

Chapter

Planning and Management Strategies for the Conservation of the Critically Endangered Fan Mussel *Pinna nobilis*: A Review of the Mar Menor Coastal Lagoon Case (Western Mediterranean)

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Abstract

The fan mussel, *Pinna nobilis*, is a bivalve mollusk endemic to the Mediterranean Sea and currently classified as critically endangered. Since 2016, the species has suffered a mass mortality event, mainly caused by the protozoan *Haplosporidium pinnae*, along with other pathogens that act synergistically to accelerate death. With mortality rates approaching 100% across the Mediterranean, surviving populations are now confined to a few refuges where the parasite's dispersal capacity is limited by environmental conditions. In Spain, the Ebro Delta and the Mar Menor lagoon represent the last areas with living individuals. The Mar Menor, which hosted more than 1.5 million specimens in 2014, has undergone severe environmental degradation and eutrophication, reducing the population to around 1000 individuals. In this context, effective conservation requires a comprehensive management plan that includes assessing historical and current populations, identifying threats and suitable areas, translocating part of the at-risk individuals, and monitoring their survival. This chapter presents a review of the process applied to the population of the Mar Menor, integrating years of research to establish a solid foundation for the conservation planning and management of threatened species.

Keywords: fan mussel, mass mortality event, sanctuary area, eutrophication impacts, conservation strategies

1. Introduction

The Mediterranean Sea is widely recognized as a global biodiversity hotspot, supporting over 17,000 marine species, around 20–30% of which are endemic [1, 2]. However, this exceptional biodiversity is under threat from multiple human-caused pressures, including pollution, habitat degradation, over-exploitation of marine resources, the spread of invasive species, and climate change [1]. These stressors collectively disrupt the structure and functioning of ecosystems, altering species interactions and population dynamics. In some cases, this leads to population collapses and extinctions. Globally, 28% of species assessed by the International Union for Conservation of Nature (IUCN) by 2025 are currently classified as threatened. Within the Mediterranean region, around 100 species are considered threatened, including 21 categorized as Critically Endangered [3]. A recent and emblematic example is the fan mussel, *Pinna nobilis* Linnaeus, 1758 (**Figure 1**), an endemic Mediterranean bivalve that has been listed as Critically Endangered since 2019 [4].

Pinna nobilis is the largest bivalve in the Mediterranean and the second largest in the world. It can reach a shell length of up to 120 cm and live for up to 45–50 years [5, 6]. Its valves are characterized by their fan-like shape, tapering to a pointed anterior end. It lives anchored to the seabed with approximately one-third of its shell buried and uses byssal threads to attach itself to coarse particles, such as shell fragments, rocks, and root networks [1, 7]. Its primary habitat is *Posidonia oceanica* seagrass meadows, although it has also been found in *Cymodocea nodosa* and *Zostera marina* meadows. It may also be found on other types of substrates, including maërl beds and fine sediments (sand and mud), which are sometimes covered by *Caulerpa prolifera* [8, 9]. This species inhabits depths ranging from 0.5 to 60 meters and tolerates a broad range of temperatures and salinities [8, 9]. As a highly efficient filter feeder, *P. nobilis* contributes to water clarity and transparency in its habitats. Furthermore, its shell provides a hard substrate that supports the settlement of numerous associated organisms, thereby enhancing local biodiversity [10, 11]. Its benthic lifestyle renders it particularly vulnerable to human activities such as fishing, bottom trawling, boat anchoring, and habitat degradation [12]. However, the species' dramatic decline has primarily been linked to infections caused by one or more pathogens [13].

In 2016, a mass mortality event (MME) began, resulting in the loss of almost 100% of known fan mussel populations throughout the Mediterranean. The main pathogen associated with the MME was the protozoan *Haplosporidium pinnae* [14].



Figure 1.
Pinna nobilis in Mar Menor coastal lagoon.

Since then, further pathogens have been identified that appear to act synergistically and contribute to high mortality. These include bacteria belonging to the genera *Mycobacterium* and *Vibrio*, as well as a hemocyte-infecting picornavirus [15–17]. Currently, isolated surviving individuals have been found in open coastal waters [18, 19]. However, the only remaining populations are located in so-called sanctuary areas, where *H. pinnae* is thought to have limited dispersal and infection capacity due to environmental conditions that differ from those in the open Mediterranean, particularly temperature and salinity [17, 20]. The optimal salinity range for the protozoan is considered to be between 36.5 and 39.7 PSU. Moreover, higher temperatures may increase the aggressiveness of the pathogen, particularly above 13.5 °C [20, 21]. Consequently, individuals have persisted in confined waters with distinct conditions, such as coastal lagoons, estuaries, and river deltas [22]. Surviving populations have been reported across the Mediterranean, including in Algeria and Tunisia, the Sea of Marmara in Turkey, which is the largest sanctuary for the species in the Eastern Mediterranean, and Greece, Italy, and France [22, 23]. The Thau Lagoon in France is particularly noteworthy due to its high abundance of individuals [24]. In Spain, only two sanctuary areas remain: the Ebro Delta in Catalonia and the Mar Menor coastal lagoon in Murcia. These populations are threatened by potential infections caused by any of the aforementioned pathogens, as well as by environmental degradation, extreme climatic events, and other anthropogenic stressors [23, 25, 26]. The effective conservation of fan mussel survivors requires a comprehensive management plan. This chapter outlines the approach adopted for the *P. nobilis* population in the Mar Menor, drawing on years of research to provide a robust basis for the conservation planning and management of this endangered species. To this end, a comprehensive compilation and critical review of all studies conducted by the research team on the lagoon population has been carried out [18, 25, 27–35].

2. Case study: The Mar Menor Coastal Lagoon

Located in the semi-arid south-east of Spain (**Figure 2**), the Mar Menor is the largest coastal lagoon in the western Mediterranean, covering an area of 135 km² with an average depth of 3.5 meters and a maximum depth of 7 meters [27]. It is separated from the Mediterranean Sea by the 22 km-long sandy barrier of *La Manga* and is connected to it through three main exchange channels: *Las Encañizadas*, *El Estacio*, and *La Gola de Marchamalo* [36]. The lagoon exhibits a net hydrological deficit of approximately 1000 mm per year, which is compensated for by continental runoff and seawater inflows [37]. Water exchange is regulated by barotropic tides induced by wind and pressure, with mean amplitudes of 0.2–0.4 meters [38]. Its high degree of isolation has led to extreme environmental conditions, including hypersalinity (40–45 PSU) and pronounced daily and seasonal thermal variability (8–31 °C). This favors communities dominated by euryhaline and eurythermal species [25, 39], with seagrass meadows of *Cymodocea nodosa* covering much of the lagoon's seabed [40]. The Mar Menor's high ecological value is recognized through multiple protection designations, including RAMSAR status and inclusion within the Natura 2000 network. The lagoon is the lowest point in the 1,250 km² *Campo de Cartagena* drainage basin, which supplies water, sediments, and nutrients via 13 ephemeral channels. The most significant of these is

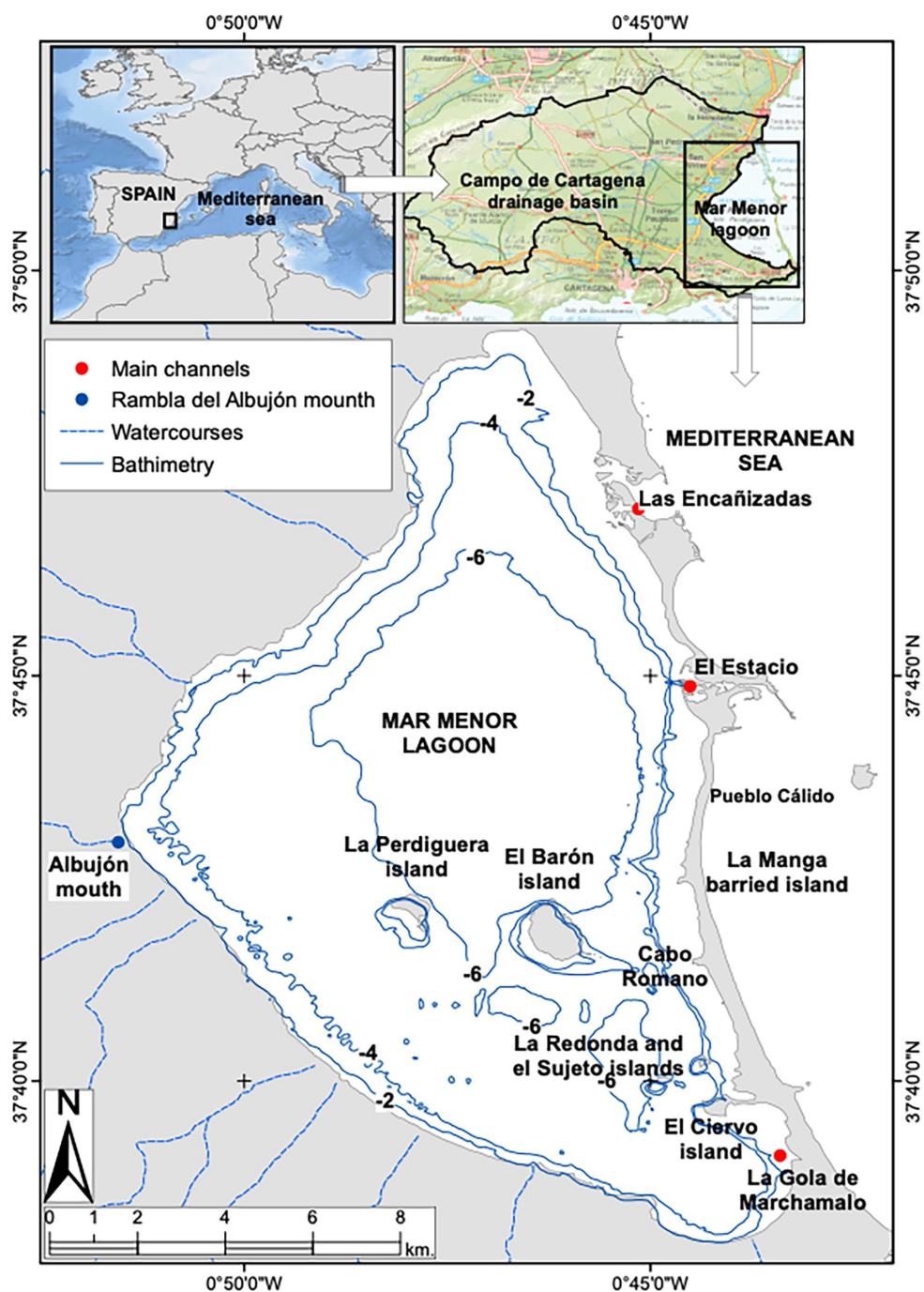


Figure 2. Location of Mar Menor Coastal Lagoon in South-Eastern Spain (Western Mediterranean).

the *Albujón Rambla* [41]. The intensification of irrigated agriculture and tourism has altered hydrological and nutrient fluxes, increasing nutrient loads and promoting eutrophication processes in the lagoon [42, 43]. Irrigated land expanded by 141% between 1988 and 2009 [44], significantly impacting wetlands and their biological communities [45]. The system's evolution follows [43] shallow lagoon model, characterized by the replacement of *Cymodocea nodosa* by *Caulerpa prolifera* (cover > 90%), and an environmental collapse following the harmful algal bloom in 2015 [46]. This resulted in the loss of 85% of seagrass meadows [47] and was further exacerbated by the 2019 DANA event, which caused anoxia, euxinia, and mass mortality of fauna. Anoxic conditions were observed again in summer 2021 [48]. Although a slight recovery has occurred since then in response to management actions in the *Campo de Cartagena*, the lagoon remains far from achieving good ecological status.

3. *Pinna nobilis* population

3.1 Historic population

Although *P. nobilis* is a common mollusk in semi-enclosed bays and Mediterranean coastal lagoons [49], it was absent from the Mar Menor until the early 1980s. In 1976, a navigation channel (*Estacio* channel) was opened, connecting the lagoon with the Mediterranean Sea [50], which modified the hydrodynamic regime and increased water renewal rates. As a result, sedimentary conditions changed, and both salinity and temperature decreased, approaching Mediterranean values [51, 52], facilitating the entry and establishment of new species, including *P. nobilis* [27]. The first record of *P. nobilis* in the lagoon dates to the early 1980s [53], after which it rapidly became a key component of the benthic community and developed one of the most important populations in the Western Mediterranean.

The colonization and dispersal of *P. nobilis* in the lagoon were evaluated using historical records, field survey data, published sources, and environmental data [27]. This allowed the dynamics of *P. nobilis* colonization and expansion in the lagoon, as well as changes in the species' distribution, to be reconstructed. From the 1980s until 2014, the population underwent a colonization and stabilization process. Until the early 2000s, population distribution was strongly influenced by proximity to the lagoon's connections with the Mediterranean Sea, particularly the *Estacio* and the *Encañizadas* [27]. However, in 2013 and 2014, the existing Mar Menor population expanded into areas farther from these connection points [27]. Random Forest models were developed to estimate the potential distribution and density of *P. nobilis* for different years using individual density and size data collected along transects throughout the lagoon, together with environmental variables (selecting the most influential factors for *P. nobilis* distribution). For the period 2013–2014, the density model predicted values ranging from 0.01 to 21.6 individuals per 100 m², with an average density of 2.181 ± 0.004 individuals per 100 m² (**Figure 3**). It was estimated that the total population size exceeded 1.5 million individuals, potentially covering approximately 54% of the total seabed area. During this period, distance from the connecting channels, distance from the shoreline, depth, and salinity were identified as key factors shaping population distribution. Individual density and size were greater in the deeper areas of the lagoon due to the stable conditions in these zones [25].

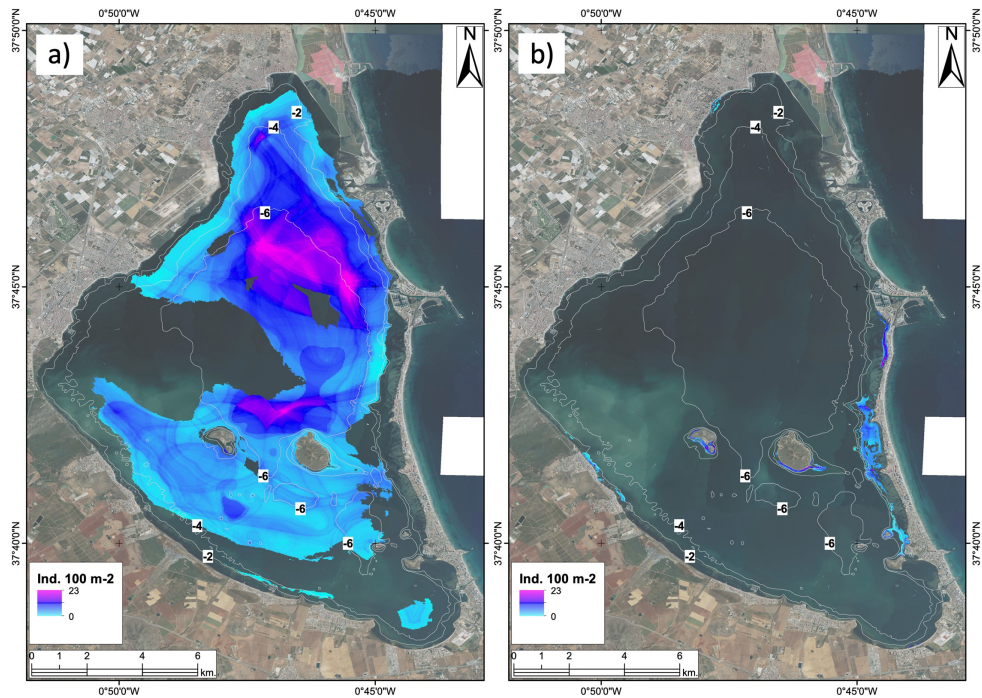


Figure 3.

Spatial prediction of *P. nobilis* density in the Mar Menor in (a) 2013–14, potential habitat area of 7385 ha [27]; (b) 2020, Potential habitat area of 2,009.7 ha [25].

In terms of sediment characteristics, the presence of *P. nobilis* was positively correlated with organic matter content and gravel-rich sediments. This is attributed to the species' requirement for coarse particles that enable them to securely anchor their byssus to the substrate [27]. There was significant mortality of *P. nobilis* in the Mar Menor, which reached its peak in 2017. This has been attributed not to the *H. pinnae* epidemic, but to the environmental collapse caused by the eutrophication crisis that affected the lagoon in 2016. The mortality rate was estimated to exceed 95%. No surviving individuals were found below a depth of 3 m, and survival above this depth was limited to around 10%, primarily in the areas surrounding the central islands and the lagoon shoreline [27]. In addition, in response to the high availability of suspended organic matter, extraordinary growth of serpulid polychaetes of the genus *Hydroides* sp. was detected. The growth of this species on some specimens of fan mussels caused a new episode of mortality. The rapid formation of calcium carbonate tube crusts ended up blocking the bivalve's valves, preventing its normal activity and causing its death [54, 55]. Subsequent eutrophication episodes (during 2019 and 2021) and other pressures have continued to affect the specimens that survived. In 2020, the potential density model estimated an average of 1.055 ± 0.006 individuals per 100 m^2 in areas with surviving individuals, with values ranging from 0.01 to 23 individuals per 100 m^2 (Figure 3). During this period, the population decreased from over one million individuals to around 1,500, and the species' potential habitat shrank from 7,385 hectares to 2,009 hectares (Figure 3).

In addition, following changes in salinity, *H. pinnae* infections and associated mortality of individuals in the Mar Menor population were observed, although these effects were mitigated once salinity increased [25].

3.2 Current population: Post-mortality diagnosis

Following successive eutrophication crises, the *P. nobilis* population in the Mar Menor suffered high mortality, leaving just over a 1000 individuals relegated to shallow areas (above 3 m depth) and far from the main watercourses that flow into the lagoon [25, 27]. This situation highlighted the importance of monitoring the environmental parameters in the lagoon and conducting exhaustive monitoring of the surviving *P. nobilis* individuals, carrying out surveys to search for newly undetected individuals, as well as possible recruits. It also became essential to monitor the growth and health status of the surviving individuals using minimally invasive techniques.

3.2.1 Environmental monitoring

Environmental monitoring of the lagoon was designed by combining physical, chemical, and biological data in order to control and detect changes in conditions that could affect the status and survival of *P. nobilis* specimens [27].

Data on salinity, temperature, and dissolved oxygen concentration, among others, were collected from the water column, as well as data on parameters associated with sediments, such as granulometry, percentage of organic matter, and redox potential [28, 29]. With regard to the biological variables characterized by their importance for *P. nobilis*, different descriptors of the macrophyte meadows in which they are found were studied, mainly evaluating cover, leaf canopy, and density, the latter in the case of seagrasses [28, 29]. The density of epibionts on the valves was also estimated.

From 2022 onwards, it was generally observed that the environmental conditions of the lagoon had improved after the most critical eutrophication events, although some specific periods with less suitable conditions were detected in certain areas of the lagoon, associated with torrential rains or seasonality. For example, values below 4 mg L⁻¹ of DO were detected on some summer days in 2022, 2023, and 2024. There were also decreases in salinity values below 39 PSU after heavy rainfall in the spring of 2022 [29].

With regard to the characterization of the sediments near *P. nobilis* individuals, in some areas, a deterioration in their conditions was detected due to an increase in organic matter and a reduction in redox potential, which was associated with higher mortality of fan mussel specimens in 2022 due to local conditions [28].

It was also observed that in locations where *P. nobilis* was present, there were mixed macrophyte meadows, in which the cover of the macroalgae *Caulerpa prolifera* was similar at all sites (50–75% bottom cover) and greater than that of the seagrass *Cymodocea nodosa* (<25%). These results corroborate those found in other studies, which show a decrease in *C. nodosa* together with an increase in *C. prolifera*, compared to data from 2014 [40]. On the other hand, it was also found that areas with greater cover of *C. nodosa* could also be associated with lower mortality in fan mussels [28].

3.2.2 Monitoring of surviving adult specimens

Since 2019, visual censuses have been carried out periodically, in collaboration with the regional government, with the aim of detecting, marking, and georeferencing, as far as possible, all living individuals of *P. nobilis* present in the lagoon. Based on this information, a specific monitoring program was established in those areas with the highest density of fan mussels, aimed at estimating the mortality and growth rates of individuals [29].

Mortality rates recorded in recent years have shown marked spatial heterogeneity, reaching particularly high values in certain areas. Between 2022 and 2024, mortality rates ranging from 22% to 86% of the individuals surveyed in the eastern sector of the lagoon were detected [29]. A high proportion of the dead specimens had disappeared completely or were found broken or overturned, possibly as a result of impacts from anchors, moorings, trampling, and similar disturbances (**Figure 4**). In a considerable number of cases, it was not possible to determine with certainty the direct cause of death, although environmental conditions are a key factor in the continued mortality of the population. In particular, in June 2023, there was a massive growth of the filamentous algae *Acinetospora crinita*, which in some cases completely covered the *P. nobilis* individuals (**Figure 4**). This phenomenon may have contributed to the observed mortality by interfering with respiration and feeding processes, as well as by generating microenvironments with hypoxic or anoxic conditions in the organisms' surroundings [28].

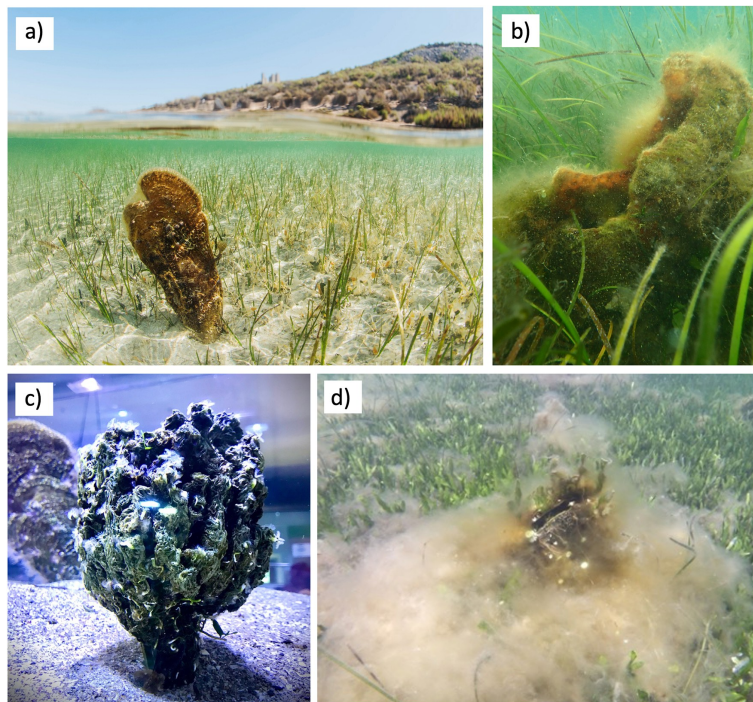


Figure 4. Individuals of *P. nobilis* in the Mar Menor killed by different threats: (a and b) broken shells due to the impact of boats and anchors; (c) massive growth of polychaete annelids (*Hydroides* spp.) after eutrophication episodes, (d) coverage by filamentous algae, primarily *Acinetospora crinita*.

In relation to the growth analysis, estimated from periodic measurements of shell length, it was observed that surviving individuals maintain positive growth, with rates between 1.4 and 2.7 cm year⁻¹ [29]. Likewise, for the year 2024, it was estimated that the maximum length of the specimens analyzed ranged between 40.7 and 59.5 cm, values which, according to the size-age relationships described for the species [56], correspond to approximate ages between 10 and 17 years [29].

In addition, and as part of monitoring the health status of the fan mussels present in the lagoon, fecal pellets and water samples from inside the valves were taken in order to assess the possible presence of the pathogen *Haplosporidium pinnae* [18, 30]. These non-invasive methodologies are considered particularly suitable for detecting this parasite because, compared to more invasive techniques such as biopsies, they allow relevant information to be obtained while minimizing the impact on surviving specimens [18, 30].

3.2.3 Recruitment rates

During the monitoring programs carried out in the study areas of the Mar Menor, special attention was paid to detecting signs of reproductive activity, such as the observation of spawning events or the presence of juvenile individuals. Additionally, between May and October from 2019 to 2024, larval collectors were installed in these plots to assess the possible recruitment of *Pinna nobilis*. Initially, no juveniles were detected settled in the sediment at any of the sampled locations, nor was the presence of recruits recorded in the installed larval collectors. Gamete release into the environment by some adults in the lagoon was observed in multiple years (2019, 2020, and 2022) [31], but there was no successful recruitment. However, in 2021 [32], some juvenile recruitment was detected for the first time since the eutrophication crisis of 2016. Unfortunately, these juveniles died shortly afterward, probably as a result of predation by the gastropod *Hexaplex trunculus*. This species experienced massive population growth after the 2016 episode, favored by its scavenging habits [32].

During the censuses carried out in the lagoon in June 2024, a total of 23 juveniles were identified [33] (**Figure 5**), despite the fact that no adult individuals were found in the area, which meant that reproductive episodes had occurred within the lagoon



Figure 5.
Pinna nobilis juvenile found and recorded in 2024.

in areas close to the recruitment area. Viable larvae and effective settlements had been generated [33]. This finding was the first evidence of successful natural recruitment of the species in the lagoon after several years without any records of new cohorts joining the population. However, after the summer period, the juveniles recorded were not seen again, so it was assumed that they had all perished, possibly due to anthropogenic causes such as poaching, uncontrolled anchoring, or physical damage associated with human activities [33]. Between late 2024 and summer 2025, more juveniles were found in various areas of the lagoon, with some even in the deep zone where no adult survivors remained. The recruitment of new juvenile cohorts suggests that, despite adverse environmental conditions, there is potential for natural recruitment that could contribute to population recovery if lagoon conditions are maintained or improved, causes of mortality are mitigated, and areas where juveniles have been observed are protected [33].

4. Identification of surviving optimal areas in Mar Menor

Assessments of the population within the lagoon, both historical and current, reveal the extreme complexity of the pressures and threats affecting the species. As is the case in many environments where multiple economic sectors, recreational activities, and cultural and ecological values converge, significant conflicts arise between these needs and the conservation requirements of the species. This context highlights the necessity of an integrative approach that considers as many of these interacting factors as possible in order to identify areas that are optimal for the long-term survival of the species, as discussed in [34].

To this end, a multi-criteria evaluation (MCE) was conducted. MCE is defined as “an explicit decision-making process related to the structuring and resolution of spatial problems involving multiple criteria and providing a system of relative weighting” [57]. This approach was combined with geographic information systems (GIS) to create a GIS-based multi-criteria decision-making analysis (GIS-MCDA) [58–60]. The process was based on an extensive review of the scientific literature and the knowledge and expertise of the research team [34]. This resulted in a methodological framework tailored specifically to the ecological and socio-environmental characteristics of the Mar Menor.

4.1 Identifying key factors and thresholds

In order to understand the conditions affecting the survival of the species, the study first identified the key variables and factors influencing its persistence, establishing thresholds for each that indicate points at which the risk of mortality increases. Eighteen factors were considered essential for this assessment (**Table 1**). Among these, depth emerged as a critical exclusionary factor. Areas deeper than 3 meters were deemed unsuitable due to the high mortality risk linked to past eutrophication events that caused anoxic conditions [27]. Consequently, these zones were excluded from the analysis to focus on areas with realistic long-term survival potential.

Having identified the key factors, baseline maps for each one were obtained either from external sources or by creating them internally. These maps provided the spatial foundation needed for subsequent analyses.

Key factor	Threshold for survival
i) Depth	< 3 meters
ii) Distance to <i>Albujón</i> mouth	> distance (m) to <i>Perdiguera</i> island (following water current in the lagoon)
iii–v) Distance to connection points with the Mediterranean Sea	> distance (m) between <i>Encañizadas</i> channel and <i>Pueblo Cálido</i> (following water current in the lagoon)
vi) Distance to urban centers	> 50 meters
vii–ix) Distance to beaches, nets, and anchoring zones	> 50 meters
x) Type of habitat	Presence of <i>Cymodocea nodosa</i>
xi–xiv) Salinity and Temperature (maximum and average at the bottom and water column)	< 36.4 PSU or > 40 PSU; < 13 °C
xv–xviii) Dissolved oxygen concentration (maximum and average at the bottom and water column)	> 4 mg L ⁻¹

Table 1.
 Eighteen identified factors affecting *P. nobilis* survival in the Mar Menor and their determinant thresholds.

4.2 Standardization of factors into suitability criteria

Each factor was converted into a standardized suitability criterion, ranging from 0 (low suitability for the survival of *P. nobilis*) to 1 (high suitability), with the threshold defined for each factor taken into account. This enables all factors to be integrated into subsequent analyses. Using the defined criteria and baseline maps, a suitability map with a spatial resolution of 10 meters was generated for each factor.

4.3 Weighting of factors

Although the factors have been standardized to allow combined analysis, they do not all carry the same weighting in terms of the survival of *P. nobilis*. For example, a drop in dissolved oxygen concentration has far more severe consequences than proximity to an urban center. Therefore, before proceeding with the integration process, each factor was assigned a level of importance (**Figure 6**), which was then converted into a corresponding weight for use in the analysis.

4.4 Criteria combination and final adequacy map

The criteria were integrated into a single analysis using a weighted linear combination to account for the relative importance of each factor. This produced a final map showing the suitability of each pixel, providing a spatial representation of the areas most suitable for *P. nobilis*. Due to the species' high sensitivity, additional scenarios were developed by excluding pixels with very low suitability values. This ensures that only areas offering realistic survival potential are highlighted. In the most restrictive scenario, in which pixels with criterion values below 0.05 were removed, 373.8 hectares of the lagoon were identified as suitable for the survival of the species, representing 2.8% of the Mar Menor's total surface area (**Figure 7**). Most of these areas exhibited suitability values between 70% and 80% [34].

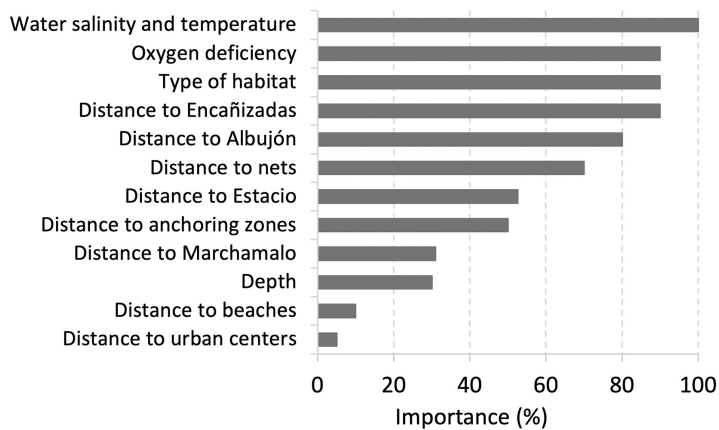


Figure 6. Level of importance (%) assigned to each threat factor for *P. nobilis* in the Mar Menor [34].

The 18 factors considered in this study can be grouped into two main categories. The first category includes variables related to the entry and dispersal of *H. pinnae*, such as distances to the three points of connection with the Mediterranean Sea and local temperature and salinity conditions. The second encompasses factors associated with anthropogenic impacts on the lagoon. Within this group, distinctions can be made between factors reflecting eutrophic conditions (e.g., distance to the *Albuñón Rambla* mouth and oxygen deficiency) and factors directly attributable to human activities (e.g., proximity to urban areas, beaches, fishing nets, and anchoring sites). Habitat type suitability is closely linked to the species' ecological preferences. The potential entry of the protozoan through the channels poses a significant threat to the survival of the lagoon's specimens. The results of this study would have differed significantly if the lagoon's environmental conditions had not been so severely impacted. For instance, if depth were not a limiting factor and hypoxic or anoxic events did not occur, the deep basin of the lagoon would likely be a favorable habitat for fan mussels, as salinity and temperature conditions would be more favorable and the risk of *H. pinnae* infection would be lower.

Optimal zones, as defined here, refer to areas suitable for the survival of adult individuals. These areas could be used as a basis for conducting comprehensive surveys of the lagoon. They could also be considered for translocation initiatives aimed at safeguarding endangered species or reintroducing individuals bred and maintained in laboratories. However, it is important to note that these zones do not necessarily represent optimal areas for recruitment, as the identification of recruitment sites requires consideration of additional specific factors [34].

4.5 Study of individuals location

Optimal survival zones are primarily located along the eastern coast, south of the *Estacio* channel, around the perimeters of *Barón* and *Perdiguera* islands, and at several points along the western coast. These results closely match the distribution of surviving individuals observed in the lagoon in 2020 [25], which confirms the reliability of the model.

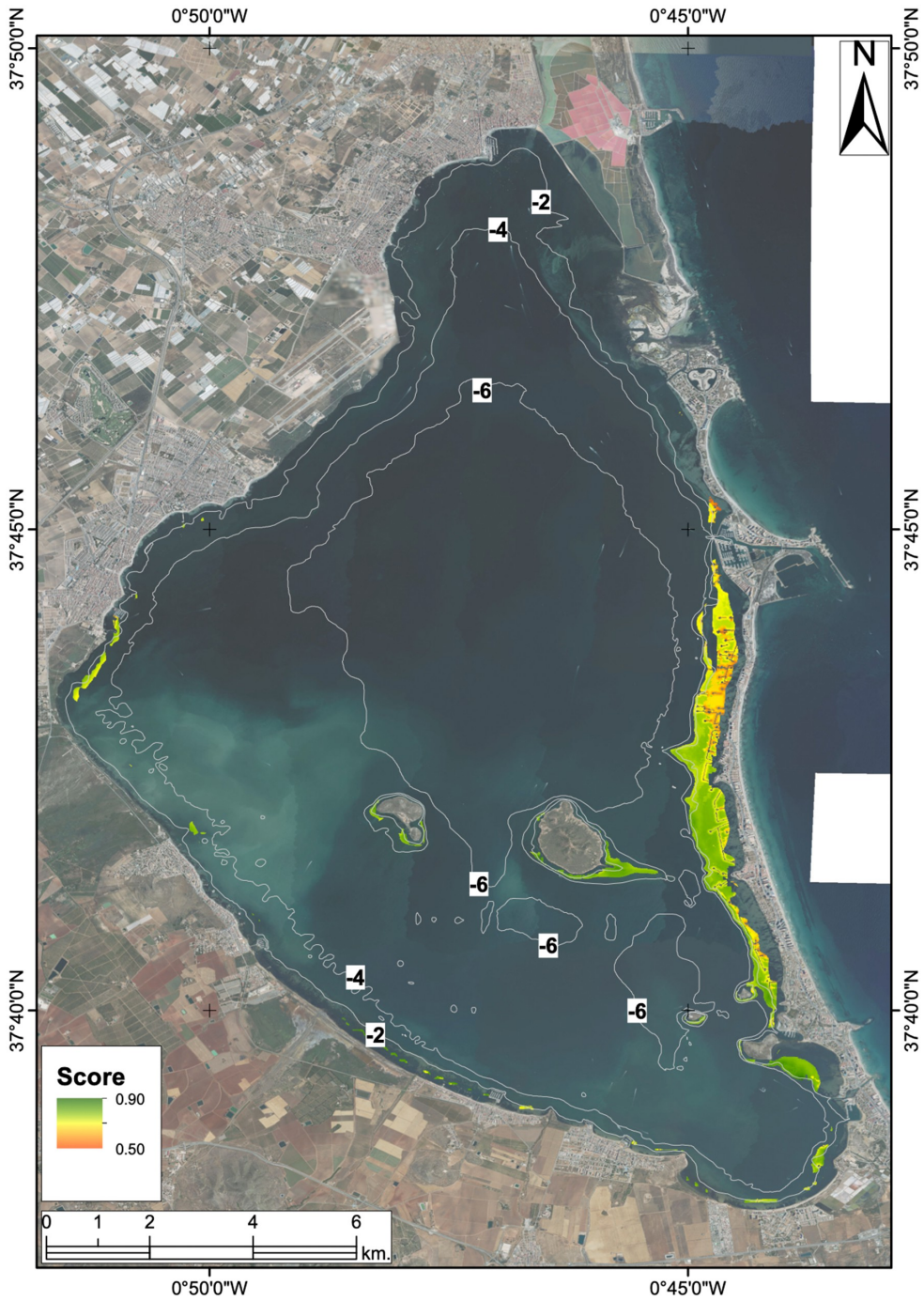


Figure 7. Suitability map for *P. nobilis* in Mar Menor based on Weighted Linear Combination (WLC), excluding pixels with any criterion lower than 0.05. Scores range from 0 (poor adequacy) to 1 (high adequacy) [34].

The detection of new juvenile recruitment in various parts of the lagoon from 2024 onwards [33] emphasizes the importance of evaluating the unique challenges each newly settled individual faces. Some recruits have been found in suboptimal areas, including the lagoon's deepest parts. As recruitment is not restricted to the most favorable or least risky zones, juveniles may be particularly vulnerable during their early life stages. The first recruits were identified in May 2024, and the presence of two age classes indicates that settlement commenced in 2023. Larval viability appears to be strongly associated with improved water quality following a significant reduction in bacterioplankton concentrations, a known limiting factor [33]. Recruitment in optimal areas generally proceeds without major complications. However, two primary types of threats have been observed in the main critical areas identified:

- Shallow areas, particularly those near the communication channels between the Mar Menor and the Mediterranean, such as the *Encañizadas*, are at risk. The main risk here is the potential influx of Mediterranean waters carrying the protozoan *H. pinnae*, which often coincides with temporary salinity drops linked to intense or recurrent rainfall [25]. These areas are also exposed to additional pressures, including impacts from boats and anchors, disturbances from fishing gear, trampling, and illegal harvesting.
- Deep areas below 3 meters are generally considered to be an ideal habitat for the species, and most fan mussel specimens were found here prior to the 2016 eutrophication crisis. Despite their suitability, these zones are classified as critical survival areas due to the risk of recurrent anoxic events associated with potential future eutrophication. Severe anoxic episodes affecting large portions of the lagoon bed are infrequent, typically resulting from the convergence of adverse conditions, such as those recorded during the eutrophication events of 2016 and 2019 [35, 48].

5. Conservation actions to manage individuals at risk

Working with endangered species, knowledge of their optimal and critical survival areas can be used to design strategies involving *in situ* actions to ensure the viability of their populations. Among these actions, the relocation of specimens from areas that may be problematic in certain situations to areas free of danger is particularly effective. Translocations are an undoubtedly useful management tool for ensuring the long-term viability of specimens settled in critical areas [61–65]. However, with any translocation, there are real risks related to genetics, behavior, and disease that must be considered. Understanding and managing the risks associated with displaced organisms can help prevent irresponsible translocations and identify opportunities for responsible ones [66–72]. Translocations for conservation purposes can contribute to the recovery of endangered species populations [73, 74].

With the aim of ensuring sustained recruitment over time to help restore the *P. nobilis* population in the lagoon, a strategy has been proposed for closely monitoring recruitment, accompanied by the translocation of some of the juveniles found in critical survival areas to optimal areas where they can establish themselves without the risk of disappearing in the event of adverse conditions.

These optimal areas for translocations have been selected by the *P. nobilis* working group in the Mar Menor, based on the knowledge acquired after years of studying the species in its natural habitat and a thorough evaluation of the different areas identified as potential translocation sites.

The translocation strategy considers the transfer of 40% of the specimens to optimal areas *in situ*. It also considers the translocation of 10% of the specimens *ex situ* to the facilities of the University of Murcia Aquarium or the future facilities of the Mar Menor Observatory, as long as there is space available to house them. The *ex situ* juveniles are undergoing a growth study, and the aim is to assess their possible resistance to pathogens such as Picornavirus, which appears to affect a significant number of specimens in the lagoon.

The specimens translocated *in situ* will be monitored over time in order to assess their successful adaptation to the new areas.

6. Conclusions: Planning and management strategies

Conserving marine ecosystems and their associated biodiversity is a complex challenge that requires multidisciplinary approaches, integrating biological and ecological knowledge with environmental management and policy [75, 76]. In this context, planning and management strategies are essential for the conservation of *P. nobilis*. They enable the effective coordination of long-term conservation actions by defining clear objectives, priorities, and targeted areas of intervention. They also support evidence-based decision-making by incorporating monitoring and evaluation frameworks, facilitating impact prevention and the implementation of protective measures, and enabling adaptive management through adjustments according to results. Overall, these strategies ensure that conservation efforts are not based on isolated measures but rather on an integrated, continuous approach.

The phases for efficient management of the critically endangered species *Pinna nobilis* in a “sanctuary”, always bearing in mind the precautionary principle, are:

Phase 1: Diagnosis and assessment, including i) Determining the exact population size, age structure, and trends; ii) Identifying the environmental factors that determine the presence and survival of the species in the sanctuary area; iii) Defining the optimal survival limits of the main environmental factors for *P. nobilis*; iv) Identification of the main pressures affecting the species; v) Analysis of the species' spatio-temporal evolution; vi) Identification of the species' survival, recruitment, and risk areas based on environmental factors and pressures.

Phase 2) Definition of the species management plan, which includes: i) Identification of action objectives; ii) Design of a monitoring plan for the species population; iii) A protocol for *in situ* management, sampling, and transfer of the species; iv) Plan for the transfer of individuals from risk areas to survival areas; v) Communication and dissemination plan.

Phase 3) Implementation of conservation and management actions, both *in situ* (spatial planning and regulation of uses to ensure the conservation of the species, habitat restoration, and elimination of pressures, population recovery actions) and *ex situ* (stock maintenance and captive breeding).

Phase 4) Environmental monitoring and evaluation plan.

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Conflict of Interest

Pilar Martínez Martínez declares that her salary was funded by the LIFE Program of the European Union. Emilio Cortés Melendreras reports that financial support was provided by the Regional Ministry of Environment, Universities, Research, and Mar Menor. Yolanda Fernández Torquemada reports that financial support was provided by the LIFE Program of the European Union. The other authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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