Ocean and Coastal Management 251 (2024) 107051

Contents lists available at ScienceDirect

Ocean and Coastal Management

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

Site selection within the maritime spatial planning: Insights from use-cases on aquaculture, offshore wind energy and aggregates extraction

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ARTICLE INFO

Keywords:
Maritime Spatial Planning
Aquaculture
Offshore wind energy
Ecosystem-based approach
Suitability zoning framework

ABSTRACT

Maritime Spatial Planning (MSP) has received increasing attention from policy-makers around the world as an ecosystem-based approach to the waters under the jurisdiction of coastal states, with the aim of enhancing socio-economic development while promoting environmental protection and conservation. However, this planning process requires abundant and diverse types of data and information that are not easily operationalised in a spatially efficient manner for MSP. Aiming to overcome this barrier, the present study proposes a suitability zoning methodology based on an ad hoc developed decision support system (i.e. INDIMAR) capable of integrating the required spatial data collected and structured around a proposed suitability framework organised around five key components: environmental sensitivity, marine conservation, natural oceanographic potential, land-sea interactions, and operational maritime uses and activities. This suitability zoning framework and decision support system was tested for individual maritime activities in different Atlantic outermost regions, configuring different use cases: aquaculture in the Canary Islands, offshore wind farms in the Madeira archipelago and aggregate extraction in the Azores. The proposed methodology has resulted in a flexible model that identifies the most suitable sites for the sustainable development of maritime activities, taking into account the natural potential and compatibility with nature conservation, while mitigating potential environmental impacts and minimising conflicts with other coastal and maritime activities. However, it's important to note that the results of this study are strongly influenced by the availability and quality of data, identifying the main gaps in each region that are recommended to be filled in view of the formal processes of MSP. In essence, this study underlines the broad applicability of the proposed methodology and framework, which can be adapted and implemented in other regions after due consideration of several aspects such as: data availability, contextual differences, legal and governance frameworks, institutional capacity and spatial interactions. By taking these aspects into account, the resulting decision support system has the potential to provide valuable insights, thereby increasing the effectiveness of MSP efforts.

1. Introduction

Over the past two decades, maritime spatial planning (MSP) processes have grown globally as an emerging practice to manage marine resources more sustainably (Ansong et al., 2017a,b). MSP processes aim to allocate maritime activities both in space and time, using

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https://doi.org/10.1016/j.ocecoaman.2024.107051
Received 7 September 2023; Received in revised form 2 February 2024; Accepted 4 February 2024
Available online 12 March 2024
0964-5691/

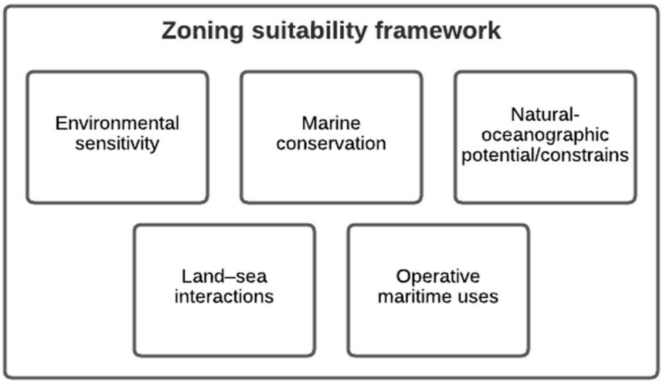

Fig. 1. Suitability zoning framework including its five fundamental - key components.

strategic planned zoning as a mechanism to allow the oceans to sustainably produce the goods and services on which the blue economy depends, while maintaining and protecting the structure and functioning of marine ecosystems (Borja et al., 2013). By strategically allocating maritime activities in both space and time, MSP aims to achieve planned zoning as a mechanism of policing/power used to protect human health and safety by limiting private uses. At the same time, it seeks to regulate common areas for a range of purposes beyond human health and safety (Agardy, 2010; Ritchie, 2011).

The marine environment meets human needs through a variety of maritime uses and activities. While new maritime activities are emerging, the expansion of existing activities continues to intensify competition for marine space (Christie et al., 2014). Thus, both marine abiotic space and associated habitats and biological counterparts are becoming increasingly scarce and threatened natural resources (IOC/UNESCO et al., 2011). Thus, the warning conditions described by Hardin (1968) about the 'tragedy of the commons' could be met in the case of the ocean - an unlimited number of users, unrestricted by any limits on their access to the space. Hardin (1968) also argues that one solution to avoid these warning conditions is to manage the relevant resources through a governance system. In this sense, MSP processes seem relevant as a public policy that aims to promote the prudent and rational use of marine areas under national jurisdiction (Calado et al., 2019).

Currently, around 50% of coastal states have some form of MSP initiative underway (Ehler, 2021), with the majority of these efforts led by European countries (Chalastani et al., 2021). In particular, the combined marine Exclusive Economic Zones (EEZs) of these countries are the largest in the world. Indeed, the European Union (EU) has been identified as a major MSP hub, where tools, initiatives, discussions and innovations are financially supported and promoted by European governments (UNESCO-IOC/European Commission, 2021). The European MSP Directive (Directive 2014/89/EU of the, 2014) created a governmental framework for the implementation of MSP processes in the member states, which committed to adopt their respective maritime spatial plans by March 2021 (Friess and Grémaud-Colombier, 2019; Ehler, 2021). The EU MSP legal framework explicitly includes environmental objectives. Many authors see the MSP process as a tool to support and implement the objectives of European environmental legislation on the sea, in particular the Marine Strategy Framework Directive 2008/89/EC (MSFD) (Haapasaari et al., 2022; Alison et al., 2015; Maccarrone et al., 2015). The development of MSP provides an ongoing opportunity to apply and update an ecosystem-based approach and to achieve and maintain Good Environmental Status (GES), which is the primary objective for European seas under the MSFD.

Existing international MSP process guides provide a structured step-by-step approach (Ehler and Douvere, 2009), through main phases (Frazão Santos et al., 2019) or by relevant general themes (UNESCO-IOC/European Commission, 2021), providing clear guidance to promote practical policy- and governance-oriented MSP initiatives.

A bibliometric assessment of progress in MSP showed that this is a rapidly growing field of research, dominated by qualitative approaches, which calls for progress in the development of quantitative and/or modelling methods (Chalastani et al., 2021). The use of data for evidence-based decision making has been highlighted as a prerequisite for effective MSP (Zuercher et al., 2022). This development leads to the formulation of geographic zoning methodologies, which divide the marine area into zones based on geographic features or characteristics that can be contrasted and associated with potential marine uses. In an effort to increase the efficiency of the developed methods and to assist planners in identifying the sustainable allocation of maritime activities, the MSP community started to develop interactive systems for analysing problems and evaluating spatial and non-spatial data, applying techniques for spatial and geostatistical analysis, commonly referred to as decision support tools (DSTs) (Sprague and Carlson 1982; Depellegrin et al., 2021).

These DSTs aim to operationalise the implementation of the ecosystem-based approach (EBA) (Depellegrin et al., 2021) through the understanding of socio-ecological system dynamics. At the same time, they provide a mechanism to evaluate management strategies prior to their implementation (Fulton et al., 2011; Stelzenmüller et al., 2013; Janβen et al., 2019).

Examples of DSTs range from specific sectoral programmes such as Marxan for MPA design (Göke et al., 2018) or InVEST for ecosystem service valuation (Montero-Hidalgo et al., 2023). Another example is the use of the Automatic Identification System (AIS) to track commercial and fishing vessels (Le Tixerant et al., 2018). Other geographic information systems such as SEANERGY have been used to assess synergies and conflicts between activities (Bonnevie et al., 2020); INDIMAR for suitability zoning for e.g. for offshore wind farms (Abramic et al., 2021), Mytilus for cumulative impact assessment (Hansen, 2019), or Tools4MSP that integrates different spatial analyses (Menegon et al., 2018).

A review of DSTs by Pınarbaşı et al. (2017) showed that these tools are mainly used by planners and marine users during specific MSP phases and steps of MSP. These include tasks such as: examining existing conditions and future scenarios for planning, and alternative management measures for plan development. Consequently, the main purpose of DSTs is to assess: environmental impacts; communication; interaction between planners and stakeholders; and site identification and scenario building. Nevertheless, large data requirements and specific technical capabilities hinder the use of DSTs in all MSP steps (Stamoulis and Delevaux, 2015). Despite the existence of a growing user-developer community (Depellegrin et al., 2021), there is still significant potential to improve DSTs to support operational MSP processes (Pınarbaşı et al., 2017).

The objective of this study is to structure the relevant data and key analyses that need to be carried out in the planning and marine plan development phases, in order to generate a suitable zoning methodology for the future development needs of existing and emerging maritime activities. The second objective is to test this methodology for different maritime activities in three use cases, namely three oceanic archipelagos with different environmental, social and economic conditions, to confirm that the methodology is flexible, adaptable and replicable.

The aim is to provide a basis for implementing suitability zoning within an ecosystem-based approach to MSP, taking into account the MSFD:

- Potential impact on the marine environment and degradation of the MSFD Good Environmental Status.
- Inconsistencies with marine conservation objectives.
- Optimal and limiting oceanographic conditions for the development of maritime activities.

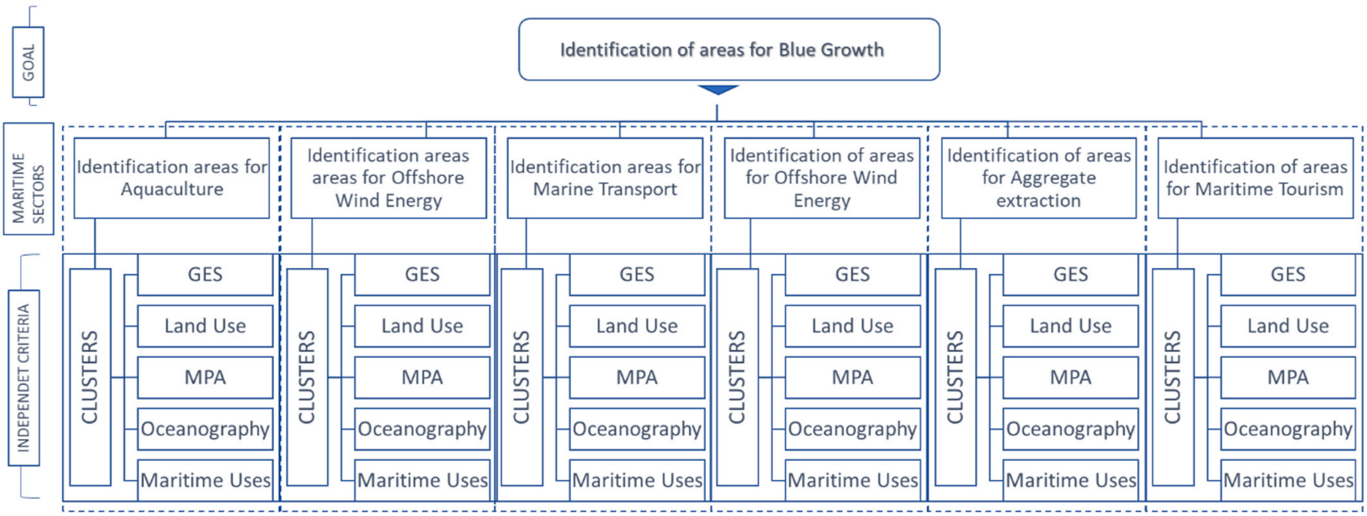

Fig. 2. -Hierarchical structure for the maritime sectors analysis (Shinoda et al., 2019) where the significance of each cluster and each maritime sector is analysed.

- Land-sea and sea-land interactions between coastal uses and maritime activities.
- Synergies and conflicts between maritime sectors.

2. Methodology

2.1. Framework for suitability zoning

The maritime sector suitability zoning approach is based on five fundamental or key components aimed at achieving environmental sustainability, identifying natural potential and avoiding conflicts with nature conservation, coastal and maritime sectors. To analyse each component, the process selects relevant parameters that characterise them and determine their 'suitability' in relation to the maritime sector in question for which we are seeking suitable locations for development. The five components considered in this study are visually illustrated in Fig. 1 and are described in more detail below.

2.1.1. Environmental sensitivity

This component includes information to analyse the sensitivity of the marine environmental components in relation to the pressures arising from the maritime sector under consideration. This involves visualising areas of robust environmental conditions where the expected environmental impacts are minimised.

In order to introduce the MSFD more deeply into the methodology and to list the parameters needed to assess environmental sensitivity, it is decided here to follow the Good Environmental Status (GES). The GES is described in COM 2017/848/EU and consists of 11 Qualitative Descriptors (QDs) and 39 related criteria elements, divided into essential features and characteristics of marine waters, as well as predominant pressures and impacts. Thus, the GES served as a checklist to go through the 11 QDs and examine the potential impacts of the maritime sectors on the marine environment.

2.1.2. Marine conservation

This section analyses the potential incompatibility of the maritime activity with marine conservation, considering the possibility that the activity may contribute to the achievement of conservation objectives. For example, marine birds conservation is in direct conflict with offshore wind energy (OWE) installations (Larsen and Guillemette 2007). However, OWE parks can act as fishery exclusion zones, thereby contributing to the conservation of biological resources (Hammar et al., 2016). When assessing the compatibility of the analysed maritime activity with marine conservation, it is imperative to include data on the expansion of marine protected areas (MPAs) and their associated conservation objectives and targets.

2.1.3. Potential/constraints of natural oceanography

It is also necessary to assess the (unfavourable) oceanographic conditions for the development of the maritime activity under consideration. Variables such as depth, wave height or current strength can constrain or facilitate the development of activities. For example, currents are essential for the dispersion of nutrient inputs from aquaculture sites, while limiting the anchoring of structures (Tsiaras et al., 2022). Similarly, wind speed is crucial for OWE as visualised by energy potential maps (Wind Europe 2020; Emeksiz and Demirci, 2019; Costoya et al., 2020; Kumar et al., 2020), but the installation of turbines is limited by bathymetry.

For the list of oceanographic parameters, the Copernicus Ocean Monitoring Indicators were used as they meet the operational requirements for monitoring and assessing ocean conditions.

2.1.4. Land-sea interactions

This component analyses the potential synergies and conflicts between the maritime activity under consideration and existing land use in coastal areas. This assessment should take into account sectors such as urban and coastal tourism development, as well as ports, land transport infrastructure, industrial areas, rural and agricultural areas and other relevant uses. In this study we have used land use or land cover data sets that provide high resolution information following a classification of anthropogenic activities within the coastal zone.

2.1.5. Operational maritime uses

Finally, as in the previous component, the potential synergies and conflicts with operational maritime uses and activities need to be analysed. For this assessment, it is necessary to collect spatial information on the distribution of existing maritime activities in order to spatially analyse potential multi-use and co-use areas with the maritime activity under consideration.

2.2. Analysing the suitability of sites through multi-criteria analysis

To generate the final suitability maps for the analysed activity, the result map of each resulting analysis was overlaid as described above. The spatial overlapping process requires the relative importance of each component and associated parameter. For this purpose, we used the Analytical Hierarchy Process (AHP) (Goepel, 2014; Saaty, 1990). Saaty (1987) stated that two levels are fundamental in the use of AHP, namely

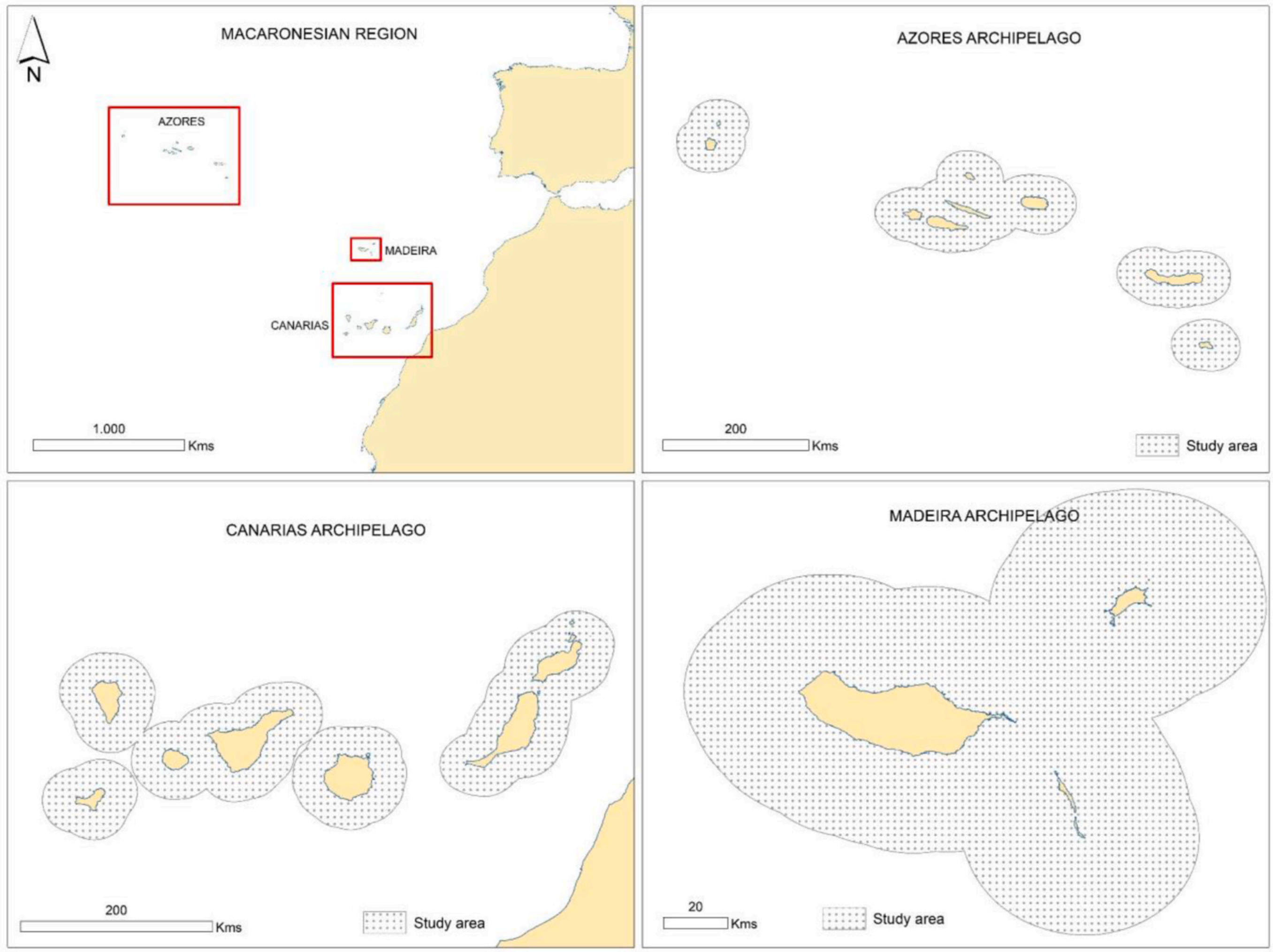

Fig. 3. Location map showing the European Macaronesian archipelagos of the Azores, Madeira and the Canary Islands. The study area (i.e. 30 km off the coast of the islands) corresponds to the spatial extent of the INDIMAR DSS.

a hierarchical structure (Fig. 2) to represent the problem being modelled and the pairwise comparisons to establish relationships - in our case between the key components and their associated parameters or spatial data sets collected (see Appendix 1; Fig. 4). Five pairwise matrices were thus developed. These matrices determine a set of weights that quantitatively reflect the relative importance or strength of each component or parameter considered in the first and second AHP hierarchical levels, respectively. In this context, at the first level, key components are compared against each other, e.g. comparing whether marine conservation is more/less relevant than conflicts between operational maritime sectors when analysing suitability zoning for a particular maritime activity. Then, at the second level, each parameter is compared with each other for the analyses within each key component, e.g. to determine the sensitivities of different environmental components, to assess (un)favourable oceanographic conditions in relation to the activity under consideration, or to assess synergies and conflicts between the activity under consideration and all other coastal and maritime uses and activities. It should be emphasised that the various analyses should be carried out in relation to a single maritime activity.

The AHP pairwise comparison technique allows quantitative assessment of the relative importance (i.e. weights) between parameters and key components through the knowledge of experts and different stakeholders. In this study, a structured process was followed to gather expert knowledge. First, a structured survey was developed to determine the weights of the first and second AHP levels using the expert knowledge within the consortium of the PLASMAR project. To facilitate the pairwise comparison of the surveys, an AHP Excel file was adapted from Goepel (2013).

Secondly, a round of expert discussion was conducted in order to reach a consensus on the determination of the different weights. The expert panel was recruited from the regional institutes and within the stakeholder workshops (following Quesada-Silva et al., 2019, and described in Abramic et al., 2021). Prior to the discussion, a non-exhaustive review of scientific and grey literature, including technical reports (see the Supplementary Material for more details on the literature review conducted for aquaculture, OWE and sand extraction), was conducted to facilitate the discussion among the experts and to support their judgement with empirical data whenever possible. For example, in order to analyse the potential environmental impacts on the GES, publications reviewing them in the context of aquaculture (Png-Gonzalez et al., 2019) and offshore wind energy (Abramic et al., 2018) were followed.

Compatibility with marine conservation was analysed, taking into account recommendations published by the International Union for Nature Conservation (IUCN) (Day et al., 2019). If the IUCN recommendation included options for the development of maritime activities within the MPA, further scientific and technical reports on specific topics were reviewed (see Supplementary Material).

With regard to the oceanographic conditions that could limit or favour the development of maritime activities, analyses were made of

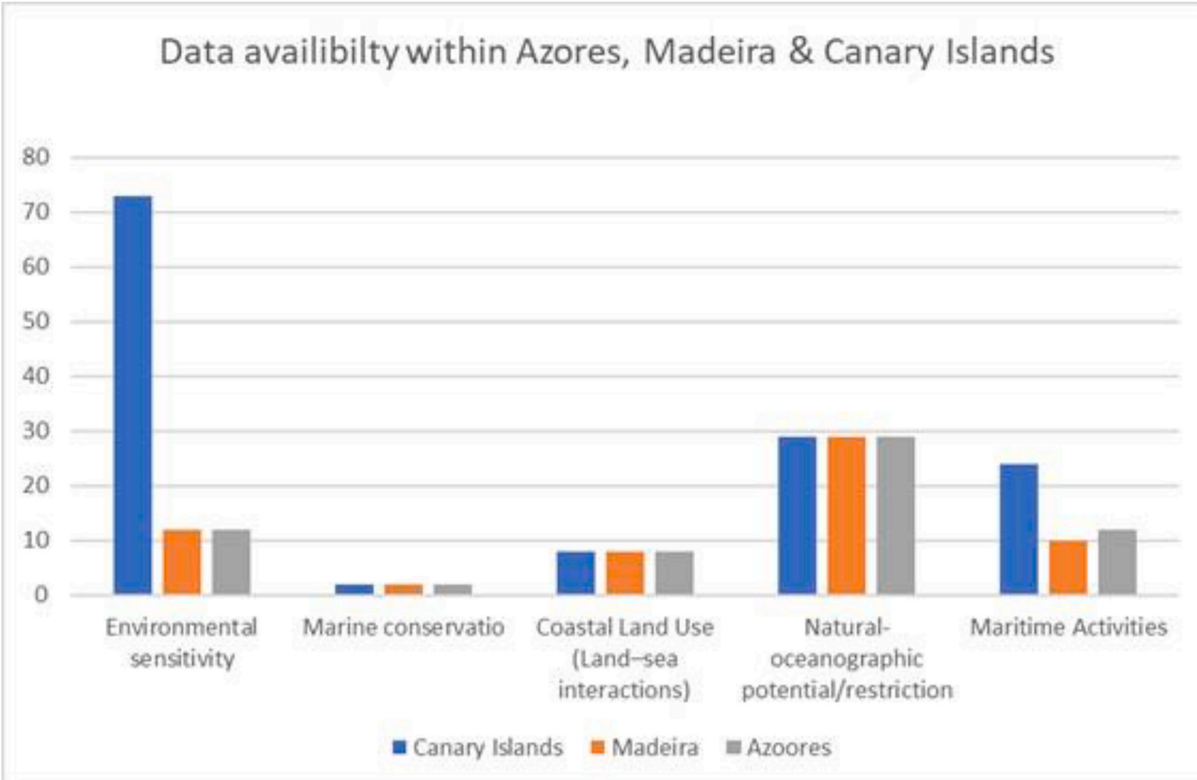

Fig. 4. Number of datasets available for archipelagos - Detailed table of data available for the Canary Islands, Madeira and the Azores in Appendix 1.

Table 1
Configuration of weights for the three scenarios considered in the Canary Islands.

Key components	First level weights for the different scenarios		
	Expert consensus (A)	Environmentalist (B)	Environmentalist with MPA's restrictions (C)
Environmental sensitivity	20.08	50.08	50.08
Marine conservation	12.88	12.31	12.31
Coastal Land Use	11.68	11.11	11.11
Natural-oceanographic potential	38.98	11.39	11.39
Maritime Activities	16.38	15.11	15.11
TOTAL	100	100	100

physical aspects (e.g. sea temperature and salinity, air pressure, bathymetry, winds, currents, waves, etc.) and chemical aspects (e.g. oxygen, nutrients, chlorophyll *a*).

Potential synergies and conflicts have also been analysed for both coastal land uses and maritime activities. For coastal sectors, the literature on land-sea interactions was reviewed, with a particular focus on the coastal distance component, while for current maritime sectors the debate revolved around conflicts and potential multiple uses with other maritime activities. Details of these reviews can be found in Appendix 2 (offshore wind review), Appendix 3 (aquaculture review) and Appendix 4 (sand mining review).

2.3. INDIMAR decision support system and integrated site suitability model

To facilitate the application of the suitability zoning methodology, the INDIMAR Decision Support System (DSS) will be used, as developed specifically for the case study regions (Abramic et al., 2021). The INDIMAR DSS is based on Geographic Information System (GIS) technology and uses spatial data layers representing the different parameters of the key components. The methodology for calculating the suitability index (R) is based on the weighted overlay technique, where each spatial data layer (i.e. parameter) is assigned a weight according to its importance for the corresponding assessment (i.e. key component) with respect to the maritime activity under consideration. This index can have a value between 0 and 10, where $R = 0$ reflects a totally unsuitable location and $R = 10$ represents the most suitable locations or sites.

In order to calculate the suitability index, it is necessary to incorporate the collected data into the system. An additional requirement is to define the type of contribution (CV) or “suitability” relationship of each parameter to the maritime activity. For more precise analyses, numerical values of parameters can be divided into ranges (e.g. considering suitable ranges of wind speed between 7 and 8.5 m/s and excluding <7 m/s and >8.5 m/s). Furthermore, qualitative parameters were divided into categories (e.g. habitat types, species or different types of MPAs). For the purpose of calculating the suitability index, CV is associated with values using the following coding: Positive contribution ($CV = 1$). Neutral contribution ($CV = 0$). Negative contribution ($CV = -1$). Excluded value ($R = 0$).

Finally, for each parameter, it is necessary to establish the weights (pW) calculated by the AHP. In this sense, the suitability index (R) is calculated as the sum of the parameter weights (pW) multiplied by the parameter contributions (CV):

$$R = \Sigma pWi^{*}\ CVi, \text{ where } \Sigma pWi = 100$$

Once DSS INDIMAR has been configured with all the parameter weights and the type of contribution, the system calculates the suitability scores for the entire study area. The system defines a grid of discrete elements (300 m × 300 m) and calculates the suitability index for each one. In order to increase the efficiency of the system and reduce the computation time, the suitability index is calculated for areas up to 30 km from the coast of the archipelagos of the Azores (37,500 km2), Madeira (12,500 km2) and the Canary Islands (45,000 km2).

2.4. Use cases and scenarios

The AHP process was repeated for three maritime activities and tested in three different use cases (Fig. 3). One suitability zoning map was produced for offshore wind farms in Madeira, another for aggregate extraction in the Azores and a third for aquaculture in the Canary Islands.

INDIMAR DSS also allows users to dynamically adjust the weights of the parameters and components and visualize the resulting suitability maps. This feature facilitates the comparison of different scenarios and changes in the configuration of parameters and key components to identify optimal locations for the analysed maritime activity. For example, after establishing the relative importance (i.e. weights) through AHP, the weights among the key components of the first AHP level can be modified to analyse different development scenarios.

To assess the robustness of the suitability zoning methodology, different policy scenarios are developed within each use case:

- Expert consensus scenario. The weights are developed by expert opinion, with the panel calculating the weights using AHP. This reflects a sustainable development zoning that balances the weights between all environmental, social and economic considerations associated with all key components.
- Conservative scenario. Where the weights associated with environmental sensitivity and marine conservation are maximized to minimize potential adverse impacts on the ecological components.
- Development scenario. Where the weights associated with favourable natural oceanographic conditions and proximity to strategic coastal infrastructure are maximized to minimize costs and promote the development of the particular activity.
- Conflict minimisation scenario. Based on higher weights given to land-sea interactions and operational maritime uses to minimize conflicts with all other activities.

These scenarios were applied to each use case according to the availability of spatial data collected for each archipelago (Table 1). Thus, the different scenarios were applied unevenly as a means of illustrating and discussing the applicability of the proposed zoning methodology (rather than assuming it) which is the ultimate goal of this article.

2.5. Data collection according to the suitability zoning framework

The data of the three use cases (Azores, Madeira, Canary Islands) were collected according to the five suitability components: marine environmental data according to the MSFD GES, distribution of MPAs and their conservation targets, oceanographic features, coastal land use and current maritime activities (Fig. 4; Appendix 1). There was a significant lack of spatial coverage for the marine environment data sets in the Portuguese archipelagos (Fig. 4, Appendix 1). In comparison, the spatial coverage for the Canary Islands is higher due to the availability of data related to the GES of the MSFD shared by the Spanish National Spatial Data Infrastructure. MPAs, coastal land use and oceanographic conditions were obtained using data products from the European Environment Agency and Copernicus (Copernicus Marine Service and Land Monitoring Service). Data on operational maritime activities and sectors are mainly obtained from local data providers/developers, with the exception of information on maritime transport, which was obtained from the EMODnet Human Activities Portal.

The use of data products from European data initiatives has two advantages. Firstly, they cover large areas - including the entire Macaronesian region. Secondly, these data sets are provided in a single, unified data model, which means that the data sets are harmonized.

The data collection process often reveals numerous data gaps. One approach to address this is to use indirect or proxy information. This type of data is used to infer or estimate a particular variable or phenomenon of interest when direct measurements are not available. In this structured data collection, land cover data is used as a proxy for information on human activities, in particular land cover. In addition, we considered the protected area of a particular marine species as an indicator of increased potential for that species to be present, in line with the recommendations of various authors such as Abramic et al., (2023), Zhang et al., (2022); Flower et al., (2020); Maccarrone et al., (2015); O'Mahony et al., (2009).

3. Results

3.1. Applying the suitability zoning methodology to the use cases

3.1.1. Suitability zoning for aquaculture in the Canary Islands

Aquaculture is a well-established sector in the Canary Islands. Therefore, the first use case aimed to identify potential suitable areas for the expansion of the marine aquaculture sector in the region according to the different scenarios designed.

Table 1 shows the weights used in the first level of the analytical hierarchy process when comparing the relative importance of the key components in analyzing suitable sites for aquaculture in the Canary Islands for the different scenarios: expert consensus (A), environmentalist (B) and environmentalist considering restrictions resulting from the designation of marine protected areas (C). Higher weight values indicate a higher relevance of all the parameters considered within each key component.

The first model, Expert Consensus (Fig. 4A, Table 2), primarily looks for suitable oceanographic conditions, such as a temperature that promotes growth of the product, site depths that do not exceed 50 m, suitable currents and wave conditions that allow construction and maintenance of the facilities without excessive costs. Oceanographic conditions are indirectly linked to economic viability, along with proximity to any ports or even smaller ports to minimize maintenance and operational economic costs. In this profile, environmental sustainability is considered, the model avoids sensitive areas (e.g. specific benthic habitats and vulnerable species), but with twice less weight than oceanographic conditions. The other three components, conservation (avoiding but not excluding MPAs with seabird conservation objectives), land-sea interaction (e.g. avoiding conflicts with coastal tourism) and potential conflicts with other maritime activities (e.g. searching the distance to offshore submarine outflows) are included in the model but with much lower weights.

For the Canary Islands, it was possible to collect spatial data availability on benthic habitats (PLASMAR Consortium, 2020) and food web models on different ecological components (Couce-Montero et al., 2015; Montero et al., 2021). This allowed the testing of applied generic governance policy scenarios, the development of the sector with less possible impact on the marine environment. INDIMAR DSS, through the environmentalist scenario, applied the highest importance to the sensitivity of ecological components. The same scenario also included the restriction of marine This was done to minimize the potential negative impact on marine protected areas over other considerations, such as higher production costs due to the remoteness of the coast. Firstly, the environmentalist scenario in INDIMAR showed that most of the zones suitable for aquaculture are located beyond a depth of 50 m (Fig. 4B, Table 2). This is due to the availability of detailed maps of benthic habitats (e.g. seagrass or maerl beds) covering this depth, beyond which they were only mapped through broader habitats without

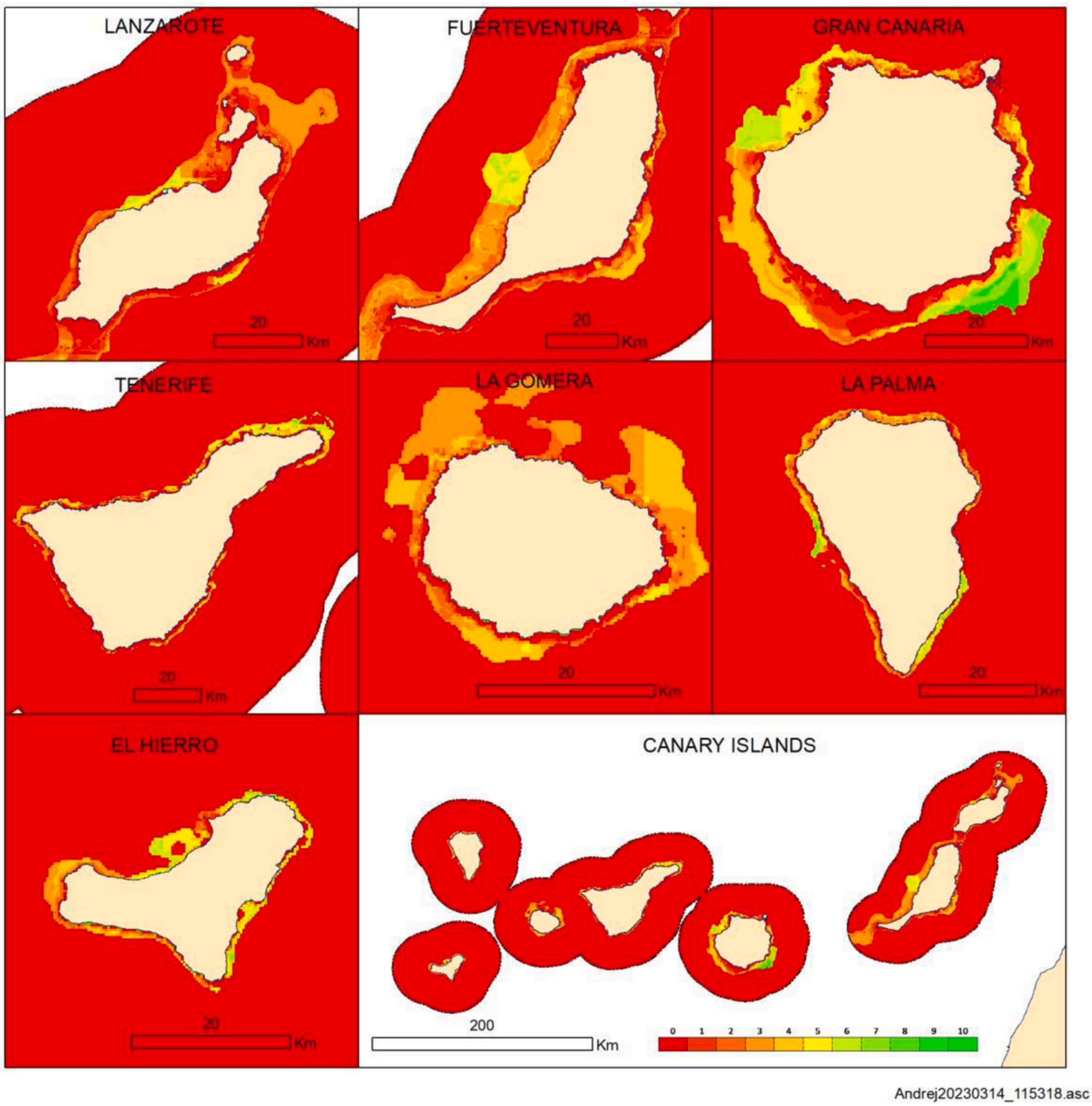

Fig. 4A. Suitability maps for aquaculture resulting from Expert consensus scenario considered for the Canary Islands.

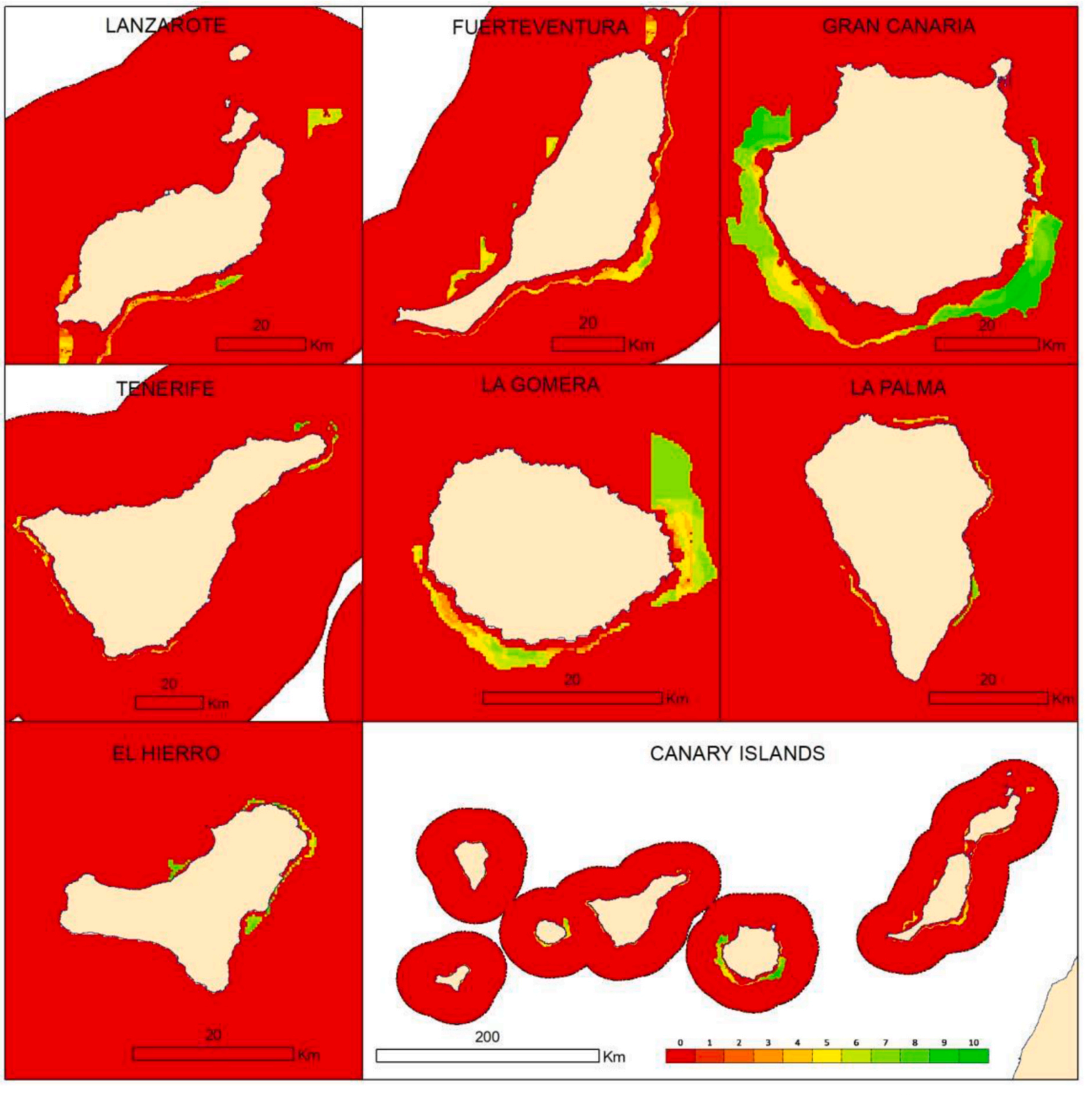

Fig. 4B. Suitability maps for aquaculture resulting from Environmental scenario considered for the Canary Islands.

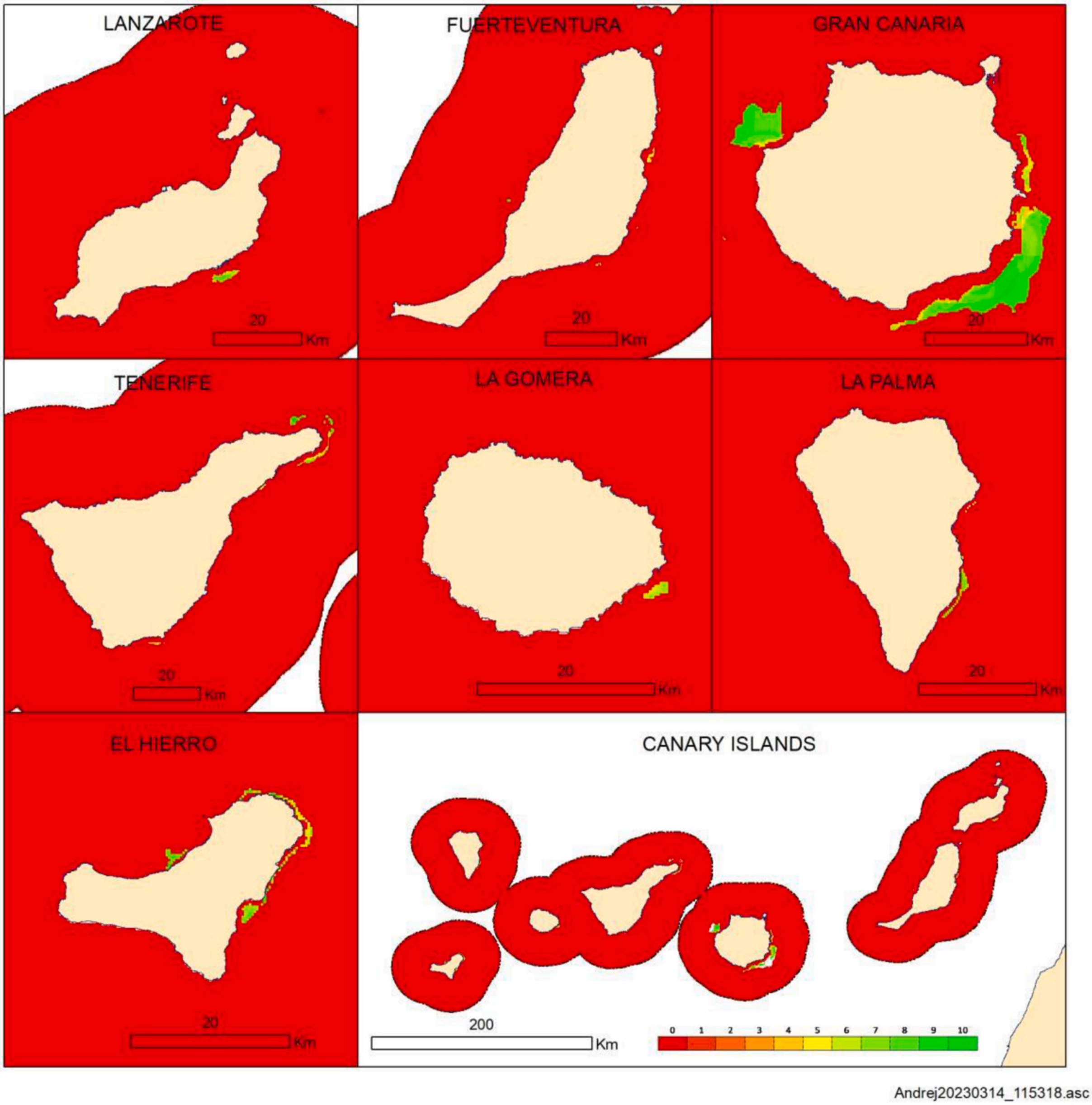

Fig. 4C. Suitability maps for aquaculture resulting from Environmental and MPAs legislation scenario considered for the Canary Islands.

Table 2
Total extension (Km2) by suitability categories of the resulting zoning for each of the scenarios considered in the Canary Islands.

Scenarios (The Canary Islands)	Area by level of suitability (Km2)										
	0	1	2	3	4	5	6	7	8	9	10
Expert consensus	42401.5	260.9	545.4	1037.7	442.9	294.9	208.0	82.1	35.2	0	0
Environmentalist	44486.5	3.8	26.7	60.3	101.3	131.9	141.4	174.3	83.7	89.0	9.5
Environmentalist with MPA's	45054.8	0	0	0.1	4.3	10.4	18.6	40.5	81.5	89.0	9.5

information at the community level (e.g. circalittoral fine sand or deep sea bed).

The third scenario, unlike the previous environmentalist scenario where aquaculture was only constrained by the spatial distribution of sensitivity of the ecological components considered, illustrates the application of specific conservation management measures resulting in fewer suitable areas (Fig. 4C, Table 2).

Table 3
Configuration of the weights for the three scenarios under consideration in Madeira.

Key components	First level weights for the different scenarios		
	Expert consensus (A)	Developmental (B)	Conflict minimisation (C)
Environmental sensitivity	35	1	9.8
Marine conservation	15	23.5	9.8
Coastal Land Use	16	24.5	60.8
Natural-oceanographic potential	30	38.5	9.8
Maritime Activities	4	12.5	9.8
TOTAL	100	100	100

3.1.2. Suitable zoning for offshore wind energy development in Madeira - second use case

At the time of writing, offshore wind energy (OWE) has not been established in Madeira. However, given the lack of a continental shelf around the archipelago, it is likely that offshore wind farms (OWFs) will be developed using floating wind turbines. These will need to be placed where the wind is suitable for this activity, while staying out of the feeding grounds and migration corridors of seabirds and sensitive benthic habitats (Abramic et al., 2022). In this context, the INDIMAR expert consensus generated a suitability profile that prioritised environmental sensitivity and natural oceanographic potential (Table 3). However, in this scenario, a notable expansion of the suitable area, i.e. largely suitable or unrestricted zones (Fig. 5A, Table 4), can be observed, resulting from a significant lack of marine environmental data (Fig. 4; Appendix 1). Significant gaps in the available environmental information were observed, particularly with respect to the distribution of coastal habitats and associated species. The limited data coverage made it difficult to identify, and therefore avoid, areas where OWE facilities would have a high impact. This may also explain the similarities between the sustainable development scenario (i.e. expert consensus) and the development scenario (Fig. 5A and Fig. 5B respectively, Table 4).

Table 3 shows the weights used in the first level of the analytical hierarchy process when comparing the relative importance of the key components in analysing suitable sites for offshore wind farms in Madeira for the different scenarios: (A) expert consensus, (B) development, (C) conflict minimisation. Higher weight values indicate higher relevance of all parameters considered within each key component.

Due to the limited availability of environmental data (see Fig. 4C, Appendix 1), further scenarios were developed to analyse suitable zoning that would maximise the natural potential for development of the OWE sector while minimising social conflicts (e.g. with coastal tourism - aesthetic visual impacts) and marine conservation issues Table 3. Suitable sites for OWE would need to be close to certain terrestrial electrical facilities to connect the turbines to the island's electrical grid, and within favourable wind speed and depth ranges (Fig. 5B).

OWE is often perceived as a threat to coastal areas heavily used for recreational and tourist activities due to visual impacts (Lloret et al., 20–22). Thus, the third profile scenario (Fig. 5C) reflects a policy of "avoiding conflict between OWE facilities and coastal tourism". Accordingly, this profile maximized the weights related to the land-sea interaction, while minimising the weights of all other components to less than 10%. As expected, this model increased the distance of suitable areas from the coast, especially from urban areas where coastal tourism is developed.

3.1.3. Appropriate zoning for aggregate extraction in the Azores - third use case

In the Azores, public policy on aggregate extraction (i.e. mainly sand) excludes from extraction all areas with potential conflict with other operational maritime activities. Thus, in the scenarios considered for this use case (Table 5), suitability zoning excludes all areas currently used by other activities, thus avoiding any type of potential conflict. This had a direct impact on the consensus of the regional experts consulted, who gave greater relevance to coastal and marine uses and activities when analysing suitable locations for marine aggregates extraction (Fig. 6A).

Data on marine ecological spatial distribution were also lacking for the Azores (Fig. 4; Appendix 1), indicating that the sensitivity of marine ecological components is overlooked, resulting in suitable zoning that most likely disregards environmental impacts (Fig. 6B). A conflict minimisation scenario was also carried out, taking into account the spatial distribution of natural aggregate deposits (Fig. 6C). Due to the

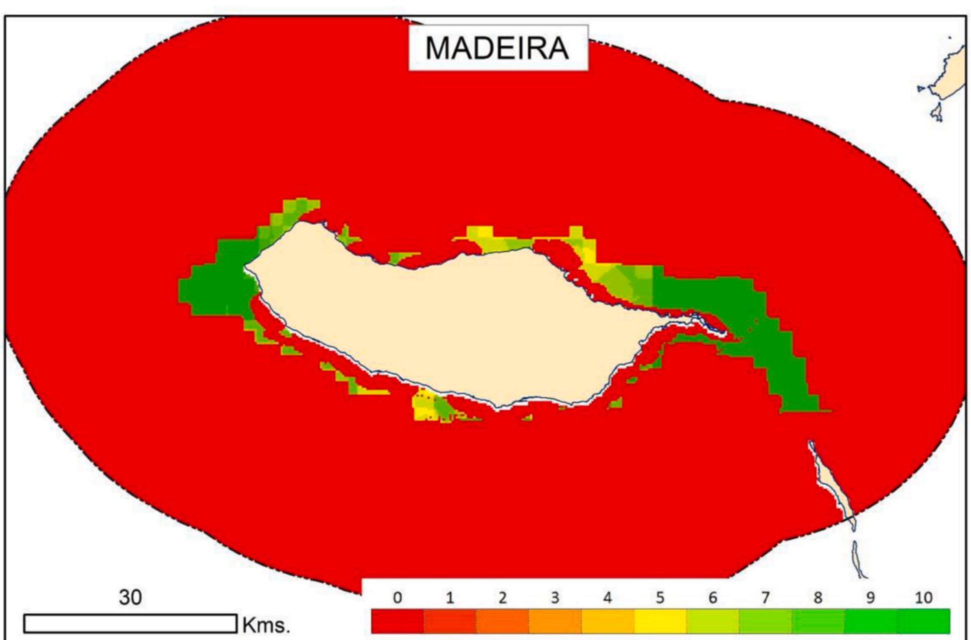

Fig. 5A. Suitability maps for offshore wind energy resulting from the expert consensus scenario considered in Madeira (see Table 3).

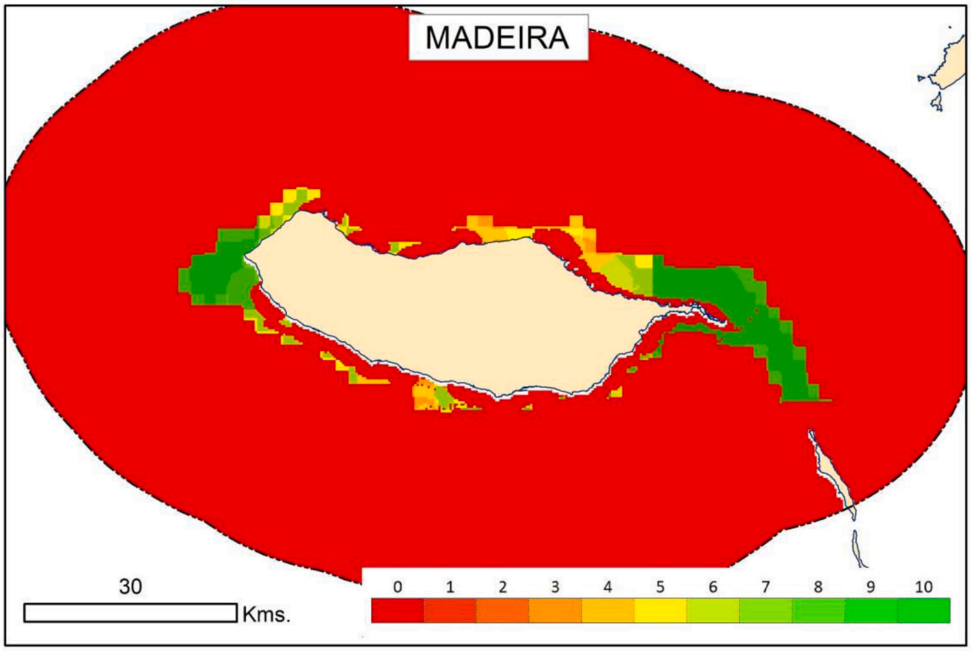

Fig. 5B. Suitability maps for offshore wind energy resulting from the Developmental scenario considered in Madeira (see Table 3).

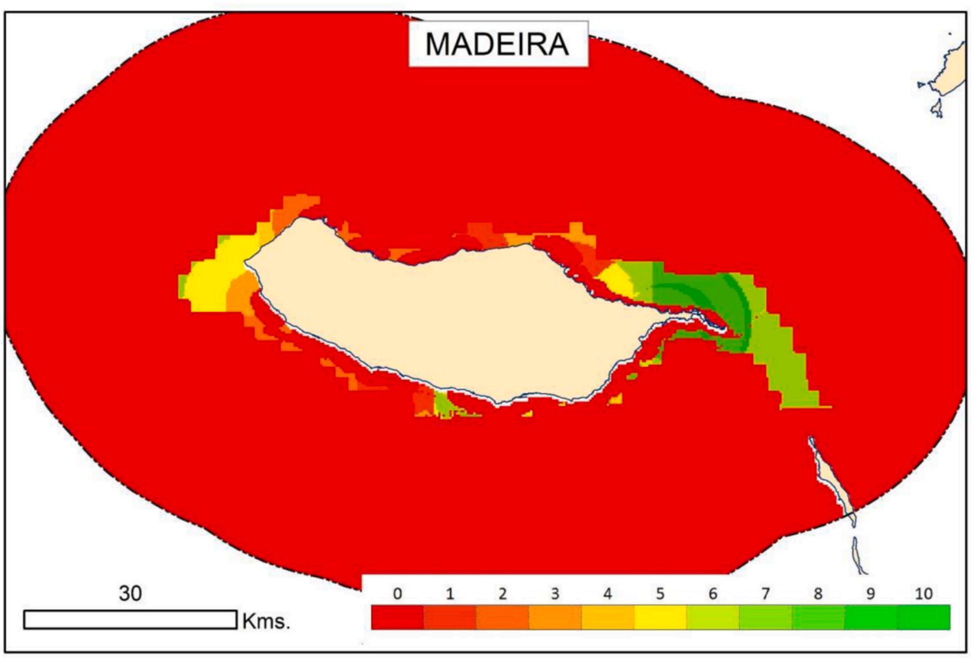

Fig. 5C. Offshore wind suitability maps resulting from the conflict minimisation scenario considered in Madeira (see Table 3).

lack of data for this case study, the spatial results are very similar (see Table 6).. However, in this scenario the suitability zoning showed lower scores in zones closer to harbours to avoid conflicts with high intensity shipping lanes.

Table 5 shows the weights used in the first level of the analytical hierarchy process when comparing the relative importance of the key components to analyse suitable locations for aggregate extraction in the Azores for the different scenarios: (A) expert consensus, (B) environmental, (C) conflict minimisation. Higher weight values indicate a higher relevance of all parameters considered within each key component.

4. Discussion

The results of this study demonstrated the applicability of the proposed suitability zoning method through the three case studies for different maritime sectors. This method considers the natural potential of oceanographic conditions and land-sea interactions to identify suitable development areas for the maritime sectors analysed, with the aim of minimising impacts on the marine environment, promoting compatibility with marine conservation and reducing potential conflicts with other coastal and maritime activities. Thus, all five components of the suitability framework are considered (Fig. 1). Moreover, the integration of all these aspects in the DSS INDIMAR has resulted in an easy to use

Table 4
Total extension (Km^2) by suitability categories of the resulting zoning for each of the scenarios considered in Madeira.

Scenarios (Madeira)	*Area by level of suitability (Km2)*										
	0	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Expert consensus	*6474.5*	*0.1*	*0*	*0*	*0*	*12.6*	*32.7*	*42.3*	*45.6*	*6.6*	*232.1*
Developmental	*6474.4*	*35.8*	*39.6*	*32.7*	*7.5*	*68.2*	*1.9*	*105.6*	*2.1*	*58.8*	*19.9*
Conflict minimization	*6474.3*	*0*	*0.2*	*12.6*	*32.6*	*29.3*	*17.8*	*40.9*	*6.6*	*66.1*	*166.0*

Table 5
Configuration of the weights for the three scenarios considered in the Azores.

Key components	First level weights for the different scenarios		
	Expert consensus (A)	Environmental (B)	Conflict minimisation (C)
Environmental sensitivity	19	50	9.25
Marine conservation	15	7.25	1.5
Coastal Land Use (Land–sea interactions)	26	18.26	27.51
Natural-oceanographic potential	10	2.25	11.5
Maritime Activities	30	22.23	50.22
TOTAL	100	100	100

and flexible tool for scenario development through the configuration of weights that allow a technical decision on whether the marine environment and/or conservation and/or natural potential and/or avoidance of conflicts with maritime and/or coastal sectors should be prioritised.

More than a conceptual development, the method was successfully tested on three different maritime sectors. The results showed that the developed method using the INDIMAR DSS model is able to provide advanced results if properly fed with data and aggregated information, following the suitability framework. A model fed with collected data that fulfils the requirements of five components provides accurate results for the introduction or expansion of the maritime sector. For example, in the case of aquaculture in the Canary Islands case study, the availability of detailed and accurate data allowed a precise assessment of suitable areas. The ability to access a wealth of information on each of the five data components ensured that the model could identify areas with optimal growth potential while minimising the risks associated with unsuitable conditions. Reliable data availability facilitated the assessment of trade-offs between different suitability components, such as oceanographic conditions and environmental sensitivity.

The fully operational model is capable of enhancing the relevance of individual or different components (e.g. marine environment and nature conservation) while still taking into account the other components included in the analysis. This choice provides the opportunity to tailor the model according to the governance strategy, producing different zoning outcomes that are consistent with a range of planning objectives. Policy-based (weight) profiles can facilitate or constrain trade-offs, increasing or decreasing the relevance of specific components, but all are considered in the analysis. In this way, the results provided contain highly useful information required for the decision-making process, as the applied method and DSS INDIMAR are aligned with the needs of the decision maker (Bolman et al., 2018).

In addition, this methodology can be used to go beyond following already established governance policy planning objectives. The INDIMAR DSS, together with the defined model, is capable of defining the MSP governance strategies. The model can provide suitable areas for the analysed sectors, test different scenarios and test components for a variety of options for trade-offs. The testing of scenarios with different constraints and limitations (e.g. related to the environment, marine conservation or minimising conflicts with other coastal and maritime activities) showed spatial changes in the distribution of suitable areas for the assessed maritime sectors depending on the configured trade-offs between the key components of the framework. This provided insights to assess whether the marine space requirements of the maritime sector are secured and what trade-offs are necessary between each of the components considered. As noted by Gimpel (et al., 2015), scenario analysis can facilitate the definition of governance and planning policies, enhance or limit component trade-offs, or, if possible, simply apply a balance of environmental, conservation, and oceanographic conditions' potentials and conflicts.

The offshore wind and sand extraction use cases in Madeira and the Azores, respectively, faced data availability challenges that affected their suitability zoning results. Both suitability models were significantly less restrictive due to the lack of environmental spatial information. This clearly shows how model results depend on data availability. After conducting a structured data collection for each case study, missing data were identified (see Fig. 4; Appendix 1). In this context, spatial results should be taken with caution, considering whether the available information is sufficient to adequately assess each of the key suitability components. Furthermore, the presence of data gaps will indicate the suitability of policy scenarios for modelling purposes.

For areas with significant data gaps on the marine environment, it was possible to model specific policies to avoid conflicts with coastal (i.e. OWE in the Madeira use case) and maritime sectors (i.e. sand extraction in the Azores use case). These profiles are suitable for developing scenarios for policy planning, with identifiable options, alternatives and suitable areas when considering specific trade-offs. The third OWE model, applied in Madeira, includes specific policies to avoid any conflict with coastal tourism, to consider multi-use, co-use or even trade-offs with maritime sectors, to develop the offshore wind farm with lower natural potential areas and foreseeable impacts on the marine environment during construction and maintenance.

However, the flexibility of the methodology developed for the other sectors does not apply to fisheries, as it poses certain challenges due to its dynamic nature, which is highly dependent on the availability and movement of resources and stocks. Unlike the other maritime sectors analysed, fisheries management requires continuous monitoring and adaptive strategies to respond to changing environmental conditions and stock dynamics. As a result, it can be more difficult to obtain all the necessary information and ensure its accuracy for effective decision

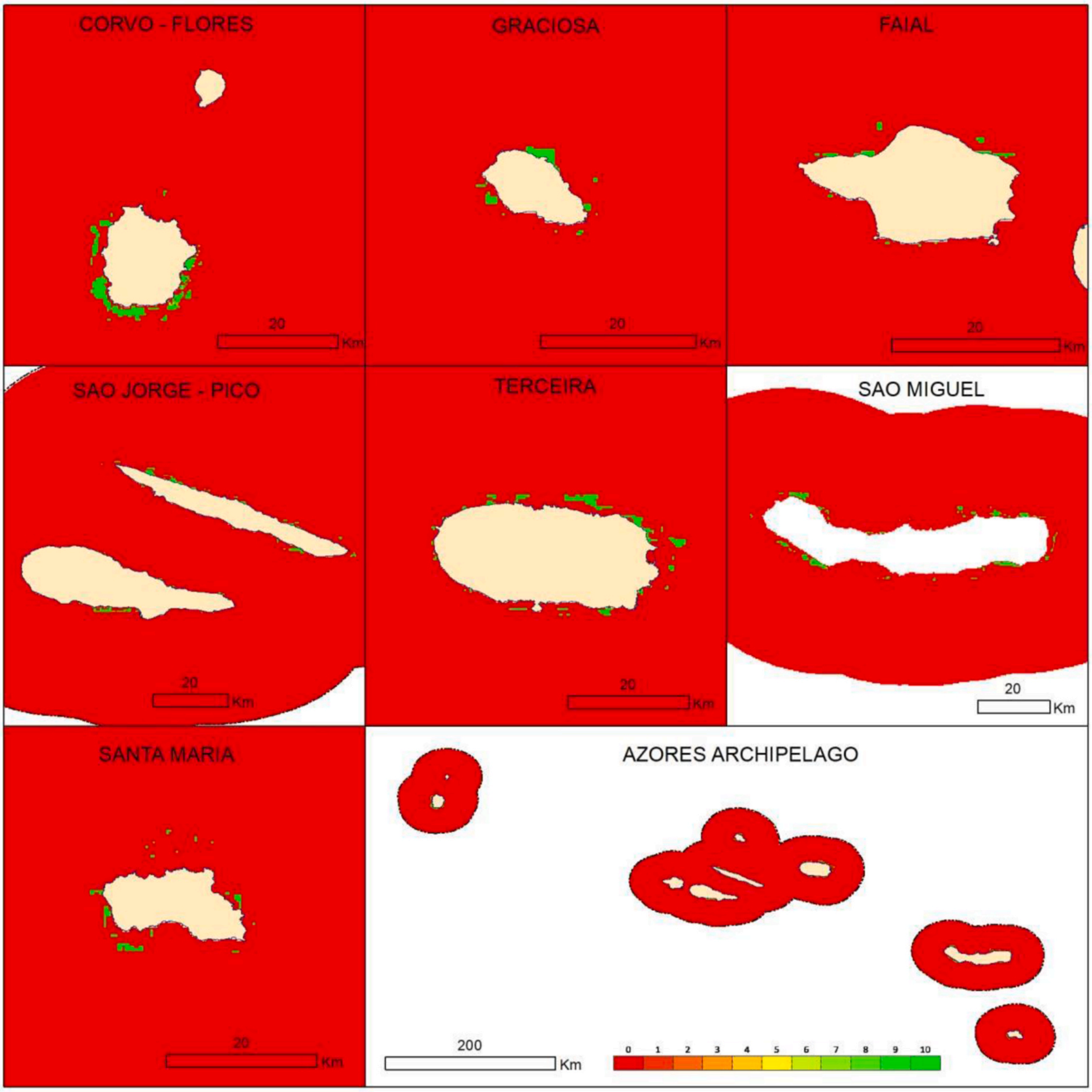

Fig. 6A. Suitability maps for the extraction of aggregates resulting from the expert consensus scenario considered in the Azores (see Table 5).

making within the developed methodology.

In this study, we tested a new methodology for three different maritime sectors, applied to three Macaronesian archipelagos with different environmental, social and economic conditions. The results showed that the suitability framework developed and applied by INDIMAR DSS is flexible and can be implemented throughout the EU Macaronesia region. In this context, the geographical coverage of INDIMAR DSS is the whole marine region, similar to the application of MYTILUS or SEANERGY developed for the whole Baltic Sea (Bonnevie et al., 2020, 2022) or the MSP Challenge simulation platform (Abspoel et al., 2021) covering the whole North Sea.

Although the method can be applied to any use case, adapting the INDIMAR DSS system to a new region is not easy. When applying the INDIMAR DSS to a different environment, several factors need to be considered:

- Inconsistencies or gaps in data can limit the effectiveness of the results provided by the DSS. It is essential to assess the availability and quality of data and spatial information specific to the new region.
- Each region has unique social, economic and environmental characteristics that shape its priorities in MSP. Adapting the system to take account of these contextual differences is necessary to ensure its relevance and applicability in the new region. The zone suitability framework does not include socio-economic components. This is a significant gap that needs to be considered in future development and in attempts to increase the adaptability of the system (Abramic et al., 2023).
- Legal and governance frameworks for MSP may vary from region to region. It is important to understand and integrate the specific legal and governance requirements of the new region into the DSS to ensure compliance and effectiveness. Similar to the socio-economic component, the future suitability framework should include a governance component that takes into account the administrative competence related to maritime sectors (e.g. competence for maritime fisheries) and analyses the marine area (e.g. who has competence for the territorial sea, the contiguous zone and the exclusive economic zone).

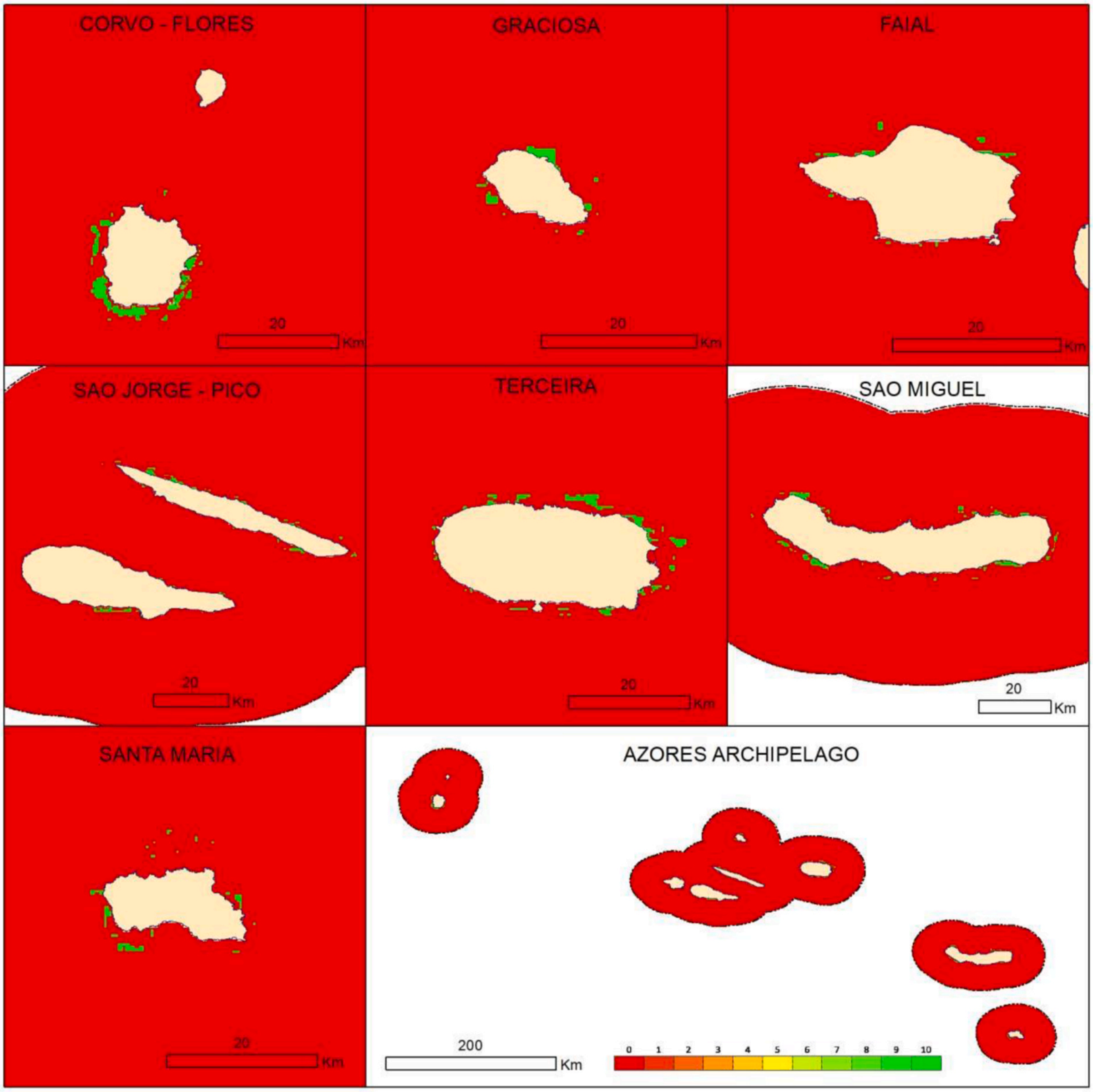

Fig. 6B. Suitability maps for the extraction of aggregates resulting from the environmental scenario considered in the Azores (see Table 5).

- The implementation of a DSS requires sufficient institutional capacity and expertise to operate and maintain the system and properly interpret the results. It is important to assess the existing institutional capacity in the new region in order to provide the necessary training and resources to support the successful implementation of the DSS.
- If the new region has cross-border or transboundary dimensions, spatial interactions and coordination with neighbouring regions become important. These considerations may not have been adequately addressed in the use case specifically due to the nature of archipelagos, and adapting the DSS to incorporate cross-border interactions may be a challenging feature for further development.

In summary, while the INDIMAR DSS has broad applicability, its implementation in a new region requires careful attention to data availability, contextual differences, legal and governance frameworks, institutional capacity and spatial interactions. Taking these factors into account, this DSS will enhance the effectiveness and relevance of the DSS in the MSP processes of the new region.

5. Conclusion

In this study, the tested methodology has shown a high degree of adaptability and applicability, whether for the introduction or expansion of the maritime sector, or for covering the diversity of maritime sectors included in the study. Using the developed methodology, it is possible to analyse additional sectors that exploits wave, tide or currents energy, maritime transport or various maritime tourism activities such as whale watching, diving, kite surfing and others. The methodology provides reliable results that can be effectively applied in practical scenarios.

It is also important to note that methodologies developed for specific locations can be adapted to other contexts. However, this adaptation should take into account various factors such as data availability, contextual differences, legal and governance frameworks, institutional capacity and spatial interactions, especially in transboundary contexts.

The zoning methodology developed here takes into account all five components of the suitability framework, adjusting the weights and seeking a balance between the marine environment, conservation,

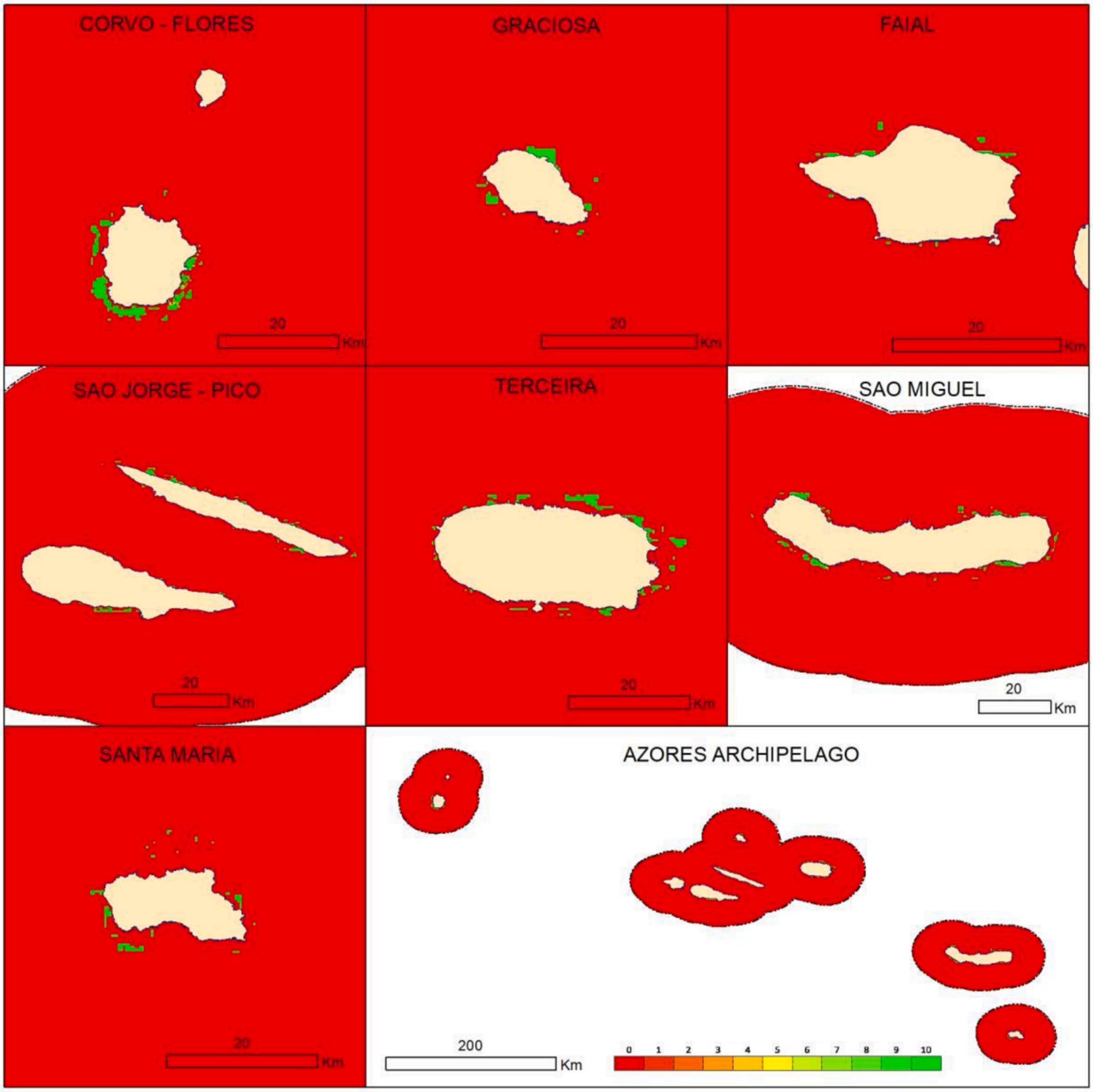

Fig. 6C. Suitability maps for the extraction of aggregates resulting from the Conflict minimisation scenario considered in the Azores (see Table 5).

Table 6
Total expansion (Km2) by suitability categories of the resulting zonation for each of the scenarios considered in the Azores.

Scenarios (The Azores)	Area by level of suitability (Km^2)										
	0	1	2	3	4	5	6	7	8	9	10
Expert consensus	35960.4	0	0	0	0	0	0.2	0	1.0	0.1	123.4
Environmental	35958.3	0	0	0	0	0	0	0.2	0.3	1.0	125.1
Conflict minimization	35958.3	0	0	0	0	0.2	0.3	0	0.8	0.2	125.1

natural oceanographic potential, land-sea interactions and marine and coastal users.

During the application of the zoning methodology to three use cases, it became clear that the results of the model were heavily influenced by the availability of data. To address this challenge, a structured data collection process following the zoning suitability framework was implemented. However, generating the new data required to improve the quality of spatial suitability analyses was beyond the scope of this study. Nevertheless, this structured process facilitated a clear understanding of which components of the framework had significant data gaps and the impact of these gaps on the results. This information allowed for a more informed interpretation of the zoning results and provided insights into areas that may require further data collection or improved data management strategies.

In conclusion, the methodology provides the flexibility to adapt the model and produce zoning results that are consistent with the governance strategy and meet planning objectives. By incorporating policy-defined profiles with associated weights and constraints, the methodology allows trade-offs to be facilitated or regulated, thereby increasing or decreasing the importance of specific components considered in the analysis. This approach enables the creation of precise policy scenarios tailored to specific maritime sectors.

These policy scenarios can be used for various purposes, such as informing the development or refinement of policies within the MSP framework, adapting governance strategies for maritime sectors and improving environmental management practices. By using these scenarios, decision-makers can evaluate different options, assess their impacts and make informed decisions that are consistent with the objectives of sustainable maritime development.

Author contributions

Ricardo Haroun: Writing – review & editing, Project administration. Deborah Shinoda: Methodology, Investigation, Conceptualization. Natacha Nogueira: Methodology, Investigation. Andrej Abramic: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Helena Calado: Writing – review & editing. Carlos Andrade: Writing – review & editing, Conceptualization. Gilberto Carreira: Project administration. Sachi Kaushik: Writing – review & editing, Conceptualization. Victor Cordero_penin: Writing – review & editing, Writing – original draft. Alejandro Garcia Mendoza: Software, Methodology. Yazia Fernandez-Palacios: Writing – review & editing. Maria Magalhães: Methodology, Investigation

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.

Data availability

Data available and searchable through metadata catalogue: http://www.geoportal.ulpgc.es/geonetwork/srv/eng/catalog.search#/home.

Acknowledgements

This work was supported by the PLASMAR project (grant number MAC/1.1a/030); PLASMAR + project (grant number MAC2/1.1a/347) under the INTERREG V-A Spain-Portugal MAC 2014–2020 (Madeira-Azores-Canarias) programme of the European Regional Development Fund (ERDF) of the European Union.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107051.

References

Abramic, A., Norton, D., Sarretta, A., Menegon, S., Katsika, M., Gekas, V., Rybka, K., Fernández- Palacios, Y., 2023. Maritime Spatial Planning Data Framework (MSPdF). How to structure input data for MSP process, monitoring and evaluation. Produced by Technical Expert Group (TEG) on Data for MSP 45. Supported by CINEA and DG MARE (EC). https://data.europa.eu/doi/10.2926/440667.

Abramic, A., Cordero-Penin, V., Haroun, R., 2022. Environmental impact assessment framework for offshore wind energy developments based on the marine Good Environmental Status. Environ. Impact Assess. Rev. 97 (July), 106862 https://doi.org/10.1016/j.eiar.2022.106862.

Abramic, A., García Mendoza, A., Haroun, R., 2021. Introducing offshore wind energy in the sea space: Canary Islands case study developed under Maritime Spatial Planning principles. Renew. Sustain. Energy Rev. 145, 111119 https://doi.org/10.1016/j.rser.2021.111119.

Abramic, A., Norton, C., Haroun, R., 2018. Finding the Balance of Blue Growth Sustainable Development within Ecosystem Approach (2.1.1 C, D). Analysis of the Offshore Wind Industry in Macaronesia under MSFD. IU-ECOAQUA, Univ. Las Palmas de Gran Canaria, p. 59. Report prepared as part of the PLASMAR Project (co-financed by ERDF as part of POMAC 2014-2020). http://hdl.handle.net/10553/56280.

Abspoel, L., Mayer, I., Keijser, X., Warmelink, H., Fairgrieve, R., Ripken, M., Abramic, A., Kannen, A., Cormier, R., Kidd, S., 2021. Communicating maritime spatial planning: the MSP challenge approach. Mar. Pol. 132, 103486 https://doi.org/10.1016/j.marpol.2019.02.057. ISSN 0308-597X.

Agardy, T., 2010. Ocean Zoning: Making Marine Management More Effective. Earthscan, London and Washington (DC), p. 220, 978-1-84407-822-6.

Alison, A., Andrady, A.L., Courtney, A, Baker, J, Bouwman, H., Gall, S., et al., 2015. GESAMP. Sources, fate and effects of microplastics in the marine environment: a global assessment. In: (Kershaw, P.F. (Ed.), IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection), Rep. Stud. GESAMP No, 90, pp. 96–p.

Ansong, J., Gissi, E., Calado, H., 2017a. An approach to ecosystem-based management in maritime spatial planning process. Ocean Coast Manag. 141, 65–81. https://doi.org/10.1016/j.ocecoaman.2017.03.005.

Ansong, J., Gissi, E., Calado, H., 2017b. An approach to ecosystem-based management in maritime spatial planning process. Ocean Coast Manag. 141, 65–81. https://doi.org/10.1016/j.ocecoaman.2017.03.005.

Bolman, B., Jak, R.G., van Hoof, L., 2018. Unravelling the myth – the use of Decisions Support Systems in marine management. Mar. Pol. 87, 241–249. https://doi.org/10.1016/j.marpol.2017.10.027.

Bonnevie, I.M., Hansen, H.S., Schrøder, L., 2020. Seanergy - a spatial tool to facilitate the increase of synergies and to minimise conflicts between human uses at sea. Environ. Model. Software 132, 104808. https://doi.org/10.1016/J.ENVSOFT.2020.104808.

Bonnevie, I.M., Hansen, H.S., Schrøder, L., Armoškaitė, A., 2022. Utilising MYTILUS for active learning to compare cumulative impacts on the marine environment in different planning scenarios. Sustainability 14, 12606. https://doi.org/10.3390/su141912606.

Borja, A., Elliott, M., Andersen, J.H., Cardoso, A.C., Carstensen, J., Ferreira, J.G., Heiskanen, A.-S., Marques, J.C., Neto, J.M., Teixeira, H., Uusitalo, L., Uyarra, M.C., Zampoukas, N., 2013. Good Environmental Status of marine ecosystems: what is it and how do we know when we have attained it? Mar. Pollut. Bull. 76 (1–2), 16–27. https://doi.org/10.1016/j.marpolbul.2013.08.042.

Calado, H., Papaioannou, E., Caña-Varona, M., Onyango, V., Zaucha, J., Przedrzymirska, J., Roberts, T., Sangiuliano, S., Vergílio, M., 2019. Multi-uses in the eastern atlantic: building bridges in maritime space. Ocean Coast Manag. https://doi.org/10.1016/j.ocecoaman.2019.03.004.

Chalastani, V.I., Tsoukala, V.K., Coccossis, H., Duarte, C.M., 2021. A bibliometric assessment of progress in marine spatial planning. Mar. Pol. 127, 104329 https://doi.org/10.1016/j.marpol.2020.104329.

Christie, N., Smyth, K., Barnes, R., Elliott, M., 2014. Co-location of activities and designations: a means of solving or creating problems in marine spatial planning? Mar. Pol. 43, 254–261. https://doi.org/10.1016/j.marpol.2013.06.002.

Costoya, X., deCastro, M., Carvalho, D., Gómez-Gesteira, M., 2020. On the suitability of offshore wind energy resource in the United States of America for the 21st century. Appl. Energy 262, 114537. https://doi.org/10.1016/J.APENERGY.2020.114537.

Day, J., Dudley, N., Hockings, M., Holmes, G., Laffoley, D., Stolton, S., Wells, S., Wenzel, L. (Eds.), 2019. Guidelines for Applying the IUCN Protected Area Management Categories to Marine Protected Areas, second ed. IUCN, Gland. Switzerland https://portals.iucn.org/library/node/10201.

Depellegrin, D., Hansen, H.S., Schrøder, L., Bergström, L., Romagnoni, G., Steenbeek, J., Gonçalves, M., Carneiro, G., Hammar, L., Pålsson, J., Crona, J.S., Hume, D., Kotta, J., Fetissov, M., Miloš, A., Kaitaranta, J., Menegon, S., 2021. Current status, advancements and development needs of geospatial decision support tools for marine spatial planning in European seas. Ocean Coast Manag. 209, 105644 https://doi.org/10.1016/j.ocecoaman.2021.105644.

Directive 2014/89/EU of the, 2014. European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning. Off. J. Eur. Union 135.

Ehler, C., Douvere, F., 2009. Marine Spatial Planning: a Step-by-step Approach toward Ecosystem- Based Management. IOC. Manuals and Guides No.53. ICAM Dossier No.6. Paris: UNESCO 2009 (English). Available at: http://unesdoc.unesco.org/images/0018/001865/186559e.pdf.

Ehler, C.N., 2021. Two decades of progress in marine spatial planning. Mar. Pol. 132, 104134 https://doi.org/10.1016/j.marpol.2020.104134.

Emeksiz, C., Demirci, B., 2019. The determination of offshore wind energy potential of Turkey by using novelty hybrid site selection method. Sustain. Energy Technol. Assess. 36, 100562. ISSN 2213-1388. https://doi.org/10.1016/j.seta.2019.100562.

Flower, J., Ramdeen, R., Estep, A., et al., 2020. Marine spatial planning on the Caribbean island of Montserrat: lessons for data-limited small islands. Conservation Science and Practice 2, e158. https://doi.org/10.1111/csp2.158.

Frazão Santos, C., Ehler, C.N., Agardy, T., Andrade, F., Orbach, M.K., Crowder, L.B., 2019. Marine spatial planning. In: World Seas: an Environmental Evaluation, second ed. Elsevier, pp. 571–592. https://doi.org/10.1016/B978-0-12-805052-1.00033-4.

Friess, B., Grémaud-Colombier, M., 2019. Policy outlook: recent evolutions of maritime spatial planning in the European Union. Mar. Pol. https://doi.org/10.1016/j.marpol.2019.01.017 (in press). Available online 19 February 2019, 103428.

Fulton, E.A., Link, J.S., Kaplan, I.C., Savina-Rolland, M., Johnson, P., Ainsworth, C., Horne, P., Gorton, R., Gamble, R.J., Smith, A.D.M., 2011. Lessons in modelling and management of marine ecosystems: the Atlantis experience. Fish Fish. 12 (2), 171–188.

Goepel, K.D., 2013. Implementing the Analytic Hierarchy Process as a Standard Method for Multi- Criteria Decision Making in Corporate Enterprises – a New AHP Excel Template with Multiple Inputs. https://doi.org/10.13033/ISAHP.Y2013.047.

Göke, C., Dahl, K., Mohn, C., 2018. Maritime Spatial Planning supported by systematic site selection: applying Marxan for offshore wind power in the western Baltic Sea, 3/15/2018 PLoS One 13 (3), 13. https://doi.org/10.1371/journal.pone.0194362.

Haapasaari, p., van Tatenhove, P.M., Jan, 2022. A Finnish regional non-binding MSP approach: what are the consequences for integrating Blue Growth and GES? Mar. Pol. 141, 105101 https://doi.org/10.1016/j.marpol.2022.105101.

Hammar, L., Perry, D., Gullström, M., 2016. Offshore wind power for marine conservation. Open J. Mar. Sci. 6, 66–78. https://doi.org/10.4236/OJMS.2016.61007.

Hansen, H.S., 2019. Cumulative impact of societal activities on marine ecosystems and their services. In: Misra, S., Gervasi, O., Murgante, B., Stankova, E., Korkhov, V., Torre, C., Rocha, A.M.A.C., Taniar, D., Apduhan, B.O., Tarantino, E. (Eds.), Computational Science and its Applications – ICCSA 2019. Springer International Publishing, pp. 577–590. https://doi.org/10.1007/978-3-030-24302-9_41.

Hardin, G., 1968. The tragedy of the commons. Science 13 162 (3859), 1243–1248. https://doi.org/10.1126/science.162.3859.1243.

IOC/UNESCO, et al., 2011. IOC/UNESCO, FAO, UNDPA Blueprint for Ocean and Coastal Sustainability.

Janßen, Holger, Göke, Cordula, Luttmann, Anne, 2019. Knowledge integration in Marine Spatial Planning: a practitioners' view on decision support tools with special focus on Marxan. Ocean Coast Manag. 168, 130–138. https://doi.org/10.1016/j.ocecoaman.2018.11.006. ISSN 0964-5691.

Kumar, A.S.V.V., Nagababu, G., Sharma, R., Kumar, R., 2020. Synergetic use of multiple scatterometers for offshore wind energy potential assessment. Ocean Eng. 196, 106745 https://doi.org/10.1016/J.OCEANENG.2019.106745.

Larsen, J.K., Guillemette, M., 2007. Effects of wind turbines on flight behaviour of wintering common eiders: implications for habitat use and collision risk. J. Appl. Ecol. 44, 516–522. https://doi.org/10.1111/J.1365-2664.2007.01303.X.

Le Tixerant, M., Le Guyader, D., Gourmelon, F., Queffelec, B., 2018. "How can automatic identification system (AIS) data be used for maritime spatial planning?" In maritime spatial planning, ecosystem approach and supporting information systems (MapSIS 2017). Ocean Coast Manag. 18–30. https://doi.org/10.1016/j.ocecoaman.2018.05.005, 1 December 2018 166: Language: English.

Maccarrone, V., Filiciotto, F., de Vincenzi, Giovanni, Mazzola, S., Buscaino, G., 2015. An Italian proposal on the monitoring of underwater noise: relationship between the EU Marine Strategy Framework Directive (MSFD) and marine spatial planning directive (MSP). Ocean Coast Manag. 118 (Part B) https://doi.org/10.1016/j.ocecoaman.2015.07.006.

Menegon, S., Sarretta, A., Depellegrin, D., Farella, G., Venier, C., Barbanti, A., 2018. Tools4MSP: an open source software package to support Maritime Spatial Planning. PeerJ Computer Science 4, 165.

Montero, L.C., Christensen, V., Hernández, J.J.C., 2021. Simulating trophic impacts of fishing scenarios on two oceanic islands using Ecopath with Ecosim. Marine Environ. Res. 169, 105341. ISSN 0141-1136. https://doi.org/10.1016/j.marenvres.2021.105341.

Montero-Hidalgo, M., Tuya, F., Otero-Ferrer, F., Haroun, R., Santos-Martín, F., 2023. Mapping and assessing seagrass meadows changes and blue carbon under past, current, and future scenarios. Sci. Total Environ. 872, 162244 https://doi.org/10.1016/j.scitotenv.2023.162244.

O'Mahony, C., Ferreira, M., Fernández-Palacios, Y., Cummins, V., Haroun, R., 2009. Data availability and accessibility for sustainable tourism: an assessment involving different European coastal tourism destinations. In: Journal of Coastal Research, Special Issue No. 56. Proceedings of the 10th International Coastal Symposium ICS 2009, vol. II, pp. 1135–1139 (5 pages). https://www.jstor.org/stable/25737964.

Pınarbaşı, K., Galparsoro, I., Borja, Á., Stelzenmüller, V., Ehler, C.N., Gimpel, A., 2017. Decision support tools in marine spatial planning: present applications, gaps and future perspectives. Mar. Pol. 83, 83–91. https://doi.org/10.1016/j.marpol.2017.05.031.

Png-Gonzalez, L., Andrade, C., Abramic, A., Nogueira, N., 2019. Analysis of the Aquaculture Industry in Macaronesia under MSFD, p. 53. Report prepared as part of PLASMAR Project (co-financed by ERDF as part of POMAC 2014-2020). http://hdl.handle.net/10553/55195.

Quesada-Silva, M., Iglesias-Campos, A., Turra, A., Suárez-de Vivero, J.L., 2019. Stakeholder Participation Assessment Framework (SPAF): a theory-based strategy to plan and evaluate marine spatial planning participatory processes. Mar. Pol. 108, 103619 https://doi.org/10.1016/j.marpol.2019.103619.

Ritchie, H., 2011. Ocean zoning—making marine management more effective. J. Environ. Pol. Plann. 13 (3), 317–319. https://doi.org/10.1080/1523908X.2011.603196.

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

Saaty, T.L., 1990. How to make a decision: the analytic hierarchy process. Eur. J. Oper. Res. 48, 9–26.

Sprague, R.H., Carlson, E.D., 1982. Building Effective Decision Support Systems.

Stamoulis, K.A., Delevaux, J.M., 2015. Data requirements and tools to operationalize marine spatial planning in the United States. Ocean Coast Manag. 116, 214–223.

Stelzenmüller, V., Lee, J., South, A., Foden, J., Rogers, S.I., 2013. Practical tools to support marine spatial planning: a review and some prototype tools. Mar. Pol. 38, 214–227.

Tsiaras, K., Tsapakis, M., Gkanassos, A., Kalantzi, J., Petihakis, G., Triantafyllou, G., 2022. Modelling the impact of finfish aquaculture waste on the environmental status in an Eastern Mediterranean Allocated Zone for Aquaculture. Continent. Shelf Res. 234, 104647 https://doi.org/10.1016/j.csr.2022.104647.

UNESCO-IOC and European Commission. MSPglobal International Guide on Marine/Maritime Spatial Planning. Paris, France, UNESCO, 152pp. (IOC Manuals and Guides no 89). http://dx.doi.org/10.25607/OBP-1666.

UNESCO-IOC/European Commission, 2021. MSPglobal international guide on marine/maritime spatial planning. In: Iglesias-Campos, A., Rubeck, J., Sanmiguel-Esteban, D., Schwarz, G. (Eds.), Maritime Spatial Planning (IOC Manual). UNESCO/European Commission. https://doi.org/10.1007/978-3-319-98696-8.

Wind Europe, 2020. Offshore Wind in Europe, Key Trends and Statistics 2019.

Zhang, Z., Plathong, S., Sun, Y., Guo, Z., Ma, C., Jantharakhantee, C., Tanboot, L., 2022. An issue-oriented framework for marine spatial planning—a case study of koh lan, Thailand. Regional Studies in Marine Science 53, 102458. https://doi.org/10.1016/j.rsma.2022.102458.

Zuercher, R., Ban, N.C., Flannery, W., Guerry, A.D., Halpern, B.S., Magris, R.A., Mahajan, S.L., Motzer, N., Spalding, A.K., Stelzenmüller, V., Kramer, J.G., 2022. Enabling conditions for effective marine spatial planning. Mar. Pol. 143, 105141 https://doi.org/10.1016/j.marpol.2022.105141.