random Forest (RF) (Breiman, 2001). Images were downloaded from Copernicus Open Access Hub repository (European Commission, 2023). Specifically, multispectral satellite images from January 2021, corresponding to a period of minimal *C. prolifera* distribution and size, as well as from October 2020, coinciding with the peak distribution and size of *C. prolifera*, were used. Visual validation of these classifications in QGIS affirmed the model's sensitivity to seasonal fluctuations in seagrass beds, in response to variations in *C. prolifera* distribution and the RF model achieved a cross-validated accuracy of 0.921 and a kappa index of 0.8346. This map's applicability is limited to shallower areas due to the limited penetration of solar radiation in the water. Nevertheless, considering that in greater depths are unsuitable for hosting fan mussels, this limitation does not pose any inconvenience.

Subsequently, each seabed type has been assigned a suitability score, ranging from 0 to 100. The highest suitability score is assigned to monospecific and mixed beds of *C. nodosa*, followed by beds of *C. prolifera*, while emerged surfaces receive the lowest rating (Table 1). The criterion score is obtained through the transformation of this suitability, with 0 indicating lower suitability and 1 signifying higher suitability.

xi-xiv) Salinity and temperature

Salinity is a limiting factor for the dispersion of *H. pinnae* (Cabanellas-Reboredo et al., 2019; Catanese et al., 2018; Katsanevakis et al., 2022; Prado et al., 2022). The entry of the parasite into the Mar Menor has been observed following temporary decreases in water salinity (Cortés-Melendreras et al., 2022). The optimal range for *H. pinnae* is stablished between 36.5 and 39 psμ or 36.5 and 39.7 psμ according to Prado et al. (2022) and Cabanellas-Reboredo et al. (2019) respectively. In addition, higher temperatures might increase the aggressivity of the pathogen, especially from 13.5 °C (Cabanellas-Reboredo et al., 2019; Prado et al., 2022). Both salinity and temperature in the lagoon are highly dynamic parameters with wide variations throughout the year (Conesa and Jiménez-Cárceles, 2007). A reduction in lagoon salinity can be extremely critical for the populations, especially when the water temperature is high. Therefore, it has been deemed essential to consider these two factors in combination. Daily values of these variables, spanning from 2017 to 2021, for both the water column and the lagoon's bottom, were obtained from OISMA and the Fishing and Aquaculture Service of the Region of Murcia (UPCT, 2023). For each day and pixel, a variable has been computed which is assigned a score of 0 if salinity falls outside the conservatively defined suitable ranges for *H. pinnae* (36.4–40 psμ) or if the temperature is equal to or lower than 13 °C. On the other hand, when salinity is within the suitable range for H. pinnae and the temperature exceeds 13 °C, the variable is calculated by subtracting 13 from the temperature (Eq. (1)).

Table 1
Suitability scores assigned to seabed type.

Type of habitat	Suitability
Cymodocea nodosa	95
Caulerpa prolifera	75
Mixed bed of *C. nodosa* and *C. prolifera*	90
Bare seabed	15
Beach	5
Infrastructure: ports, docks, buildings, etc.	0
Terrestrial vegetation	0
Rocky seabed	2

$$\text{If salinity} < 36.4psu \lor salinity > 40psu \lor temp < 13^\circ C, \text{then Variable} = 0 \text{ If salinity} > 36.4psu \land salinity < 40psu \land temp > 13^\circ C, \text{then Variable} = temp - 13 \quad (1)$$

These daily grids were used to generate maps reflecting the daily average and maximum observed value of this variable, considering both the water column and the seabed bottom, as the specimens may be affected by the water conditions at these two depths, especially at shallow depths. As these variables are dynamic and experience significant changes throughout the year, it is considered valuable to study both the worst-case scenarios (maximum conditions) and the average conditions in which the specimens live. For each cell in the grid the mean is calculated along all available daily values. The same is done for the maximum. Once this coefficient is obtained, it is transformed into a criterion assuming a score of 1 when the variable is zero and decreases linearly to 0 as it approaches the maximum observed value (Eq. (1)). This process yielded four different criterion layers: maximum temperature/salinity for both the bottom (xi) and water column (xii), and average temperature/salinity for both the bottom (xiii) and water column (xiv). Consequently, this study encompasses not only average values but also worst-case scenarios for these two critical factors within the lagoon.

xv-xviii) Dissolved oxygen concentration

The development of hypoxia and anoxia conditions in the lagoon during eutrophication events poses a significant threat. Ruiz et al. (2021) identified oxygen levels below 4 mg/L as being stressful, especially for benthic organisms such as fan mussels. Therefore, in this study, oxygen depletion below 4 mg.L^{-1} is considered problematic. Oxygen concentration data in the water column and at the lagoon's bottom were obtained using raster layers provided by OISMA and the Fishing and Aquaculture Service of the Region of Murcia (UPCT, 2023) from 2017 to 2021. A variable was computed for each day and pixel. This is set to 0 when the oxygen concentration exceeds 4 mg.L^{-1}. If the concentration falls below 4 ppm, it is calculated by subtracting 4 from this concentration (Eq. (2)).

$$\text{If } O_2 \geq 4, \text{then Variable} = 0 \text{ If } O_2 < 4, \text{then Variable} = O_2 - 4 \quad (2)$$

Because the interest in studying both the average and the worst case scenario, as with salinity and temperature, we obtained the annual averages and daily maximums of this variable, both for the bottom and the water column (xv-xviii); they were linearly transformed into a criterion that is 1 when the variable is zero and 0 when it reaches the maximum observed value.

2.2.2. Importance and weighting factors

After selecting the factors and defining the criteria, an importance score was assigned to each factor, with values ranging from 0 (indicating no importance for the species' survival) to 100 (representing the highest importance). This importance score was determined based on existing literature, coupled with the knowledge and experience of the authors, and meetings with experts (Supplementary Material, Table S1, Appendix A). These importances were transformed to weights with equation (3).

$$w_i = \frac{r_i}{\sum_{k=1}^{n} r_k} \quad (3)$$

where w_i is the normalised weight for the ith criterion, n is the number of criteria under consideration (k = 1,2, …,n) and r_i is the importance of the criterion (Malczewski, 1999).

2.2.3. Suitability model aggregation

The final suitability raster map has been determined using a Weighted Linear Combination (WLC) compensatory technique, the most often used decision rule in GIS (Malczewski, 2004), of the 18 factors. The score in each cell is obtained as:

$$S_j = \sum_{i=1}^{k} w_i \bullet x_i \bullet \prod_{j=1}^{m} c_j \quad (4)$$

where S_j is the suitability of the jth pixel, x_i is the criterion score of factor i, w_j is the weight of factor i, c_j are constraints codified as 0 when pixel is allowed and 1 when it si allowed, k is the total number of factors and m is a total number of constraints. In this study, a single constraint has been considered, depth, so that suitability set to zero for cells where the depth exceeds 3 m (Cortés-Melendreras et al., 2022; Giménez-Casalduero et al., 2020).

Finally, two additional layers were computed, wherein cells are eliminated if any criterion score falls below 0.01 or 0.05. This allows for an evaluation of the final suitability under more restrictive conditions. Additionally, for each final map, the surface area of the lagoon corresponding to each suitability level has been determined.

Complementary to suitability raster map, the suitability classes have been obtained from K-Means cluster algorithm of the numerical suitability scores obtained with Weighted Linear Combination (WLC). This technique attempts to determine k non-overlapping clusters maximizing the between-cluster variance and minimizing the within-cluster variance (Xu et al., 2018). The number of optimal classes has been obtained using the Elbow Method, which estimates and compares Within-Cluster-Sum of Squared Errors (WSS) for different values of k classes, selecting the class for which WSS does not decrease significantly.

3. Results

3.1. Criterion maps

The criterion maps obtained have been attached in the Supplementary Material (Figs. S1–S3, Appendix A). It is noteworthy that the criteria for maximum temperature/salinity in the bottom and water column (Fig. S2(xi-xii)) indicate relatively low maximum suitability scores, specifically 0.17 and 0.08, respectively. Therefore, in areas where suitability is high according to these criteria, it is quite lower in comparison to the rest of the factors, which reach up to adequacy score 1. The maximum salinity/temperature criteria exhibit a distinct pattern between the lagoon bottom and the water column. In the bottom, the scores are even less favourable in shallow areas, whereas in the water column, suitability is minimal throughout the lagoon (Fig. S2). Regarding the average salinity/temperature scores in the bottom, they mirror the same pattern as the maximum scores, with higher suitability in the deeper zone, while in the water column, suitability remains at a medium-low score across most of the lagoon (Fig. S3). In the case of oxygen deficiency, both the maximum and average scores are more favourable in the shallow areas, with the least suitability conditions in the deeper zone and the southern part of the lagoon (Fig. S3).

3.2. Importance and weighting factors

To establish the importance scores, the most determinant factor was identified based on expert experience and scientific literature (Table 2). Salinity/temperature, which is critical to the spread of *H. pinnae* in the lagoon, was assigned the highest importance score (100), and of all other factors were assessed in relation to this. In the case of the salinity/temperature and oxygen deficiency factors, given the existence of 4 layers for each, their importance values have been evenly distributed among them to avoid overrepresenting these variables. Distance to the Encañizadas, seabed type, and oxygen deficiency (90) are also related to the entry of *H. pinnae*, the ecological preferences of the species, and the

Table 2
Importance and assigned weight for each factor.

Factor	Importance	Weight
i) Depth	30	0.0429
ii) Distance to Albujón	80	0.1145
iii) Distance to Encañizadas	90	0.1288
iv) Distance to Estacio	52.65	0.0754
v) Distance to Marchamalo	31	0.0444
vi) Distance to urban centres	5	0.0072
vii) Distance to beaches	10	0.0143
viii) Distance to anchoring zones	50	0.0716
ix) Distance to nets	70	0.1002
x) Type of habitat	90	0.1288
xi) Maximum salinity/temperature at the bottom	25	0.0358
xii) Maximum salinity/temperature at the water column	25	0.0358
xiii) Average salinity/temperature at the bottom	25	0.0358
xiv) Average salinity/temperature at the water column	25	0.0358
xv) Maximum oxygen deficiency at the bottom	22.5	0.0322
xvi) Maximum oxygen deficiency at the water column	22.5	0.0322
xvii) Average oxygen deficiency at the bottom	22.5	0.0322
xviii) Average oxygen deficiency at the water column	22.5	0.0322

eutrophic conditions within the lagoon, respectively. The distance to the mouth of the Albujón (80) and to nets (70) were considered not as crucial as the previous ones. The distance to the other two connection channels were deemed less critical to the species' survival and assigned lower importance scores (52.65 and 31). The distance to anchoring zones has been considered of moderate importance (50). Depth was not considered a highly determinant factor as it was already considered as a major constraint when lower than 3 m (30), while the distance to beaches (10) and urban areas (5) has been considered the least critical.

Subsequently, each importance value is divided by the sum of all of them (698.65), resulting in the determination of weights (Table 2).

3.3. Suitability maps

An optimal area for the survival of *P. nobilis* of 1797.58 ha is obtained (Fig. 2(A)), which corresponds to 13.31 % of the lagoon total area (Table 3). Most of this zone exhibits suitability scores between 0.7 and 0.8. If pixels where any criterion scores is below 0.01 and 0.05 are excluded, the optimal area is reduced to 1424.87 and 373.73 ha, respectively (10.55 % and 2.77 % of the lagoon's total area; Table 3, Fig. 2(B–C)). In both cases, the largest area also corresponds to suitability scores between 0.7 and 0.8. When considering a more restrictive scenario, where pixels with criterion scores below 0.1 are removed, no suitable area for *P. nobilis* is obtained in the lagoon. Examining the map representing the most restrictive scenario possible reveals that suitable areas are located on the east coast, south of the Estacio channel, some regions surrounding the perimeter of the Barón and Perdiguera islands, and some points along the west coast (Fig. 2). Complementary to sustainability maps, zoning maps based on K-Means with GIS-MCDA are included on Supplementary Material section S3 (Table S2 and Fig. S4, Appendix A).

Table 3
Optimum sites extension based on WLC, expressed in hectares and as a percentage of the total area of the lagoon, results from the combination of all the factors and excluding pixels with criteria scores lower than 0.01 and 0.05.

Suitability	18 factors (ha)	>0.01 (ha)	>0.05 (ha)	18 factors (%)	>0.01 (%)	>0.05 (%)
0–0.5	1.48	0.00	0.00	0.01	0.00	0.00
0.5–0.6	59.35	28.13	7.81	0.44	0.21	0.06
0.6–0.7	313.51	192.00	58.05	2.32	1.42	0.43
0.7–0.8	1058.46	855.75	214.33	7.84	6.34	1.59
0.8–0.9	364.49	348.96	93.56	2.70	2.58	0.69
0.9–1.0	0.03	0.03	0.03	0.00	0.00	0.00
Total	1797.32	1424.87	373.73	13.31	10.55	2.77

3.4. Comparison of suitability maps

The map excluding pixels with any criteria below 0.05 closely align with the year 2020 spatial density prediction in Cortés-Melendreras et al. (2022) (Fig. 3 (B)). These authors forecasted a potential area of 323.34 hectares in year 2017 and 200.97 hectares in year 2020 based on

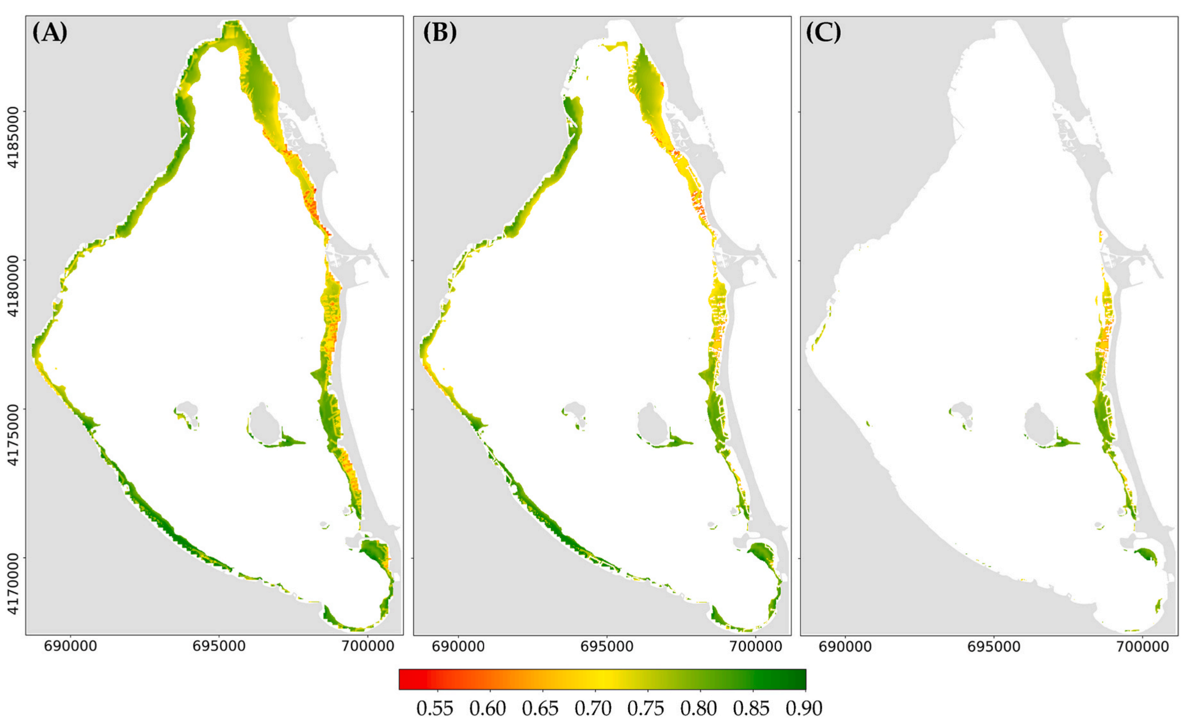

Fig. 2. Suitability maps based on Weighted Linear Combination (WLC). Scores range from 0 (poor adequacy) to 1 (good adequacy), considering A) all the 18 criteria factors, B) excluding pixels with any criteria lower than 0.01, and C) excluding pixels with any criteria lower than 0.05.

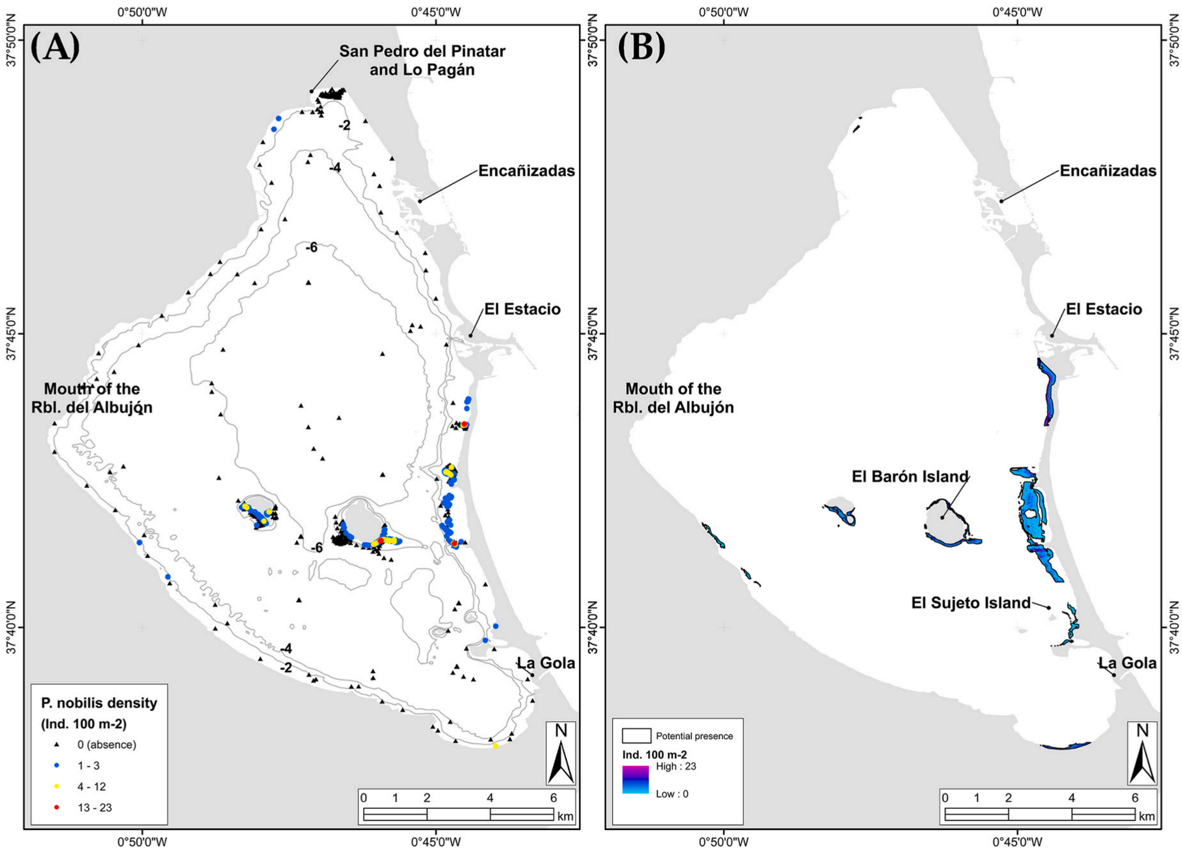

Fig. 3. A) Dataset and B) spatial prediction of density of *P. nobilis* in 2020. Source: Based on Cortés-Melendreras et al. (2022).

the identification of determining factors influencing the species' distribution in the lagoon and a total of 845 points in a final data-set (Fig. 3 (A)) based on multiple sampling sources from 2016 to 2020 (Cortés-Melendreras et al., 2022, p.4). In our case, utilising the GIS-MCDA approach, we have identified 373.73 hectares with suitability exceeding 50% (Table 3) and 307.92 hectares, with suitability exceeding 70% (2.28% of the lagoon's total area, Table 3), that correspond to optimal zones for the survival of *P. nobilis*. These regions are located along the coastal perimeter of La Manga, particularly to the south of Estacio channel, the perimeter of the Baron and Perdiguera islands, as well as selected points along the west coast (Fig. 2(C)).

4. Discussion

Currently, the fan mussel in the Mediterranean Sea is facing an extremely critical situation. With its populations nearly entirely vanished, areas serving as sanctuaries are crucial for the species' conservation. Along the Spanish coastline, only two distinct regions have been identified as sanctuaries. The Ebro Delta in Catalonia and the Mar Menor lagoon in the Region of Murcia. However, these areas cannot be considered sanctuaries *sensu stricto* (Cortés-Melendreras et al., 2022; Prado et al., 2022). A marine sanctuary is a delimited portion of the ocean that is outside the reach of anthropogenic pressure, for the regeneration and sanitation of that ecosystem and its biodiversity (Beaumont et al., 2007). They are protected and conserved through legal regulations (Day et al., 2019).

The Mar Menor could have served as a sanctuary for an extensive population, boasting over one and a half million individuals in 2014 (Giménez-Casalduero et al., 2020). However, following the environmental collapse of the lagoon in 2016, a clear distribution pattern was observed in the individuals; all those located more than 3 m deep had disappeared. Naturally, at these depths, the diminished light due to the massive growth of phytoplankton leads to the mortality of bottom vegetation, a decrease in oxygen concentrations, and the mortality of benthic fauna (Giménez-Casalduero et al., 2020; Sandonnini et al., 2021a, 2021b). Therefore, depth has been identified as the primary limiting factor, restricting the possibility of hosting fan mussels to the lagoon's perimeter and its islands. Regarding the individuals in shallow areas, it was estimated that they suffered a 90% mortality rate after the 2016 eutrophication episode (Giménez-Casalduero et al., 2020). Subsequent eutrophic episodes in the lagoon, coupled with various other factors, have significantly reduced the number of individuals, leaving just around 1000 fan mussel individuals in the entire lagoon (Cortés-Melendreras et al., 2022).

The 18 factors employed in this study can be categorised into two main groups: firstly, those related to the entry and dispersion of *H. pinnae* (distances to the three points of connection with the Mediterranean Sea and values of temperature/salinity), and secondly, those linked to anthropogenic impacts on the lagoon. Among the latter, distinctions can be drawn between factors related to eutrophic conditions (distance to the mouth of Albujón and oxygen deficiency) and those directly attributable to human activities (distance to urban areas, beaches, nets, and anchoring). Regarding the type of habitat factor, its suitability is closely linked to the species' ecological preferences (Katsanevakis and Thessalou-Legaki, 2009; MAAMA, 2012).

When considering factors related to the entry of *H. pinnae* into the lagoon, the criterion maps for distances to each of the channels connecting with the Mediterranean Sea reveal a general trend. The area closest to the east coast tends to exhibit lower suitability, while suitability increases as we move towards the interior of the lagoon, farther from the connection areas with the Mediterranean Sea. The potential entry of the protozoan through the channels is one of the great threats to the survival of the specimens in the lagoon, so it was important to validate the survival thresholds of the pathogen based on the salinity and temperature conditions of the lagoon. Across almost the entire lagoon, there is a high probability of having favourable conditions for the entry of *H. pinnae*, whether in the water column or at the seabed. The criteria applied to these variables significantly influence the results of the present study, since very low values of adequacy have been obtained. Of particular interest is the emphasis on the variables at the bottom, where adequacy for *P. nobilis* survival is generally lower in the shallow areas compared to the deeper zones. This pattern aligns with the well-documented salinity stratification in the lagoon, with the surface layer exhibiting lower salinity and the deeper layer displaying higher salinity and greater temporal stability (Fraile-Nuez et al., 2017). In situations of massive influx of water from the Mediterranean Sea, due to storms or runoff from torrential rain, the water mass is stratified, facilitating the entry of the pathogen into the surface layer. Therefore, in deeper areas, characterised by higher salinities, *P. nobilis* may have a greater refuge from the risk of protozoan infection. Conversely, lower oxygen deficiency conditions are observed in the surface zone, linked to the eutrophic conditions of the water. These conditions have significantly influenced the current distribution of *P. nobilis* individuals in the lagoon. As mentioned by Prado et al. (2021), ecosystems where fan mussels are less vulnerable to the disease causing the Mass Mortality Event are simultaneously more vulnerable to other environmental factors such as meteorological phenomena (e.g., the Gloria storm in the Ebro Delta) or eutrophication in the case of the Mar Menor lagoon.

The situation is undeniably complex, and the results of this study would have differed considerably if the environmental condition of the lagoon had not been so severely impacted. If depth were not a limiting factor, and if hypoxia or anoxia did not occur, the deep basin of the lagoon would have been of great interest for hosting fan mussels, where salinity and temperature variables are more optimal (with lower risk of infection by *H. pinnae*). The obtained scores for the optimal area were notably limited in comparison to the total area of the lagoon, especially in the more restrictive maps. Among the three suitability maps obtained, the most restrictive one seems to offer the most viable proposal for identifying optimal zones.

It is essential to clarify the specific meaning of an optimal zone for the species. For this purpose, GIS-MCDA is a tool of special interest in marine and coastal spatial planning (Tammi and Kalliola, 2014). Furthermore, the use of K-Means with GIS-MCDA makes it possible to obtain a zoning based on groups that are more similar in terms of criteria values. This approach is helpful for management and is convenient for decision makers to allocate limited resources in the design intervention (Shi and Zeng, 2014; Xu et al., 2018).

The lagoon's populations face considerable challenges for reproduction due to unfavorable environmental conditions. When identifying the optimal areas for the recruitment of individuals reproduced in the natural environment, other factors not accounted in this study should be considered. Moreover, low population densities and substantial distances between individuals can severely hinder reproductive success (Katsanevakis et al., 2022). Furthermore, there is evidence of predation on juveniles by the gastropod species *Hexaplex trunculus* (Cortés-Melendreras et al., 2021). In the present study, optimal zones refer to areas suitable for the survival of adult individuals. The optimal areas we have provided can serve as valuable references for conducting comprehensive surveys within the lagoon. These areas may also be considered for potential translocation efforts aimed at safeguarding endangered individuals or for reintroducing individuals that have been bred and maintained in a laboratory setting.

MCDA can be sensitive to the weight values chosen. In cases where there is not high confidence in these values, weight sensitivity analysis can be useful to show spatially how dependent the final adequacy values are on the selected weights (Chen et al., 2009; Feizizadeh and Blaschke, 2014; Więckowski and Sałabun, 2023).

5. Conclusions

In this contribution, through the weighted combination of 18 factors, 307.92 hectares of the lagoon (2.28%) have been determined as potential areas for the survival of *Pinna nobilis*, with an adequacy greater than 70%. These results can be used for future translocation and reintroduction projects.

GIS-MCDA is an excellent tool for addressing decisions in complex scenarios, although its participatory nature may introduce subjective elements. It can help decision-makers formally structure multifaceted decisions and evaluate alternatives. As indicated by Tammi and Kalliola (2014), the combined use of GIS and MCDA tools allows for the generation of easily interpretable data, enabling the quantification and visualisation of aspects such as criteria, trade-offs, or alternatives.

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Ethics approval and consent to participate

Not applicable.

Availability of data and materials materials-methods

The dataset used and analysed during the current study are available from the corresponding author on reasonable request.

CRediT authorship contribution statement

Pilar Martínez-Martínez: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francisco Alonso-Sarría:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Francisco Gomariz-Castillo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Data curation. **Enrique Reñé-Sánchez:** Resources, Investigation, Data curation. **Emilio Cortés-Melendreras:** Resources, Investigation, Data curation, Conceptualization. **Yolanda Fernández-Torquemada:** Resources, Investigation, Data curation. **Francisca Giménez-Casalduero:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Francisco Alonso Sarria reports financial support was provided by Spanish Agencia Estatal de Investigación. Yolanda Fernandez Torquemada reports financial support was provided by LIFE Programme of the European Union. Emilio Cortés Melendreras reports financial support was provided by *Consejería de Agua, Agricultura, Ganadería, Pesca y Medio Ambiente* (CARM). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107265.

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