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RESEARCH ARTICLE

Addressing ocean planning challenges in a highly crowded sea space: a case study for the regional sea of Catalonia (Western Mediterranean) [version 1; peer review: 2 approved]

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Abstract

Background

This study performs an exploratory analysis of current-future sustainability challenges for ocean planning for the regional seas of Catalonia located in the Western Mediterranean (Spain).

Methods

To address the challenges we develop an Maritime Spatial Planning (MSP)-oriented geodatabase of maritime activities and deploy three spatial models: 1) an analysis of regional contribution to the 30% protection commitment with Biodiversity Strategy 2030; 2) a spatial Maritime Use Conflict (MUC) analysis to address current and future maritime activities interactions and 3) the StressorGenerator QGIS application to locate current and anticipate future sea areas of highest anthropogenic stress.

Open Peer Review

Approval Status ✔✔

	1	2
version 1 01 Mar 2024	✔ view	✔ view

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Results & Conclusions

Results show that the i) study area is one of the most protected sea areas in the Mediterranean (44–51% of sea space protected); ii) anthropogenic stressors are highest in 1–4 nautical miles coastal areas, where maritime activities agglomerate, in the Gulf of Roses and Gulf of Saint Jordi. iii) According to the available datasets commercial fishery is causing highest conflict score inside protected areas. Potential new aquaculture sites are causing highest conflict in Internal Waters and the high potential areas for energy cause comparably low to negligible spatial conflicts with other uses. We discuss the added value of performing regional MSP exercises and define five challenges for regional ocean sustainability, namely: Marine protection beyond percentage, offshore wind energy: a new space demand, crowded coastal areas, multi-level governance of the regional sea and MSP knowledge gaps.

Keywords
Maritime Spatial Planning, spatial conflicts, MSFD pressures, stressors, offshore wind energy, aquaculture, marine protection, Spain

1. Introduction

The coastal region of Catalonia (Spain, Western Mediterranean) belongs to the Mediterranean regions with highest revenue in relation to Blue Economy (BE, 2020). The Blue Economy is estimated to have directly employed 214496 people in 2017 (5.8% of the total employment in Catalonia), generated €25 billion of revenue and €7.3 billion of Gross Value Added (GVA) (3.4 % of the GVA in Catalonia; BE, 2020). In addition, the regional authorities have launched a regional Blue Economy Strategy of Catalonia 2030 (Estratègia Marítima, 2021) with ambitions for sustainable development across Blue Economy sectors and the marine resource. In 2017, through a Royal Decree 363/2017, the Spanish government transposed to Spanish law the European Maritime Spatial Planning (MSP) Directive 2014/89/EU, setting the path to a national framework for maritime spatial management. This resulted in 2021 to the drafting of the first maritime spatial plan of Spain, hereafter POEM - "*Planes de Ordenación del Espacio Maritime*" (POEM, 2021). The process is preceded by an increasing segment of scientific literature in Spain, applying analysis techniques to address ecosystem-based management and the spatial organization of present and future Blue Economy activities. This includes among others the analysis of future sectorial space demands for marine renewable energy (Abramic *et al.*, 2021; Díaz & Soares, 2021; Pınarbaşı *et al.*, 2019; Salvador *et al.*, 2019), transboundary challenges in MSP (Gómez-Ballesteros, *et al.*, 2021; Pınarbaşı *et al.*, 2020) environmental impact assessment of maritime activities (Abramic *et al.*, 2022; Muñoz *et al.*, 2018) or potentials for ocean multi-use (Saenz-Aguirre *et al.*, 2022; Veigas & Iglesias, 2013). The majority of these studies focus on study areas at regional or at spatial subdivision scale. At the current stage no studies exist, addressing marine multi-sectoral interactions, nor do regional ocean planning studies exist for Catalonia region addressing existing and future MSP challenges for the region. According to a review of MSP practices around

Europe performed by van den Burg *et al.* (2023), 24% of MSP studies have a regional geographic scale. In fact regional MSP case study funded by European and national funding entities resulted into valuable contribution to the national MSP processes in different regions of European seas: examples include the Scottish Sustainable Marine Environment Initiative (SSMEI, 2018) aimed at testing new approaches to improve sustainable management of Scottish marine resources through the setup of pilot projects (e.g. Shucksmith *et al.*, 2014), the ICZM-MSP regional pilot study in Emilia-Romagna Region (Barbanti & Perini, 2018; Farella *et al.*, 2020) or the case study on assessing and mapping marine ecosystem services in the Latvian MSP through the ESMERALDA Project (Burkhard *et al.*, 2018; Veidemane *et al.*, 2017). Given these experiences and the iterative character of ocean planning (Ehler & Douvere, 2009), it is of pivotal importance now and in future to perform regional ocean planning exercises that can foster knowledge and competences in MSP and inform decision-makers and Blue Economy stakeholders on the regional challenges of sustainable use of maritime space. This research applies MSP-driven geospatial analysis techniques to 1) quantify regional contribution to EU Biodiversity Target 2030 of 30% sea protection; 2) locate interactions in terms of spatial conflict analysis among present and future maritime sectors and 3) applies anthropogenic stress areas in the light of the POEM's zoning typologies.

Based on the results we formulate five emerging regional challenges for sustainable use of the maritime space, suggest actionable (non-) spatial management measures and highlight the benefits and challenges of regional MSP research.

2. Methods

The exploratory analysis is based on a step-wise approach highlighted in the conceptual framework below (Figure 1). In summary this includes: 1) the definition of the study
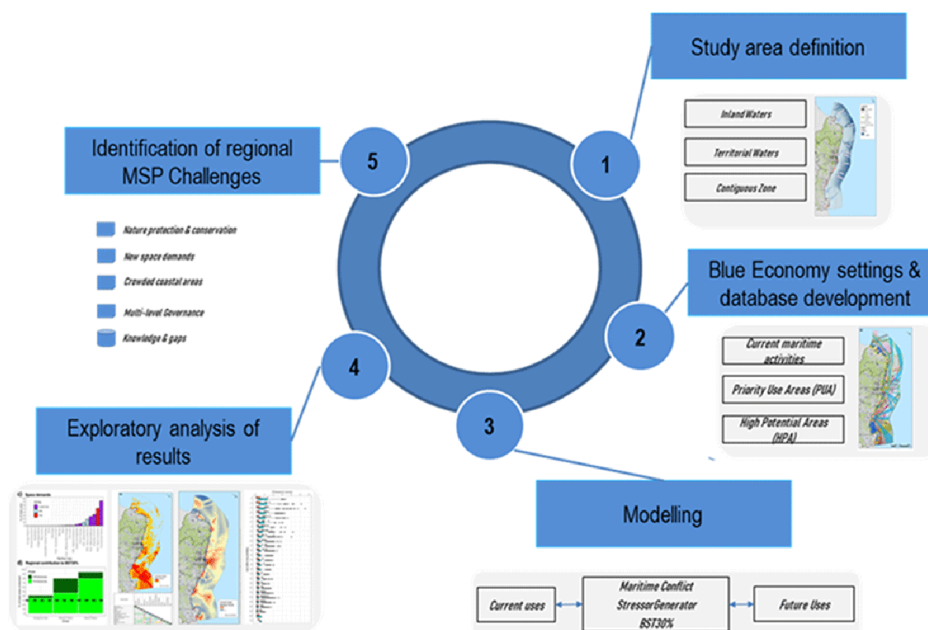
Figure 1. Conceptual framework applied in this case study area.

area into three zoning areas (see section 2.1), 2) the creation of a multi-sectoral database of the most representative Blue Economy activities in Catalonia region (see Annex 1 for Blue Economy characterization in Depellegrin & Martí Llambrich, 2024) including the human activities emerging from the zoning solutions settled in the Strategic Environmental Assessment (SEA) of the POEM; 3) the analysis of regional contribution of Biodiversity Strategy 2030 (see section 2.4); the application of a maritime use conflict (MUC) analysis using the Tools4MSP Modelling Framework (Tools-4MSP, 2022; section 2.5); application of the QGIS-based *StressorGenetor* Plugin (section 2.6); 4) Exploratory analysis and evaluation of results oriented to address the regional challenges on sustainable use of maritime space (see section 3 and 4) and the relevance of the applied regional case studies for further research in the area (see section 5); and 5) identification of emerging challenges in sustainable use of maritime space.

2.1. Study area definition

The regional study area is located in the Levantine-Balearic subdivision (Western Mediterranean) defined within the *Planes de Ordenación del Espacio Maritime* (POEM), the national maritime spatial plan of Spain (Figure 2). In order to make a MSP relevant analysis on regional level we define the study area as the regional Internal Waters (IW) including the three subregions, The Gulf of Sant Jordi (1151 km²; 6.3%), the IW of Barcelona-Arenys de Mar (Bar-AdM; 122.8 km²; 0.7%) and the Gulf of Roses (379.3 km²; 2%), the 12 nm limit defined by the Territorial Waters (8124 km²; 44%) and the Contiguous Zone (8627 km²; 47%). Total area of the study area is 18026 km². The geospatial data resource for the subregions is provided by the EMODNet Geoviewer (European Marine Observation and Data Network, 2023). The coastline is 580 km long and the sea depth range is 0 to -2205 meters. The subregions are highly relevant for regional MSP and were selected to demonstrate the data-driven approach of the geospatial tools (MUC and StressorShift analysis) in addressing complex interactions of maritime activities in a subregion that agglomerates the majority of current maritime activities and incorporates all the future maritime activities according to the Spanish MSP. From an administrative point of view, there are three coastal provinces (Girona, Barcelona and Tarragona), north-eastern boundary is with France (Occitania region) and south-western regional boundary is with the Valencian Community (Spain).

2.2. MSP conditions in the study area

The POEM distinguishes different types of zoning (BOE-A-2022-21389):

1) *Priority-Use-Areas (PUA)* are sea areas where current activities take place in their designated space, that where not yet carried out. These are sea areas where general-interest must be guaranteed by minimizing the risks to these areas.

2) *High-Potential-Areas (HPA)* are sea areas where certain sectoral activities whose potential development is foreseeable and which require the identification of the most suitable space for
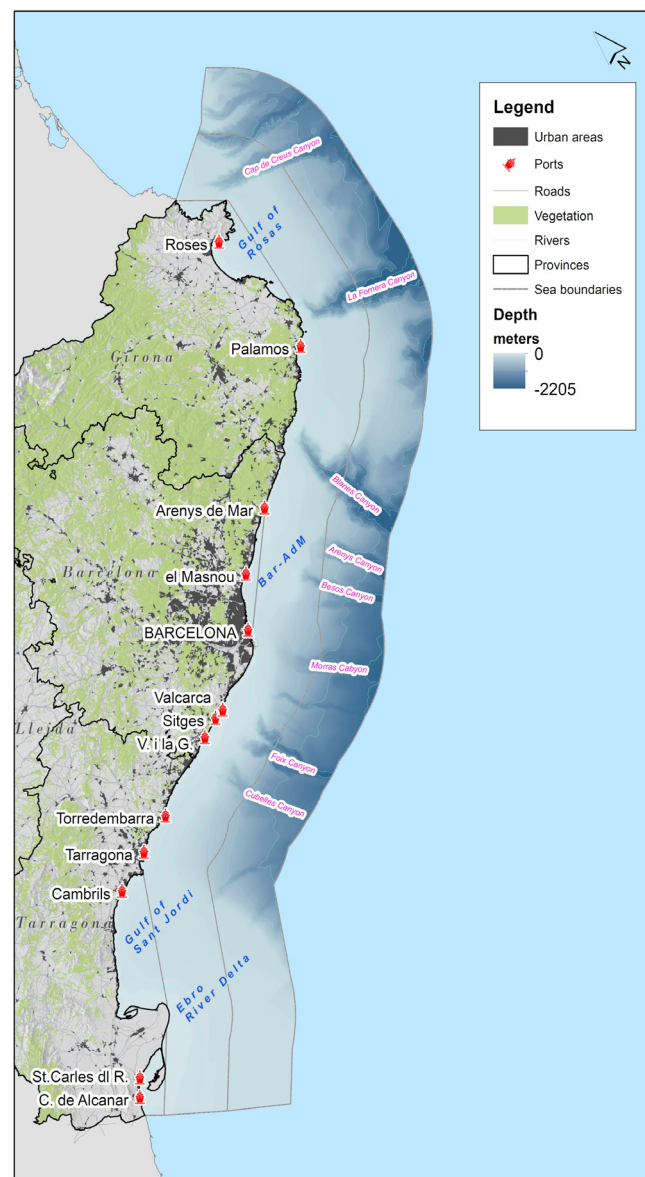
Figure 2. Inland waters, Territorial Waters and Contiguous zone; including bathymetry of the study area and most representative submarine canyons.

its development to minimize potential environmental effects and maximize synergies and coexistence between the different uses and activities (POEM, 2021). We apply these zoning concepts inside the study area as follows: i) *HPA - Offshore Wind Energy* (OWE) refers to high potential areas for renewable energy located in the Territorial Waters in front of the Gulf of Roses. One of the projects described in the *Initial Environmental Assessment* proposals named Tramuntana (BlueFloat, 2021) foresees the installation of about 63 floating wind turbines (15 MW each; 137 m turbine height). We apply this potential OWE design proposal due to the availability of the *lon/lat* coordinates of the park extent. For other proposals of installation capacity and design in the Gulf of Roses we refer to

4COffshore (2023) Platform. Minimum distance to shore is approx. 14 km (distance to closest port is approx. 24.6 km). *ii) PUA – Biodiversity* include protected marine spaces, including the Nature 2000 Network, subject to both national and regional management. *iii) PUA - National Defence* comprise military areas used for National Defence activities in amphibious, underwater and surface military exercises and *iv) PUA - Aggregate Extraction* includes areas containing strategic sand deposits, necessary for coastal protection measures and climate change mitigation. HPA areas include: *v) HPA - Biodiversity* includes expert-based definition of new areas of high ecological value of habitats, birds, cetaceans that according to the POEM (2023) that may be suggested as Natura 2000 Sites to accomplish Biodiversity Strategy 2030 targets and *vi) HPA - aquaculture* are new areas for aquaculture facilities development defined by the Junta *Nacional Asesora de Cultivos Marinos* (JACUMAR, 2023).

2.3. MSP settings and geodatabase development

The multi-sectoral MSP database (Table 1) is fully open source composed by publicly accessible data from international (AAPG-Explorer, 2019; GFW, 2021; PADI, 2023; Protected Planet, 2023), European (European Marine Observation and Data Network - EMODNet Geoviewer, 2023; Tools4MSP - Menegon *et al.*, 2018a), national (BlueFloat, 2021; CEDEX-INFOMAR, 2022; CNMC, 2022; POEM, 2021) and regional (GenCat, 2022a; GenCat, 2023) data providers. In order to optimize the relevance of the regional study for decision-making and harmonize the modelling procedures we structure the MSP database according to the POEM's disposition of zoning of maritime activities into current uses and future uses. The database includes 13 existing maritime uses (E) and 4 future uses (F) that are not in place at the current stage (HPA: offshore wind energy and material extraction, aquaculture and biodiversity). The geodatabase development includes three types of indicators, namely intensity of maritime activities; presence/absence of maritime activities and planning prioritization areas (PUA and HPA). In Figure 4 of the results section we provide a synthesis map of the existing and future maritime activities in Catalonia.

2.4. Marine protection targets

The developed MSP database is applied to address the 30% sea area protection commitments defined within the Biodiversity Strategy 2030 (BS 2030). The BS2030 is Europe's comprehensive plan for the conservation and restoration of nature (EEA, 2023). It is the framework mentioned in the Royal Decree 150/2023 approving the Spanish Maritime Spatial Plan in February 2023. To monitor the 30% protection target in the study area we apply the method developed by the European Environment Information and Observation Network (EIONET; Agnesi *et al.*, 2020). EIONET performs three-annual monitoring of progress in MPA implementation in European seas and is therefore guiding instrument for the monitoring of the 30% protection target. In line with Agnesi *et al.* (2020) and BS2030 we calculate the distance to Biodiversity Strategy Target 2030 ($BST_{30\%}^i$) by taking into consideration three types of MPA areas according to the areal percentage

of *i)* Natura2000 MPA network (SPA - Special Protected Areas and SIC - Site of Community Interest; $p_{SPA/SIC}$), *ii)* national/regional designated areas (p_{NAT}) and *iii)* Regional Sea Convention (p_{RSC}). The distance refers to the protection coverage in % compared to the 30% target of the BS2030. The dataset used for the calculation is collected from the Protected Planet Database for the study area. The following algorithm is applied for the *i-th* sea space (Inland Waters, Territorial Waters and Contiguous Zone) as follows:

$$BST_{30\%}^i = p_{PUA} + p_{HPA}$$

whereas,

$$p_{PUA} = p_{SPA/SIC} + p_{NAT} + p_{RSC}$$

p_{PUA} are the Priority Use Areas for Biodiversity that reflect the existing marine protected areas in the region (see Figure 4a) three types of marine protected areas defined in EIONET (Agnesi *et al.*, 2020) and p_{HPA} are the High Potential Areas for Biodiversity, and reflect the maximum extent of possible future marine protected areas development according to an earlier version of the POEM version of the year 2022, prior to the approved POEM of February 2023 (*Real Decreto 150/2023*).

2.5. Maritime Spatial Conflict analysis

Cross-sectorial spatial conflicts emerge when there is competition for sea space and when potential new sectors pose novel sea space demands. In order to analyse the interaction of human activities we apply a Maritime Use Conflict (MUC) Analysis available in the Tools4MSP modelling framework, an MSP-oriented open source geospatial modeling framework (Menegon *et al.*, 2018a) applied across Europe (North Sea – Guşatu *et al.*, 2021; Baltic Sea – Depellegrin *et al.*, 2020; Strait of Sicily-Malta – SIMWESTMED, 2018). The modelling framework uses a MUC tool based on the methodology provided by COEXIST (Gramolini *et al.*, 2010) and has the purpose to locate current sea space conflicts and potential future sea space conflicts emerging from potential OWE development and HPA for biodiversity and aquaculture development. The analysis of sectoral conflicts is an important component when drafting or supporting maritime spatial plans (BALTICScope, 2017; SPro, 2018) and subject of diverse geospatial applications across European seas (Coccoli *et al.*, 2018; Menegon *et al.*, 2018b; Pataki & Kitsiou, 2022) and around the globe (Hou *et al.*, 2022; Roy *et al.*, 2022; Socrate & Verón, 2022). Current cases of application focus on geographic scales of regional, national or seabasin level. The MUC is a fully novel application for the study area. It uses an automated procedure to rasterize all input human activities at 1 km x 1km cell resolution and then categorizes the activities according to five traits: vertical, spatial (horizontal), temporal scale, mobility and location. A three-fold system of rules is used to determine the conflict score using pairwise maritime use vs. use relation. A definition of attributes and rules for MUC application are available in the Table 2.

Table 1. Regional MSP geodatabase: Overview of multi-sectoral geospatial data resources collected for the study area. Note: C – Current uses and F – Future uses. Annex 2 in Depellegrin and Martí Llambrich (2024) provides a visualization of the geodatabase.

Human activity	Status	Description	Source
PUA			
Shipping corridors	C	[*trips/cell*] The dataset uses AIS data from the year 2021 including different shipping types of shipping activities Tanker, Cargo, Sailing, Passenger	EMODNet Geoviewer, 2023
Commercial Fishery	C	[*hours/cell*] Hours of fishing by different fishing vessels (Trawling Tuna pursue seines, set_gillnets, pole_and_line, drifting long lines, dredge fishing).	GFW, 2021
Aquaculture	C	[*presence/absence*] Finfish and active mollusc aquaculture sites.	EMODNet Geoviewer, 2023; Gencat, 2022b
Marinas	C	[*number of berths*] 54 marinas of Catalonia including berth numbers.	PdG, 2023
Underwater Cultural Heritage	C	[*presence/absence*] 10 shipwrecks within 60 meter depth accessible for recreational scuba diving	PADI, 2023
Oil and Gas (wells, licensing sites oil&gas platforms)	C	[*presence/absence*] Casablanca Oil Platform, exploration wells and active hydrocarbon exploration areas. The Oil Platform and the wells were prepared for the analysis by applying a safety buffer of 500 meters	EMODNet Geoviewer, 2023; UNCLOS, 1982
Cables & Pipelines	C	[*presence/absence*] Includes actual routes of telecommunication cables. The dataset was prepared by applying a safety buffer of 500m. The oil and gas pipeline connects the Casablanca platform to Tarragona port. A safety buffer of 500 meters was applied.	AAPG-Explorer, 2019; CNMC, 2022; EMODNet Geoviewer, 2023; UNCLOS, 1982; UNCLOS, 1982
Ports	C	[*presence/absence*] 13 regional industrial ports.	EMODNet Geoviewer, 2023
Ports areas	C	[*presence/absence*] 2 anchoring areas in front of Barcelona and Tarragona port.	GFW, 2023
Desalination	C	[*presence/absence*] Desalination plants located in coastal municiaplities only.	EMODNet Geoviewer, 2023
Discharge points	C	[*presence/absence*] Waste water discharge points	EMODNet Geoviewer, 2023
PUA - Nature protection	C	[*presence/absence*] These areas comprise the protected marine spaces, including the Nature 2000 Network, subject to both national and regional management. The regulation of uses and activities within these areas is done by the management body responsible for that protected space, using the relevant space management tool.	Protected Planet, 2023
Aggregates extraction	F	[*presence/absence*] The areas identified in this category contain strategic sand deposits, extraction of which may be necessary for coastal protection measures, including combating climate change	POEM, 2021
National defence	C	[*presence/absence*] The areas identified with this category comprise the areas used for National Defence activities in amphibious, underwater and surface military exercises.	EMODNet Geoviewer, 2023
High Potential Areas (HPA)¹			

HPA

Human activity	Status	Description	Source
Offshore Wind Energy (OWE)	F	[*presence/absence*] Areas for possible development of infrastructure for the commercial exploitation of offshore wind energy. Also hybrid renewable energy technologies can be considered. We use the polygon proposed by BlueFloat (2021) for the Tramuntana project. This includes a submarine corridor (sea-land interconnection with OWE) The dataset was prepared by applying a safety buffer of 500m. The possible landing station is also included.	BlueFloat, 2021; EMODNet Geoviewer, 2023; POEM, 2021
Biodiversity	F	[*presence/absence*] Areas with high-potential for benthic habitats, high-value areas for birds and cetaceans, high-value areas for species of community interest and high-value areas for cetaceans.	POEM, 2021
Aquaculture	F	[*presence/absence*] Areas for developing new aquaculture facilities. They comprise those areas provided by the regional authorities, through JACUMAR, in the Proposal for spatial planning of aquaculture. Within the HPA zones of aquaculture development we apply a 5 km buffer from ports to define potential areas for development.	POEM, 2021

The following algorithm was applied to the study area as follows (Menegon *et al.*, 2018b):

$$MUC = \sum_{i=1}^{l} \sum_{j=i+1}^{l} c_{i,j}\, p(U_i)\, p(U_j)$$

- *c = potential conflict score between use i and j*

- *p(Ui) = presence (1) or absence (0) of the i-th human use in the raster cell (1 km x 1 km)*

- *p(Uj) = presence (1) or absence (0) of the j-th human use in the raster cell (1 km x 1km)*

In order to detect conflict shift areas, referring to sea areas having a net increment of spatial conflicts we define a MUC_{Shift} as the difference among the conflict of current uses (MUC_C) and future uses (MUC_F) as $MUC_{Shift} = MUC_C - MUC_F$. A categorization of current and future uses is provided in Table 1.

2.5. Stressor propagation among current and future uses

To investigate the spatial behaviour of cumulative environmental pressures exerted by existing and future human activities, we perform an exploratory analysis on how the intensity and spatial distribution of stressors shifts with future human activities in the study area could change. For this purpose, we apply a novel QGIS Plugin named *StressorGenerator* that enables the application of an additive multi-stressor propagation model. The model is semi-automated, because final aggregation of the generated stressor rasters for present and future maritime activities is performed by the user through GIS software (e.g. ArcGIS raster calculator) and R-programming language for graphical visualization of results (R Core Team, 2022). Figure 3 provides an overview of the Graphical-User-Interface of the *StressorGenerator* and the steps to setup a model run: 1) the geospatial layers of maritime activities (in line, point or polygon geometry) are prepared for a study area by converting each layer into a single or multi-point feature and are uploaded in shapefile format; 2) a stressor database in excel table (*xlsx* format) is developed defining the type of pressure exerted. Currently 11 stressors were adapted from the European Environment Information and Observation Network (EIONET - Korpinen *et al.*, 2019). The propagation of stressors is isotropic using a distance range from *1 km*-local (e.g. seabed disturbance, physical loss of seabed, etc…) stressor to *30 km*-long range stressor (e.g. underwater noise or change of hydrodynamic regime) by different maritime activities. In absence of a dedicated underwater noise propagation model and hydrodynamic model to represent for instance wind wake, the isotropic propagation of the *StressorGenerator* above 30 km is considered too uncertain. The advantage, of the use of EIONET stressor categories is that they were specifically standardized for each European seabasin and therefore enable a comparative use across different marine biogeographic areas; 3) define a common projection for the shapefiles (EPSG-3035); 4) define cell resolution (1 km x 1km); 5) create a raster of the summed stressors for each human activity (resolution 1 km^2) and finally 6) define path to store results in an output folder. The stressor model is climate

change aware by incorporating the thermal sea water stress as Mediterranean averaged sea-surface-temperature 99th percentile extremes for the period 1987-2019 (32 years) retrieved from Copernicus Marine Service (CMEMS, 2023). Also, to address eutrophication phenomena we apply a *Chlorophyll-a* anomaly for the years 2006-2021 using Copernicus Climate Service (CCS, 2023).

The equations below describe the additive nature of the stressor propagation model applied within the *StressorGenerator* for current uses ($S^c_{additive}$), future uses ($S^F_{additive}$) and current + future uses*:*

$$S^c_{additive} = \sum_{k=0}^{n} S_{U_C} \qquad \text{(stressors for current uses),}$$

$$S^F_{additive} = \sum_{k=0}^{n} S_{U_F} \qquad \text{(stressors for future uses)}$$

and

$$S_{additive} = S^c_{additive} + S^F_{additive} \qquad \text{(summed stressors)}$$

Whereas S_{U_C} are the stressors exerted by *n* current activities and S_{U_F} by *n* future uses as defined in Table 1. The model transforms all shapefiles into rasters and then performs a normalized inverse Euclidean distance to produce standardized stressor propagation rasters of value (1-0). The equation for the standardized Euclidean distance for current or future stressors is defined as follows: $D_{stress} = 1 - ((S_{U_{C/F}} - S_{U_{C/F}}min) / (S_{U_{C/F}}max - S_{U_{C/F}}min))) * (S_{U_{C/F}}max - S_{U_{C/F}}min) + S_{U_{C/F}}min$.

PUA for biodiversity (including Natura2000 MPA network; national/regional designated areas and Regional Sea Convention) and HPA for biodiversity are omitted from this model because they are considered as stressor receiving sea areas. In order to detect stressor shifts, referring to sea areas having a net increment of stressors we define a S_{Shift} as the difference among the current pressures (p_{U_C}) and future use pressures (p_{U_F}), as $S_{Shift} = S^c_{additive} - S^F_{additive}$.

3. Results
3.1. Zoning patterns and sea space demands of current and future sea uses

Figure 4a presents the multi-sectoral distribution of current maritime activities in Catalonia's regional sea. A fundamental zoning distinction can be noticed: 1) The southern subregion of the regional sea in front of Tarragona Province is highly crowded in its coastal and offshore areas due to the presence of military areas, protected areas, oil and gas sector (Casablanca Platform, pipeline, wells and active licences), finfish and mollusc aquaculture activities (Ebro Delta), intense shipping traffic and port activities. In comparison the northern subregion of the regional sea in front of the Province of Girona, the oil and gas sector is almost absent, there are numerous underwater cultural heritage sites. 2) In the Inland Waters of the Gulf of Sant Jordi and Gulf of Roses intense fishing activities inside their protected areas can be noticed, presence of marinas (about 9170 berths in the Gulf of Roses and 2558 berths in the Gulf of Sant Jordi respectively) and aquaculture facilities. 3) High
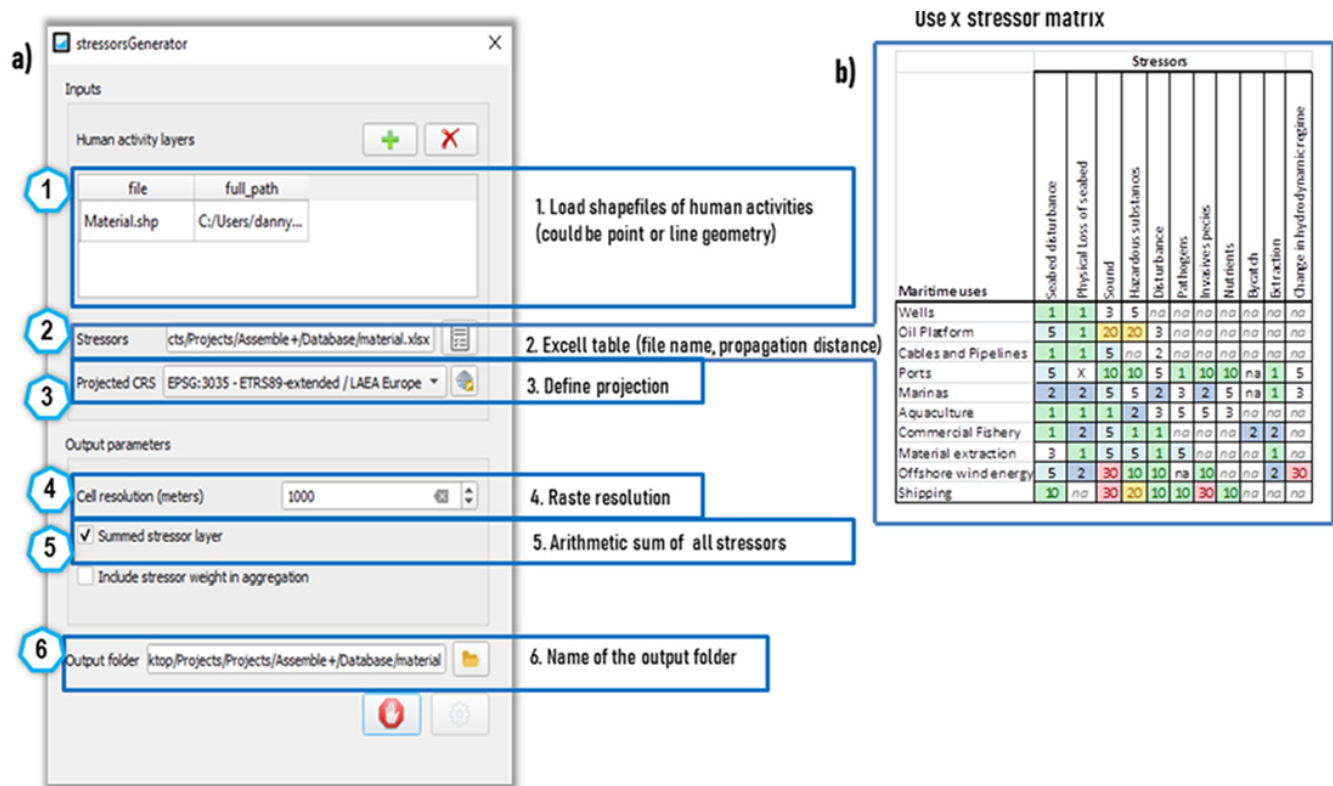
Figure 3. a) Graphical-User-Interface, description and steps for setup of the QGIS *StressorGenerator* plugin applied for the study area. **b**) Maritime use – stressor matrix with respective propagation distances in km applied in this study.

Table 2. Attributes for each maritime use and three-rules overview for the MUC.

Attributes	Rational
Spatial	Describes the spatial characteristics of the maritime use
Temporal	Describes the temporal demand of the maritime use
Vertical	Describes the physical characteristics of the maritime use in the water column
Mobility	Describes the behavior of the maritime use in the sea space
Rules	
Verticality	if vertical domain of activity 1 is different from vertical domain of activity 2 and no one of them interests the whole water column then conflict score is equal to 0;
Mobility	If both activities are "mobile" then conflict score is equal to the minimum of temporal domain plus the minimum of spatial domain.
Rule 1 & 2 combined	if Rule1 and Rule2 cannot be applied then the conflict score is equal to the maximum value of temporal domain plus the maximum value of spatial domain.
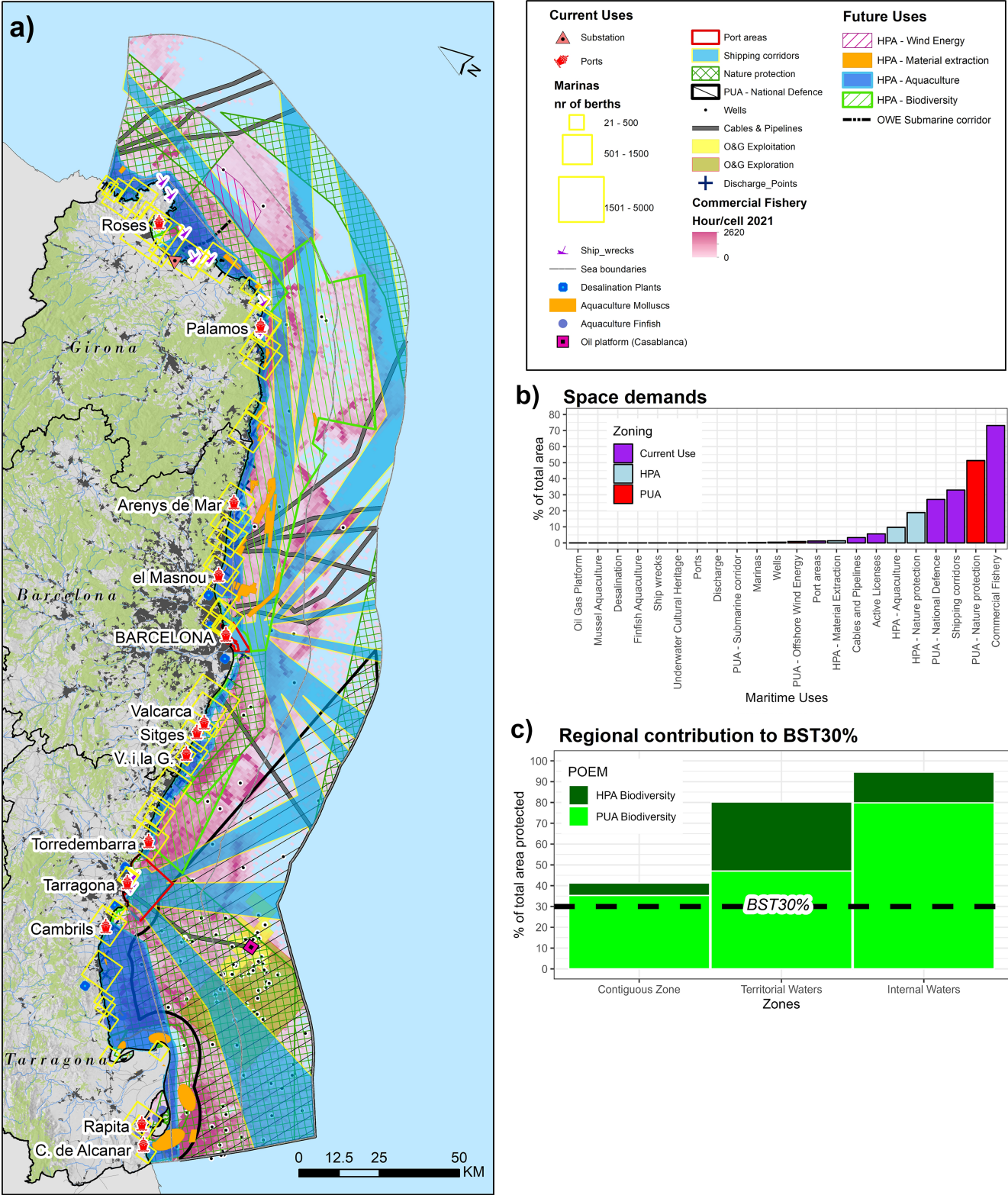
Figure 4. a) Spatial distribution of maritime activities with according spatial distribution of current uses and PUA/HPA; **b**) space demands expressed in % of total study area and **c**) barplot, developed in ggplot2 (R Core Team, 2022) representing regional contribution to 30% sea protection target defined by the Biodiversity Strategy (BST30%) by the three subregion (Internal Waters; Territorial Waters and Contiguous Zone)

intensity patterns of commercial fishery concentrate also inside protected areas in the Territorial Waters, and especially in three SPA Birds sites, namely *Espacio marino del Delta de l'Ebre-Illes Columbretes*; *Costes del Garraf/Espacio marino del Baix Llobregat-Garraf* and *Espacio marino de l'Empordà*.

Figure 4b describes the space demand in % to the total study area. Future maritime activities (HPA - Biodiversity, PUA - offshore wind farm with submarine corridor, PUA - Material Extraction sites and HPA - Aquaculture) total an overall increase in sea space demand of 31%. It is worth noticing that the increase of anthropogenic activities in coastal areas and in offshore areas is due to the development of new material extraction sites and the potential development of an offshore wind energy site and the extension of areas of conservation as HPA biodiversity sites.

Commercial fishery covers the most significant amount of space with 73% followed by marine protected areas with 51% respectively[1]. Shipping corridors cover about 33%, but can be considered to occupy more extensive space when considering smaller intensity shipping corridors especially in coastal areas. Another important sea use is military areas (27%) in the southern subregion of the study area in front of the Ebro Delta. Future maritime activities include a +19% increase of HPA for biodiversity. The net gain of potential regional area-based management features compared to the existing sites is 37% with a resulting potential of 70% of total regional sea space protected in Catalonia. Other future uses are HPA for aquaculture development (+10% of new sea space required), material extraction (+1.4% of new sea space required). Comparably, only 1% of sea space would be required by the HPA for OWE (0.9%) including the interconnector sub-corridor (0.1%). Also worth noting is that 13 maritime activities have sea space demands ≤1% (see Figure 4b).

3.2. Marine nature protection targets
In total 51% of the study area is protected, meaning that the BS2030 protection target of 30% is potentially met for this segment of the study area (see Figure 4c). In particular, in the Catalan sea space 80% of Internal Waters, 47% of Territorial Waters and 35% of the Contiguous Zone are marine protected areas. While it is not the scope of this study to discuss the suitability of the HPA - Biodiversity sites as potential protected areas, their integration into some form of area-based management regime would result into about 95% (+15% net gain) protection of Internal Waters, about 80% (+33% net gain) protection of Territorial Waters and about 41% (+6% net gain) protection of the Contiguous Zone. This would make Catalonia one of the most protected regional sea areas in the Mediterranean and Europe. However, where the challenges rely is to include in the 30% target a 10% of strictly protected area. There are three strictly protected areas in the Costa Brava (*Les Illes Medes; Les Llaunes and Cap de Norfeu*; Protected Planet, 2023). While they are classified as marine protected areas they are spatially land-based strictly protected areas so that the

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[1] depending on calculation method this could result into 44% (communication from former reviewer).

actual contribution to the 10% target of protection of sea space can be considered negligible.

3.3. Overview of regional spatial conflicts
About 56% of the sea space has some degree of spatial conflict. Figure 5a identifies the maritime spatial conflicts of current uses of the sea space. The highest MUC index (score ~1) are located in front of the Ebro river outlet due to the presence of protected areas in combination with intense commercial fishing activities, the presence of the Oil and Gas sector (Casablanca Platform, wells and exploration/exploitation fields), the presence of military areas and shipping corridors departing from the port of Tarragona. On overall, based on the conflict matrix, highest spatial conflict occurs among commercial fishery sector *vs* marine protected areas (score 153), commercial fishery *vs* military areas (score 94) and commercial fishery *vs* shipping (score 71). Other noticeable spatial conflicts occur among military areas *vs* protected areas (score 108) and military areas *vs* shipping (score 59).

The integration of future uses will increase spatial conflicts by 18% in the study area. Figure 5b highlights the emerging future spatial conflicts with presence of future human activities of the sea and conflict shift areas, where net gain of conflict score will occur. Conflicts increase in Inland Waters due substantial potential for HPA - Aquaculture development in the Gulf de Sant Jordi and Gulf of Roses and in coastal areas from Barcelona-Vilanova i la Geltru and from Barcelona-Palamós due to the potential increase of aquaculture development and HPA - material extraction sites. The conflict matrix including future uses shows that, HPA – Aquaculture sites can increase the spatial conflict with commercial fishery and shipping. HPA – Biodiversity sites increase the spatial conflict with commercial fishery, shipping, cables and pipelines and coastal tourism. HPA - Material extraction with aquaculture and protected areas. Surprisingly, the spatial conflicts in the Territorial Waters due to the potential development HPA - OWE remain negligible. This is because compared to other regional sea areas the area has comparably low intensity maritime activities.

3.4. Anthropogenic stressors in the Catalan sea space
The Figure 6 presents current anthropogenic stressors and stressor shifts due to future uses. According to model results the sea areas of highest cumulative stressors are located in front of Barcelona, Tarragona and Palamós ports, in the Internal Waters (Gulf of Roses and Sant Jordi) and the entrance to the industrial port, the southern subregion of the Ebro Delta, Gulf of Roses. In the Territorial Waters high stressor areas are caused by intense commercial fishing activities located in front of Cap de Creus, sea areas off Palamós and southern Ebro Delta. In the contiguous zone, stressors are generated by offshore activities, shipping corridors and by the Oil & Gas Platform in front of the Ebro Delta.

The Stressor shift areas in Figure 6b show that cumulative stressors emerging from future sea uses increase in coastal waters, especially in the Barcelona Province and southern Ebro River Delta and Territorial Waters of Girona Province.

a)

b)

Conflict shift

Current Uses
MUC Score
1
0
— Sea boundaries

Curr + Fut
MUC Score
1
0
— Sea boundaries

Current Uses

| Current Uses	Aquaculture	Discharge points	Ports	Military areas	Port areas	Protected areas (PUA)	O&G Platform	O&G Exploration/Extraction	Cables & Pipelines	Shipping	Marinas	Commercial Fishery	UCH
Aquaculture													
Discharge points	0.1												
Ports	0	0											
Military areas	0	0	0										
Port areas	0	0	0	0.6									
Protected areas (PUA)	0.8	0.6	0.1	108	7.7								
O&G Platform	0	0	0	4.3	0	3.4							
O&G Exploration/Extraction	0	0	0	34	0	40	1.9						
Cables & Pipelines	0	0	0	3.5	0.7	9.3	0	0.5					
Shipping	0.2	0	0.1	59	4.7	96	1	5.6	0				
Marinas	0	0.1	0.3	0	0	0.9	0	0	0	0.5			
Commercial Fishery	0.5	0.7	0.1	94	7.8	153	3	15	15	71	0.3		
UCH	0	0	0	0	0.1	0.1	0	0	0	0	0	0.2	

C+F Uses

Conflict Shift

C+F Uses	Aquaculture + HPA	Discharge points	Ports	Military areas	Port areas	Protected areas (PUA+HPA)	PUA -OWE	O&G Platform	O&G Exploration/Extraction	HPA - Material Extraction	Cables & Pipelines	Shipping	Marinas	Commercial Fishery	UCH
Aquaculture + HPA															
Discharge points	1														
Ports	0	0													
Military areas	10	0	0												
Port areas	1	0	0	0.6											
Protected areas (PUA+HPA)	114	1.1	0.4	108	8										
PUA -OWE	0	0	0	0	0	0									
OGEXTR	0	0	0	4.3	0	3.8	0								
OGRES	0	0	0	34	0	40	0	1.9							
HPA - Material Extraction	13	0	0	0	0	26	0	0	0						
Cables & Pipelines	3	0	0	3.5	0.7	17	0	0	0.5	2					
Shipping	41	0	0	59	4.7	192	0	1	5.6	12	0				
Marinas	2	0	0	0	0	2	0	0	0	0	0	0.5			
Commercial Fishery	71	0.7	0	94	8	224	3	3	15	17	16	71	0.3		
UCH	0.4	0	0	0.1	0.1	0	0	0	0.1	0	0	0	0.2		

Figure 5. a) MUC of current uses; **b**) MUC of current uses and future uses including PUA/HPA zoning; **c**) conflict matrix for current uses **d**) conflict matrix including current and future uses including conflict shift (blue cells), where a net increase of conflict score is expected.
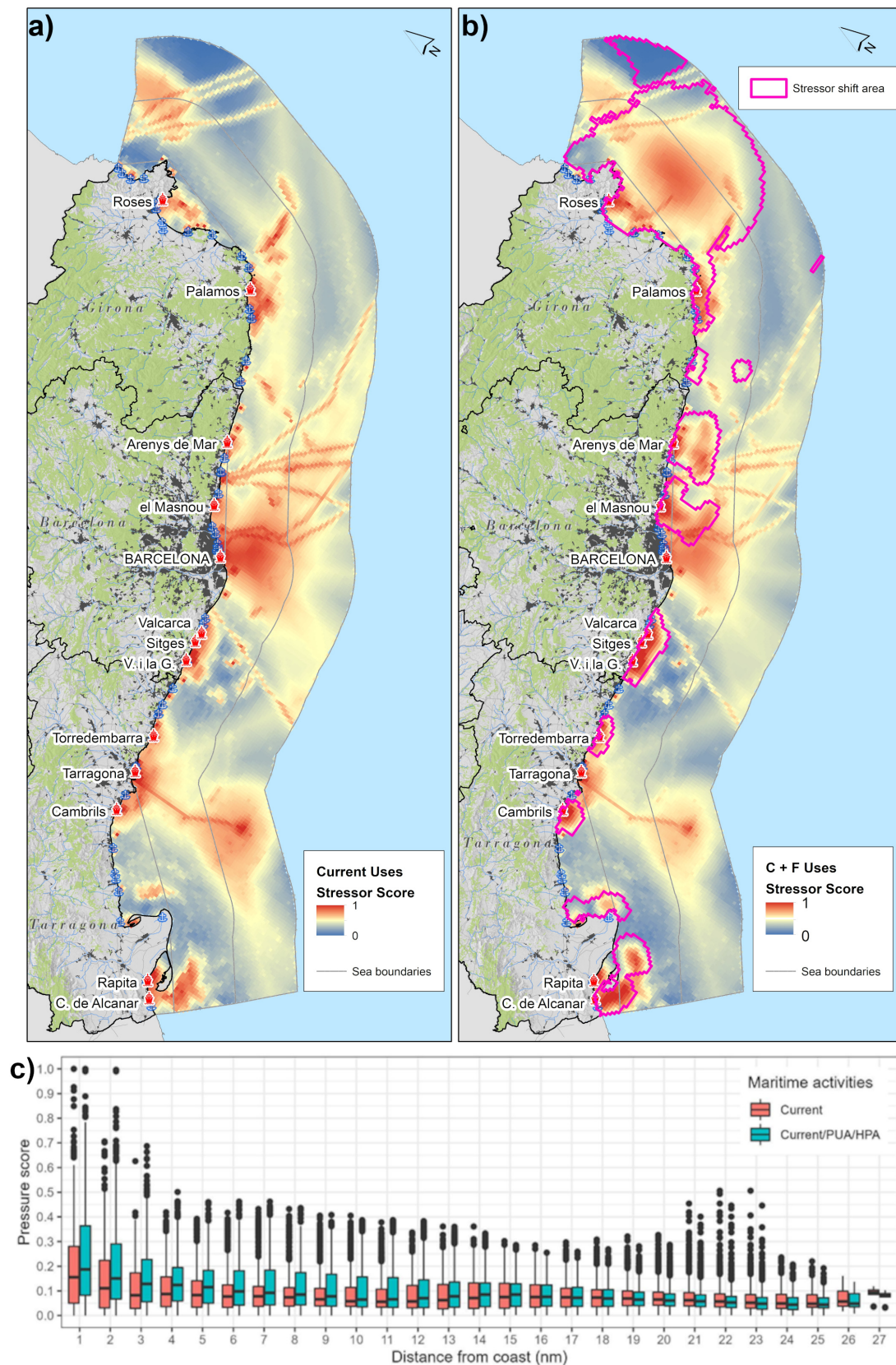
Figure 6. a) Stressors exerted by current uses; **b**) additive stressors generated by current and future uses with highlighted areas of stressor shifts; **c**) Boxplots comparing stressor shifts in current *vs* current and future sea uses. Note: dots refer to maximum and minimum outliers.

Figure 6c describes the current and future stressor shifts as distance gradient from coastline in nautical miles (nm). The 1–4 nm area is subjected to approx. 30% of the stressor intensity. From Figure 6 (right) it can be noticed that the sea areas subjected to stressor shift are either localized at subregion scale, while other sea areas are affected by stressor shift in multiple subregions, such as for instance in the Gulf of Rosas and the adjacent Territorial Waters.

4. Discussion
The research presents a database and state-of-the-art analytical techniques to support decision-making in MSP exemplified for the coastal region of Catalonia. An exploratory analysis resulted to be particularly useful in this context, because it informs decision-makers about the pre-existing sectoral conditions and forecasts emerging trends from future maritime activities based on the PUA/HPA zoning mechanisms defined within the national POEM. The presented models can be deployed at different spatial scales (from national to seabasin level). In the following section we formulate five challenges emerging from the analysis that reflect the horizontal multi-sectoral objectives defined in the Spanish Maritime Spatial plan. Challenge 1 & 2 addresses co-existence among existing maritime activities and emerging ones (HMO-2); challenge 3 discusses minimization of spatial conflicts (HMO-1); challenge 4 discusses the need for coordination among administrations in coastal-marine interface and challenge 5 discusses the need for further scientific research, by highlighting data gaps and model limitations.

4.1. Challenge 1: Marine protection beyond percentage
Marine protection and enforcement of conservation objectives remains a main challenge in the Western Mediterranean and in the study area (Company *et al.*, 2012; García *et al.*, 2021; Perry *et al.*, 2022). Our analysis shows spatial conflict of protected areas with various maritime activities in the region, especially commercial fishery, coastal tourism (in the form of marinas), shipping and oil and gas extraction and exploration (Figure 5). Recent scientific literature and Mediterranean initiatives evidence that marine protected areas suffer from increased anthropogenic pressures from existing maritime activities in the study area especially from high-risk[2] commercial fishing activities (e.g. trawling) in protected areas of the Western Mediterranean (Mazaris *et al.*, 2019; MedReAct, 2022; Med Sea Alliance, 2023; Muñoz *et al.*, 2018; Perry *et al.*, 2022), in particular in SIC - *Sistema de cañones submarinos occidentales del Golfo de León* (García *et al.*, 2021), in submarine ecological hotspots such as *La Fonera Canyon* on the Catalan margin of the NW Mediterranean (Martín *et al.*, 2014; Paradis *et al.*, 2017). Our results (see map Annex 3 in Depellegrin & Martí Llambrich, 2024) indicate that about 56% of the fishing efforts (including trawling) in 2021 in the regional sea of Catalonia occur inside the actual marine protected areas (PUA - Biodiversity) and another 26% could potentially occur

in potential future HPA – Biodiversity sites. In addition, environmental pressures caused by coastal and nautical tourism are posing continuous threats to coastal areas and vulnerable habitats (Gonzalez *et al.*, 2020). Significant is that about 62% (20,037 berths out of 31,000 total marina berths; PdG, 2023) are located inside or in front of marine protected areas: *i*) 57% (11,434 berths) in marinas of Girona Province; *ii*) 19% (about 3,805 berths) in marinas of Barcelona Province and *iii*) 24% (about 4,798 berths) in Tarragona Province (see map of Annex 4 in Depellegrin & Martí Llambrich, 2024). In late December 2022 the Spanish Government approved the national strategic plan for natural heritage and biodiversity (Miteco, 2022a). A key action point of the plan is the establishment of 8 new marine Natura2000 sites in the Spanish sea space within 2023–24 in support of the EU Biodiversity Strategy 2030 requirement to protect 30% of the sea areas (Miteco, 2022a; see map Annex 5 in Depellegrin & Martí Llambrich, 2024). A key aspect in integrating new MPA is a comprehensive understanding of the MSP conditions and maritime activities occurring in the proximity of candidate MPA areas (Grorud-Colvert *et al.*, 2021).

Our results provide practical insights that can support new marine protected areas selection:

1) It is of pivotal importance to reach the 10% target of strictly protected areas ideally in the 1–4 nm conflict zone (Figure 5b) that can be *de facto* be no-go-area. This would relieve ecological resources from current spatial conflicts and anthropogenic stressors highlighted in this study.

2) Evaluate sea areas allocated as future HPA - Biodiversity areas settled in the POEM as candidate areas of the Natura2000 for regional proposals.

3) Align the candidate marine Natura2000 network selection with the Spanish Green Infrastructure Strategy (Article 15.3 of Law 33/2015; Biodiversity-Europe, 2023) by considering offshore areas like submarine canyon protection due to their high ecological functions and connectivity role (Fernandez-Arcaya *et al.*, 2017; Paradis *et al.*, 2017).

4) Couple the practical insights of the study based on data-driven approach and geospatial techniques with participatory MPA co-design process (Horta e Costa *et al.*, 2022) and the analysis of anthropogenic effects as a function of different levels of protection of existing MPAs and future Biodiversity protection sites.

4.2. Challenge 2: Offshore Wind Energy, a new regional sea space demand
In European seas, the development of OWE is a strategic cornerstone of the transition towards a sustainable Blue Economy (EC, 2020; EC, 2021). In 2022, The Spanish Ministry of Ecological Transition has defined a national roadmap for offshore wind and marine energy development (Miteco, 2022b), setting the pathway for an industrial and technological transition using ocean renewable energy development as a vector of innovation. The presented study provides a set of valuable insights

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[2] According to Perry *et al.* (2022) high-risk refers to fishing gear known to pose potential risk to habitats, e.g. trawling; "High-risk" is the term used by the "EU Action Plan: Protecting and restoring marine ecosystems for sustainable and resilient fisheries" (COM(2023) 102 final; https://oceans-and-fisheries.ec.europa.eu/system/files/2023-02/COM-2023-102_en.pdf)

in relation to the potential OWE development site worth to be highlighted:

1) The potential OWE site in front of the Gulf of Roses has low to negligible (score 0 to 0.3; Figure 6d) multi-sectoral spatial conflicts. AIS-tracked maritime transport activities have relatively low route intensity compared to intensive shipping activities in other areas from Barcelona and Tarragona port to Balearic Islands, Morocco and Italy. Fishery displacement that is one of the most severe socio-economic impacts of potential OWE farm development (Gill *et al.*, 2020; Marine Scotland, 2022; MSP-EC, 2021), show that the fishing effort in area occupied by the farm stays relatively low, because part of OWE site is partially coinciding with a fishery closed-area (CSIC, 2022).

2) The MUC analysis (Figure 5d) evidences that potential OWE site is localized outside three types of commonly constrained areas: military areas (Abramic *et al.*, 2021; Díaz *et al.*, 2019; Sourianos *et al.*, 2017), marine protected areas (POEM, 2021) and high intensity shipping lanes (Argin *et al.*, 2019; Peters *et al.*, 2020; Virtanen *et al.*, 2022).

3) According to the Global Wind Energy Council dataset (GWEC, 2021), about 30% (5497 km^2) of the study area has a potential suitable sea space for floating OWE development (see Annex 6 OWE potential *versus* constrains map in Depellegrin & Martí Llambrich, 2024). This suitable space is distributed over the northern subregion (Gulf of Roses) and the southern subregion (Tarragona – Ebro river outlet). The collected regional MSP data and model results show that the Tarragona-Ebro river outlet subregion is a highly constrained area, because *i*) it is located inside the SPA- *Espacio marino del Delta de l'Ebre-Illes Columbretes*, *ii*) it is an area for national defence, *iii*) it is a sea area of high intensity maritime traffic (including tankers cargos and ferries) and of intense fishery activity (see MUC score Figure 5a).

4.3. Challenge 3: Crowded coastal areas

Model results suggest that zoning types defined within PUA and the HPA are likely to increase potential spatial conflicts and pressure to coastal areas especially in the coastal areas from 1–4 nautical miles (Figure 6c). While the scope of the study is not to address the effects of the stressors exerted by the multiple maritime activities on ecological resources, it is intuitive that the additive nature of the stressor model will localize highest ecological impacts as a function of the geographic co-occurrence of the maritime activities, eutrophication phenomena and thermal stress from climate change. As a consequence, an emerging solution to tackle current and future sea space competition and alleviate coastal areas from the additive anthropogenic stressors in the 1–4 nm zone, is for example a regional-scale analysis of opportunities for ocean multi-use (Schupp *et al.*, 2019). Examples of formal integration of multi-use or co-location solutions are included into very recent marine governance frameworks, such as for example the Portuguese

Maritime Spatial Plan (Calado *et al.*, 2024; PSOEM, 2023), pilot MSP studies such as for Emilia-Romagna (Barbanti & Perini, 2019), national scientific research projects (ACUFLOT, 2022) and other studies (EU-MSP, 2023; Weiss *et al.*, 2018). For Catalonia, regional multi-use planning measures would be effective at stimulating a move of sea space use outside the 4 nautical miles coastal area by current sea uses (coastal tourism, fishery and aquaculture). Positive regional multi-use examples combining coastal tourism with tuna aquaculture exist in L'Ametlla del Mar in Tarragona Province (TripKay, 2023), while ongoing research for addressing the sustainability of OWE potentials with aquaculture development were addressed in the Aquawind project (https://aquawind.eu/) in the Canary Islands. In highly crowded regions, such as inland waters, the analysis of spatial interactions for certain indicators may be overly simplistic. A resolution of 1 square km might prove insufficient for densely populated coastal areas, where activities often occur very precisely and at finer scales. In such scenarios, an effective enhancement could involve adopting a multi-resolution approach or considering a more adaptable spatial interaction model. This could entail not only accounting for overlapping uses but also incorporating buffering techniques or accounting for remote interactions. This may also entail the need to collect more detailed and higher resolution data for those areas at sub-regional level.

4.4. Challenge 4: Multi-level governance

In MSP the development of multi-level governance mechanisms of continuous coordination and cooperation among administrations at different territorial scales is essential when addressing ocean sustainability goals. For instance, according to the Spanish Constitution (art. 149) central governments have numerous competences on the sea (such as on offshore energy, national navigation, fishing beyond internal waters, ports of general interest –such as Barcelona and Tarragona ports, according to Annex I.9 of the State Ports and Merchant Navy Law–, defense and Armed Forces), regional governments have responsibilities on coastal and nearshore maritime activities (fishing in internal waters, aquaculture, coastal planning and management, recreational fishing, marinas, tourism, leisure and maritime-coastal sports; art. 148 Spanish Constitution; arts 119&149 of the Statute of Autonomy of Catalonia). Given the complexity of interactions of these sectors, the strengthening of participatory processes and methods with stakeholders at different territorial levels remains pivotal for future iterations of the POEM. Of particular importance are areas of Land-Sea Interaction (LSI). Coastal-maritime areas are highlighted as crowded coastal areas where also potential different administrative structures and responsibilities overlap. For instance regional coastal management plans with the maritime-terrestrial public domain. Above all, a synergic coordination of maritime-coastal governance gains prominence in the light of regional climate change phenomena. Along the national and regional Climate Change Adaptation Strategies (ESCACC, 2021; Miteco, 2020) an increasing segment of literature pertinent to the Catalan sea areas project intensifying climate-induced threats to the Catalan sea areas, such as 1) reduced habitat availability for pelagic fish due to the synergic effect of climate change and fishery activities (Ouled-Cheikh *et al.*, 2022); 2) increased high intensity ocean warming events also called Marine Heat

Waves (Hobday *et al.*, 2016) that affect marine biological processes with severe consequences on regional coastal tourism (Juza *et al.*, 2022) and finfish aquaculture production (López Mengual *et al.*, 2021) and 3) sea level rise-induced coastal erosion will affect 70% of Catalonia's beaches in the coming decades (Cads, 2017). The phenomenon is associated with economic damages to the regional coastal tourism sector estimated at 2.2 billion € (20% of the regional GDP) by the end of the century (Garola *et al.*, 2022; Jiménez *et al.*, 2017). Our MSP database is climate change-aware, meaning that incorporates a 32 year sea surface temperature anomaly dataset (CMEMS, 2023), but given the severity and socio-economic importance of the regional coastal environment further datasets should be incorporated to address and project climate change impacts for regional blue economy activities.

4.5. Challenge 5: Regional MSP knowledge base and gaps

In terms of sectoral datasets, it is essential to retrieve data that can address spatio-temporal mobility patterns of the tourism sector at a regionally relevant planning scale. In Catalonia this sector plays a prominent role, however datasets are missing that are capable of better interpreting its interaction with other maritime activities and marine protected areas. This gap could be tackled through the use of high resolution remote sensing techniques to detect small boat nautical tourism mobility (González *et al.*, 2020) and an extension of regional surveys of mooring activities.

Regional datasets of fishing activities by gear type from regional authorities can further complement the datasets (ICATMAR, 2021) Also datasets on artisanal fishery, which is an important Blue Economy activity for regional coastal communities (Carbonell, 2020) needs to be further integrated into the analysis. Both datasets would provide additional means for the analysis of spatial conflicts and stressor analysis.

In the study area, the aquaculture development shows to be the Blue Economy sector to have the highest space demands in the Inland waters of the Gulf of San Jordi, the Gulf of Roses and in southern and northern coastal waters of Barcelona (Figure 4). Given the increasing importance of aquaculture in the Mediterranean (UfM, 2021) and its potential regional space demands in Catalonia, there is the need to identify MSP-based techniques that enable to better define suitable sites taking into consideration spatial, ecological and socio-economic conditions (Graham *et al.*, 2020; Porporato *et al.*, 2020; Venier *et al.*, 2021) and define planning strategies that can address the regional ocean multi-use potential.

A further knowledge gap is the absence of regional data derived from local spatial knowledge from maritime sectors. This include socio-ecological knowledge on marine ecosystem services, spawning grounds, fishery closure areas, coastal landscape features and information on regional diving hot-spots, their frequency of visitation or information on recreational mooring sites. This would produce knowledge that could better characterize the regional sea space and act as enabler for more informed spatial planning, stimulate stakeholder participation and increase acceptance of Maritime Spatial Plans (Pennino *et al.*, 2021; Said & Trouillet, 2020). The regional scope of the study makes it particularly suitable to extend the developed database with the mentioned socio-ecological knowledge.

The stressor propagation analysis developed using a QGIS plugin resulted in a promising instrument to address future planning challenges. For instance, the stressor propagation can be coupled with ecological datasets such as EUNIS Habitat maps (EU-Seamap, 2021) and different techniques of marine species suitability models (El-Gabbas *et al.*, 2021; Guşatu *et al.*, 2021; Schickele *et al.*, 2020) in order to perform a risk-based cumulative effect assessment. The *StressorGenerator* can be further complemented with pressure types aligned with MSFD pressures, that offers a more detailed definition of pressures that is commonly used in European cumulative effect assessment studies, such as marine litter, synthetic or non-synthetic compounds, etc… (Casimiro *et al.*, 2021; Korpinen & Andersen, 2016; Menegon *et al.*, 2023). Also pressure specific spatial models should be integrated, such as simulations of wind turbine wake behaviour (e.g. Raghukumar *et al.*, 2022), hydrodynamic models to better take into account riverine inputs and their 3-dimensional dispersion. This is essential considering the presence of the Ebro river Delta in southern subregion of the study area that can be a source of multiple environmental stressors (micro plastics - Simon-Sánchez *et al.*, 2019; pesticides - Peris *et al.*, 2022; and eutrophication - Busch *et al.*, 2016; Garnier *et al.*, 2021). An improvement within the spatial models proposed in the stressor shift model is the use of open source software package OpenDrift (Dagestad *et al.*, 2018) programmed in python. The software enables particle drift modelling in marine environments and can for instance be taken into consideration for different pollutant dispersion as a function of depth, such as oil spills.

5. Conclusion

The presented study is the first MSP-oriented regional study for Catalonia, addressing the interaction of multiple maritime activities on the marine environment and identifying sea areas of highest stress due to current and emerging future space demands. The results of the research can inform national and regional decision making on the current and future maritime spatial settings of the region of Catalonia. The results provided by this study can be transferred to other coastal regions, on a POEM-subdivision scale (e.g. Levantine-Balearic) or even on the entire national sea space. The presented geo-statistical information provides a valuable starting point to create a regional MSP knowledge database for Catalonia. It is structured to mimic POEM's maritime sectors and zoning types PUA/HPA and the maritime sectors identified in the regional Maritime Strategy 2030. Ideally, the presented database and models could feed already existing regional GIS-based platforms (e.g. *visor maritim* of the Generalitat de Cataluña: https://sig.gencat.cat/visors/visor_maritim.html) or contribute to future advancements aiming at increasing the regional knowledge on ocean planning opportunities and challenges.

In terms of data, our study highlighted shortcomings on nautical tourism mobility data, commercial/artisanal fishing and high resolved regional ecological dataset for the marine environment that are essential for future regional cumulative effect assessment. In parallel, shortcomings should be tackled on the development of new methods and framework that can extend the traditional MSP paradigm towards more equitable integration of regional marine ecosystem services studies, transition-based science and socio-economic cost-benefits analysis of Blue Economy sectors. Within the progress of the development of future Maritime Spatial Plans, offshore sea areas requiring shipping corridors re-routing or where displacement risks for coastal tourism activities and commercial fisheries are likely should become integral part of SEA through a i) protocol of analysis, ii) data requirements to address the conflicts/synergies and a iii) portfolio of applicable measures.

Our results show that spatial conflicts and stressors occur independently from the territorial administrative structures and responsibilities in coastal-maritime realms. The research provides the seeds for future updates of regional-national adaptation plans and for more integrated governance processes aimed at achieving common ICZM-MSP goals.

Data availability

Underlying data
The data that support the findings of this study are derived from the following resources available in the public domain:

EMODNet Geoviewer, 2023 (https://emodnet.ec.europa.eu/geoviewer/); Global Fish Watch, 2021 (https://globalfishingwatch.org/); Gencat, 2022a (https://agricultura.gencat.cat/ca/ambits/pesca/proteccio-recursos-litoral/esculls-artificials/llistat-ubicacio/); PdG, 2023 (https://ports.gencat.cat/mapa-i-sistema-portuari-catala/#puntZonaNord); PADI, 2023 (https://www.padi.com/); Protected Planet, 2023 (https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA); POEM, 2021 (https://www.miteco.gob.es/es/costas/temas/proteccion-medio-marino/spanishmsplansummary_tcm30-532936.pdf).

Zenodo: Dataset used in Addressing ocean planning challenges in a highly crowded sea space: a case study for the regional sea of Catalonia (Western Mediterranean), https://doi.org/10.5281/zenodo.10263416 Depellegrin and Martí Llambrich (2023).

Extended data
Zenodo: Supplementary material for the manuscript Depellegrin *et al.*, 2024: Addressing ocean planning challenges in a highly crowded sea space: a case study for the regional sea of Catalonia (Western Mediterranean) https://doi.org/10.5281/zenodo.10540658 (Depellegrin & Martí Llambrich, 2024).

The annex 1 to 6 mentioned in this manuscript can be downloaded as Supplementary Material.

References

AAPG-Explorer: **Casablanca: Spain's Biggest Oil Field**. 2019; accessed 03/01/2023.
Reference Source

Abramic A, Cordero-Penin V, Haroun R: **Environmental impact assessment framework for offshore wind energy developments based on the marine Good Environmental Status.** *Environ Impact Asses Rev.* 2022; **97**: 106862.
Publisher Full Text

Abramic A, García Mendoza A, Haroun R: **Introducing offshore wind energy in the sea space: Canary Islands case study developed under Maritime Spatial Planning principles.** *Renew Sust Energ Rev.* 2021; **145**: 111119.
Publisher Full Text

ACUFLOT: **Interacciones entre la ACUicultura offshore y la energía eólica FLOTante: retos y oportunidades hacia la "transición ecológica" del espacio marítimo español (ACUFLOT)**. 2022; accessed 07/01/2023.
Reference Source

Agnesi S, Annunziatellis A, Chaniotis P, *et al.*: **Spatial Analysis of Marine Protected Area Networks in Europe's Seas III**. ETC/ ICM Technical Report 3/2020: European Topic Centre on Inland, Coastal and Marine waters. 2020; 40.
Reference Source

Argin M, Yerci V, Erdogan N, *et al.*: **Exploring the offshore wind energy potential of Turkey based on multi-criteria site selection.** *Energy Strateg Rev.* 2019; **23**: 33–46.
Publisher Full Text

BALTICScope: **Determining permitted sea uses**. 2017; accessed 03/01/2023.
Reference Source

Barbanti A, Perini L, (eds.): **Fra la terra e il mare: analisi e proposte per la Pianificazione dello Spazio Marittimo in Emilia-Romagna**. 2018.
Publisher Full Text

BE (Blue Economy Report): **The EU Blue Economy Report 2020**. 2020; accessed 07/11/2023.
Reference Source

Biodiversity-Europe: **Green infrastructure**. 2023; accessed 21/01/2023.
Reference Source

BlueFloat: **PROYECTO "PARQUE EÓLICO MARINO FLOTANTE TRAMUNTANA, CATALUÑA"**. Documento Inicial de Proyecto. 2021.

BOE-A-2022-21389: **Resolución de 2 de diciembre de 2022, de la Dirección General de Calidad y Evaluación, por la que se formula declaración ambiental estratégica de los "Planes de ordenación del espacio marítimo"**.
Reference Source

BS (Biodiversity Strategy) 2030.
Reference Source

Burkhard B, Maes J, Potschin-Young M, *et al.*: **Mapping and assessing ecosystem services in the EU - Lessons learned from the ESMERALDA approach of integration.** *One Ecosyst.* 2018; **3**: e29153.
Publisher Full Text

Busch JA, Andree KB, Diogene J, *et al.*: **Toxigenic algae and associated phycotoxins in two coastal embayments in the Ebro Delta (NW Mediterranean).** *Harmful Algae.* 2016; **55**: 191–201.
PubMed Abstract | **Publisher Full Text**

Cads: **Climate Change in Catalonia. Executive Summary of the Third Report on Climate Change on Catalonia.** 2017.
Reference Source

Calado H, Frazão Santos C, Quintela A, *et al.*: **The ups and downs of maritime spatial planning in Portugal.** *Mar Policy.* 2024; **160**: 105984.
Publisher Full Text

Carbonell E: **Entre redes, patrimonio y turismo - Between nets, heritage and tourism: mutaciones de la pesca artesanal en la costa norte de**

Barcelona (Cataluña). *Estud Atacamenos.* 2020; **65**: 3–19.
Reference Source

Casimiro D, Quintela A, Matias J, *et al.*: **Cumulative Impacts and Strategic Environmental Assessment: Literature review.** In *support of Deliverable 3.2 of the SIMAtlantic project (EASME/EMFF/2018/1.2.1.5/SI2.806423)*. 2021; 26.
Reference Source

CCS: **Eutrophication indicators for the Northwest European Shelf and Mediterranean Sea from 2006 up to 2100.** 2023.
Publisher Full Text

CEDEX-INFOMAR: **Visor de Informacion Geografica Marina**. 2022; accessed 04/12/2022.
Reference Source

CMEMS: **Mediterranean Sea Surface Temperature extreme from Reanalysis**. 2023.
Publisher Full Text

CNMC: **¿Qué cables submarinos conectan el territorio español? Enganchados a los cables submarinos (II)**. 2022; accessed 16/11/2022.
Reference Source

Coccoli C, Galparsoro I, Murillas A, *et al.*: **Conflict analysis and reallocation opportunities in the framework of marine spatial planning: A novel, spatially explicit Bayesian belief network approach for artisanal fishing and aquaculture.** *Mar Policy.* 2018; **94**: 119–131.
Publisher Full Text

Company JB, Ramirez-Llodra E, Sardà F, *et al.*: **3.8. Submarine canyons in the Catalan Sea.**
Reference Source

CSIC (Institut de Ciencies del Mar): **Catalonia adds 20 permanent no-take zones to its marine protected areas.** 2022; accessed 08/02/2023.

Dagestad KF, Röhrs J, Breivik Ø, *et al.*: **OpenDrift v1.0: a generic framework for trajectory modelling.** *Geosci Model Dev.* 2018; **11**(4): 1405–1420.
Publisher Full Text

Depellegrin D, Marti Llambrich C: **Dataset used in Addressing ocean planning challenges in a highly crowded sea space: a case study for the regional sea of Catalonia (Western Mediterranean).** [Data set]. *Zenodo.* 2023.
http://www.doi.org/10.5281/zenodo.10263416

Depellegrin D, Marti Llambrich C: **Supplementary Material to Addressing ocean planning challenges in a highly crowded sea space: a case study for the regional sea of Catalonia (Western Mediterranean)**. 2024.
http://www.doi.org/10.5281/zenodo.10540658

Depellegrin D, Menegon S, Gusatu L, *et al.*: **Assessing marine ecosystem services richness and exposure to anthropogenic threats in small sea areas: A case study for the Lithuanian sea space.** *Ecological Indicators.* 2020; **108**: 105730.
Publisher Full Text

Díaz H, Fonseca RB, Guedes Soares C: **Site selection process for floating offshore wind farms in Madeira Islands.** *Advances in Renewable Energies Offshore.* 2019; 729–737.
Reference Source

Díaz H, Soares CG: **A Multi-Criteria Approach to Evaluate Floating Offshore Wind Farms Siting in the Canary Islands (Spain).** *Energies.* 2021; **14**(4): 865.
Publisher Full Text

EC (European Commission): **Study on the offshore grid potential in the Mediterranean region**. 2020.
Publisher Full Text

EC (European Commission): **Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - on a New Approach for a Sustainable Blue Economy in the EU Transforming the EU's Blue Economy for a Sustainable Future**. Brussels: European Commission, 2021.
Reference Source

EEA (European Environmental Agency): **EU Biodiversity Strategy for 2030**. 2023; accessed 28/07/2023.
Reference Source

Ehler C, Douvere F: **Marine Spatial Planning: a step-by-step approach toward ecosystem-based management.** intergovernmental Oceanographic Commission and Man and the Biosphere Programme. iOC Manual and Guides no. 53, iCaM Dossier no. 6. Paris: UneSCO, 2009.
Reference Source

El-Gabbas A, Van Opzeeland I, Burkhardt E, *et al.*: **Dynamic Species Distribution Models in the Marine Realm: Predicting Year-Round Habitat Suitability of Baleen Whales in the Southern Ocean.** *Front Mar Sci.* 2021; **8**: 802276.
Publisher Full Text

EMODNet (European Marine Observation and Data Network): **Geoviewer**. 2023.
Reference Source

ESCACC30: **Strategic Reference Framework for Adaptation to Climate Change for the Horizon 2030. Executive summary**. 2021.
Reference Source

Estrategia Maritima: 2021; accessed 22/12/2022.
Reference Source

EU-MSP: **Story 4: Spain (Aquaculture and Tourism)**. accessed 09/01/2023.
Reference Source

EU-Seamap: **Seabed habitats**. 2021; accessed 06/02/2023.
Reference Source

Farella G, Menegon S, Fadini A, *et al.*: **Incorporating ecosystem services conservation into a scenario-based MSP framework: An Adriatic case study.** *Ocean Coast Manag.* 2020; **193**: 105230.
Publisher Full Text

Fernandez-Arcaya U, Ramirez-Llodra E, Aguzzi J, *et al.*: **Ecological Role of Submarine Canyons and Need for Canyon Conservation: A Review.** *Front Mar Sci.* 2017; **4**: 5.
Publisher Full Text

García S, Blanco J, Marín P, *et al.*: **Paper parks in Spain - Bottom trawling inside marine protected areas**. Oceana, Madrid, 2021.
Publisher Full Text

Garnier J, Billen G, Lassaletta L, *et al.*: **Hydromorphology of coastal zone and structure of watershed agro-food system are main determinants of coastal eutrophication.** *Environ Res Lett.* 2021; **16**: 023005.
Publisher Full Text

Garola A, López-Dóriga U, Jiménez JA: **The economic impact of sea level rise-induced decrease in the carrying capacity of Catalan beaches (NW Mediterranean, Spain).** *Ocean Coast Manag.* 2022; **218**: 106034.
Publisher Full Text

GenCat (Generalitat de Cataluña): **Especies-interes-pesquer - cloissa-japonesa**. 2023; accessed 08/01/2023.
Reference Source

GenCat (Generalitat de Cataluña): **Artificial reef distribution in Catalunia**. 2022a; accessed 09/01/2023.
Reference Source

GenCat (Generalitat de Cataluña): **Development of aquaculture in the framework of the 2030 Maritime Strategy of Catalonia**. 2022b.
Reference Source

GFW (Global Fish watch): 2021; accessed 17/11/2022.
Reference Source

GFW: **Anchoring areas**. 2023; accessed 13/11/2023.
Reference Source

Gill A, Degraer S, Lipsky A, *et al.*: **Setting the Context for Offshore Wind Development Effects on Fish and Fisheries.** *Oceanog.* 2020; **33**(4): 118–127.
Publisher Full Text

Gómez-Ballesteros M, Cervera - Núñez C, Campillos-Llanos M, *et al.*: **Transboundary cooperation and mechanisms for Maritime Spatial Planning implementation. SIMNORAT project.** *Mar Policy.* 2021; **127**: 104434.
Publisher Full Text

González DA, Campanales S, Grimalt M: **Managing the environmental sustainability of nautical tourism in Mediterranean MPAs**. Capboating Project. Edited by eco-union, 2020; 24.
Reference Source

Graham P, Falconer L, Telfer T, *et al.*: **A modelling approach to classify the suitability of shallow Mediterranean lagoons for Pacific oyster, *Crassostrea gigas* (Thunberg, 1793) farming.** *Ocean Coast Manag.* 2020; **192**: 105234.
Publisher Full Text

Gramolini R, Grati F, Fabi G, *et al.*: **GRID GeoReference interactions database.** Deliverable D39 COEXIST Project. Interaction in coastal waters: a roadmap to sustainable integration of aquaculture and fisheries. 2010.
Reference Source

Grorud-Colvert K, Sullivan-Stack J, Roberts C, *et al.*: **The MPA Guide: A framework to achieve global goals for the ocean.** *Science.* 2021; **373**(6560): eabf0861.
PubMed Abstract | **Publisher Full Text**

Gusatu LF, Menegon S, Depellegrin D, *et al.*: **Spatial and temporal analysis of cumulative environmental effects of offshore wind farms in the North Sea basin.** *Sci Rep.* 2021; **11**(1): 10125.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

GWEC (Global Wind Energy Council): **Spain - Offshore-Wind-Technical-Potential**. 2021; accessed 05/01/2023.
Reference Source

Hobday AJ, Alexander LV, Perkins SE, *et al.*: **A hierarchical approach to defining marine heatwaves.** *Prog Oceanogr.* 2016; **141**: 227–238.
Publisher Full Text

Horta e Costa B, Guimarães MH, Rangel M, *et al.*: **Co-design of a marine protected area zoning and the lessons learned from it.** *Front Mar Sci.* 2022; **9**: 969234.
Publisher Full Text

Hou Y, Xue X, Liu C, *et al.*: **Marine Spatial Planning Scheme evaluation based on the conflict analysis system - A case study in Xiamen, China.** *Ocean Coast Manag.* 2022; **221**: 106119.
Publisher Full Text

ICATMAR (Institut Català de Recerca per a la Governança del Mar): **State of fisheries in Catalonia 2021, Part 2: stock assessment (ICATMAR, 22-05) Barcelona**. 2021; 110.
Publisher Full Text

JACUMAR (Junta Nacional Asesora de Cultivos Marinos): **Junta Nacional Asesora de Cultivos Marinos**. 2023; accessed 03/01/2023.
Reference Source

Jiménez JA, Valdemoro HI, Bosom E, *et al.*: **Impacts of sea-level rise-induced**

erosion on the Catalan coast. *Reg Environ Change.* 2017; **17**: 593–603.
Publisher Full Text

Juza M, Fernández-Mora A, Tintoré J: **Sub-regional marine heat waves in the Mediterranean Sea from observations: long-term surface changes, sub-surface and coastal responses.** *Front Mar Sci.* 2022; **9**: 785771.
Publisher Full Text

Korpinen S, Andersen JH: **A Global Review of Cumulative Pressure and Impact Assessments in Marine Environments.** *Front Mar Sci.* 2016; **3**.
Publisher Full Text

Korpinen S, Klančnik K, Peterlin M, *et al.*: **Multiple pressures and their combined effects in Europe's seas.** ETC/ICM Technical Report 4/2019: European Topic Centreon Inland, Coastal and Marine waters. 2019; 164.
Reference Source

López Mengual I, Sanchez-Jerez P, Ballester-Berman J: **Offshore aquaculture as climate change adaptation in coastal areas: sea surface temperature trends in the Western Mediterranean Sea.** *Aquacult Environ Interact.* 2021; **13**: 515–526.
Publisher Full Text

Marine Scotland: **Assessing fisheries displacement by other licensed marine activities: good practice guidance - literature review**. A303088-S00-REPT-001-A02. 2022.
Reference Source

Martín J, Puig P, Masqué P, *et al.*: **Impact of bottom trawling on deep-sea sediment properties along the flanks of a submarine canyon.** *PLoS One.* 2014; **9**(8): e104536.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Mazaris AD, Kallimanis A, Gissi E, *et al.*: **Threats to marine biodiversity in European protected areas.** *Sci Total Environ.* 2019; **677**: 418–426.
PubMed Abstract | **Publisher Full Text**

MedReAct: **Exposing the hidden costs of trawling in the Western Mediterranean**. Fundació ENT, 2022; accessed 24/07/2023.
Reference Source

Med Sea Alliance: **Atlas - A Med Sea Alliance Platform**. 2023; accessed 23/07/2023.

Menegon S, Depellegrin D, Farella G, *et al.*: **Addressing cumulative effects, maritime conflicts and ecosystem services threats through MSP-oriented geospatial webtools.** *Ocean Coast Manag.* 2018b; **163**: 417–436.
Publisher Full Text

Menegon S, Fadini A, Perini L, *et al.*: **A geoportal of data and tools for supporting Maritime Spatial Planning in the Adriatic-Ionian Region.** *Environ Model Softw.* 2023; **160**: 105585.
Publisher Full Text

Menegon S, Sarretta A, Depellegrin D, *et al.*: **Tools4MSP: an open source software package to support Maritime Spatial Planning.** *PeerJ Comput Sci.* 2018a; **4**: e165.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Miteco: **Plan Nacional de Adaptacon al cambio climático**. 2020.
Reference Source

Miteco: **PLAN ESTRATÉGICO DEL PATRIMONIO NATURAL Y DE LA BIODIVERSIDAD A 2030**. 2022a; accessed 10/01/2023.
Reference Source

Miteco: **Roadmap for offshore wind and marine energy in Spain**. NIPO: 665-22-024-5. 2022b.

MSP-EC: **Offshore Wind and Fisheries**. Conflicting elements. 2021; accessed 03/01/2023.
Reference Source

Muñoz M, Reul A, Gil de Sola L, *et al.*: **A spatial risk approach towards integrated marine spatial planning: A case study on European hake nursery areas in the North Alboran Sea.** *Mar Environ Res.* 2018; **142**: 190–207.
PubMed Abstract | **Publisher Full Text**

Ouled-Cheikh J, Coll M, Cardona L, *et al.*: **Fisheries-enhanced pressure on Mediterranean regions and pelagic species already impacted by climate change.** *Elementa: Science of the Anthropocene.* 2022; **10**(1): 00028.
Publisher Full Text

PADI (Professional Association of Diving Instructors): 2023; accessed 03/01/2023.
Reference Source

Paradis S, Puig P, Masqué P, *et al.*: **Bottom-trawling along submarine canyons impacts deep sedimentary regimes.** *Sci Rep.* 2017; **7**: 43332.
PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Pataki Z, Kitsiou D: **Marine Spatial Planning: Assessment of the intensity of conflicting activities in the marine environment of the Aegean Sea.** *Ocean Coast Manag.* 2022; **220**: 106079.
Publisher Full Text

PdG (Ports de Generalitat): **Mapa i sistema portuari català**. 2023; accessed 07/01/2023.
Reference Source

Pennino MG, Brodie S, Frainer A, *et al.*: **The Missing Layers: Integrating Sociocultural Values Into Marine Spatial Planning.** *Front Mar Sci.* 2021; **8**: 633198.
Publisher Full Text

Peris A, Barbieri MV, Postigo C, *et al.*: **Pesticides in sediments of the Ebro River Delta cultivated area (NE Spain): Occurrence and risk assessment for aquatic organisms.** *Environ Pollut.* 2022; **305**: 119239.
PubMed Abstract | **Publisher Full Text**

Perry AL, Blanco J, García S, *et al.*: **Extensive Use of Habitat-Damaging Fishing Gears Inside Habitat-Protecting Marine Protected Areas.** *Front Mar Sci.* 2022; **9**: 811926.
Publisher Full Text

Peters JL, Remmers T, Wheeler AJ, *et al.*: **A systematic review and meta-analysis of GIS use to reveal trends in offshore wind energy research and offer insights on best practices.** *Renew Sustain Energy Rev.* 2020; **128**: 109916.
Publisher Full Text

Pınarbaşı K, Galparsoro I, Alloncle N, *et al.*: **Key issues for a transboundary and ecosystem-based maritime spatial planning in the Bay of Biscay.** *Mar Policy.* 2020; **120**: 104131.
Publisher Full Text

Pınarbaşı K, Galparsoro I, Depellegrin D, *et al.*: **A modelling approach for offshore wind farm feasibility with respect to ecosystem-based marine spatial planning.** *Sci Total Environ.* 2019; **667**: 306–317.
PubMed Abstract | **Publisher Full Text**

POEM: **PLANES DE ORDENACIÓN DEL ESPACIO MARÍTIMO.** Executive Summary, 2021.
Reference Source

Porporato EMD, Pastres R, Brigolin D: **Site Suitability for Finfish Marine Aquaculture in the Central Mediterranean Sea.** *Front Mar Sci.* 2020; **6**: 772.
Publisher Full Text

Protected Planet. 2023; accessed 17/11/2023.
Reference Source

PSOEM. 2023; accessed 12/01/2023.
Reference Source

R Core Team: **R: A language and environment for statistical computing.** R Foundation for Statistical Computing, Vienna, Austria, 2022.
Reference Source

Rac-spa: **SPAMIs.** 2022; accessed 16/11/2022.
Reference Source

Raghukumar K, Chartrand C, Chang G, *et al.*: **Effect of Floating Offshore Wind Turbines on Atmospheric Circulation in California.** *Front Energy Res.* 2022; **10**: 863995.
Publisher Full Text

Real Decreto 150/2023. de 28 de febrero, por el que se aprueban los planes de ordenación del espacio marítimo de las cinco demarcaciones marinas españolas (POEM).
Reference Source

Roy S, Hossain MS, Badhon MK, *et al.*: **Development and analysis of a geospatial database for maritime spatial planning in Bangladesh.** *J Environ Manage.* 2022; **317**: 115495.
PubMed Abstract | **Publisher Full Text**

Saenz-Aguirre A, Saenz J, Ulazia A, *et al.*: **Optimal strategies of deployment of far offshore co-located wind-wave energy farms.** *Energy Convers Manag.* 2022; **251**: 114914.
Publisher Full Text

Said A, Trouillet B: **Bringing 'Deep Knowledge' of Fisheries into Marine Spatial Planning.** *Maritime Studies.* 2020; **19**: 347–357.
Publisher Full Text

Salvador S, Gimeno L, Sanz Larruga FJ: **The influence of maritime spatial planning on the development of marine renewable energies in Portugal and Spain: Legal challenges and opportunities.** *Energy Policy.* 2019; **128**: 316–328.
Publisher Full Text

Schickele A, Leroy B, Beaugrand G, *et al.*: **Modelling European small pelagic fish distribution: Methodological insights.** *Ecol Model.* 2020; **416**: 108902.
Publisher Full Text

Shucksmith R, Gray L, Kelly C, *et al.*: **Regional marine spatial planning – The data collection and mapping process.** *Mar Policy.* 2014; **50**: 1–9.
Publisher Full Text

Schupp MF, Bocci M, Depellegrin D, *et al.*: **Toward a common understanding of ocean multi-use.** *Front Mar Sci.* 2019; **6**.
Publisher Full Text

Simon-Sánchez L, Grelaud M, Garcia-Orellana J, *et al.*: **River Deltas as hotspots of microplastic accumulation: The case study of the Ebro River (NW Mediterranean).** *Sci Total Environ.* 2019; **687**: 1186–1196.
PubMed Abstract | **Publisher Full Text**

Socrate J, Verón E: **Analysis of uses and activities in the Argentine Sea. Bases for a Marine Spatial Planning in the North Argentina Basin.** *Mar Policy.* 2022; **139**: 105014.
Publisher Full Text

Sourianos E, Kyriakou K, Hatiris GA: **GIS-based spatial decision support system for the optimum siting of offshore windfarms.** *European Water.* 2017; **58**: 337–343.
Reference Source

SPro: **Addressing conflicting spatial demands in MSP**. 2018; accessed 03/01/2023.
Reference Source

SSMEI: **Scottish Sustainable Marine Environment Initiative (SSMEI) – Factsheet**. 2018; accessed 01/01/2023.
Reference Source

SIMWESTMED: **Supporting Maritime Spatial Planning in the Western Mediterranean region**. 2018; accessed 26/01/2023.
Reference Source

TripKay: **Tuna Tour, nadar entre atunes rojos en alta mar**. 2023; accessed 09/01/2023.
Reference Source

UfM (Union for the Mediterranean): **Towards a Sustainable Blue Economy in the Mediterranean región**. 2021; accessed 02/01/2023.
Reference Source

UNCLOS: **United Nations Convention on the Law of the Sea**. 1982; accessed 03/01/2023.
Reference Source

van den Burg SWK, Skirtun M, van der Valk O, *et al.*: **Monitoring and evaluation of maritime spatial planning – A review of accumulated practices and guidance for future action.** *Mar Policy.* 2023; **150**: 105529.
Publisher Full Text

Veidemane K, Ruskule A, Strake S, *et al.*: **Application of the marine ecosystem services approach in the development of the maritime spatial plan of Latvia.** *In J Biot Sci, Ecosyst Serv Manag.* 2017; **13**(1): 398–411.
Publisher Full Text

Veigas M, Iglesias G: **Wave and offshore wind potential for the island of Tenerife.** *Energ Convers Manage.* 2013; **76**: 738–745.
Publisher Full Text

Venier C, Menegon S, Possingham HP, *et al.*: **Multi-objective zoning for aquaculture and biodiversity.** *Sci Total Environ.* 2021; **785**: 146997.
PubMed Abstract | **Publisher Full Text**

Virtanen EA, Lappalainen J, Nurmi M, *et al.*: **Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design.** *Renew Sustain Energy Rev.* 2022; **158**: 112087.
Publisher Full Text

Weiss CVC, Ondiviela B, Guinda X, *et al.*: **Co-location opportunities for renewable energies and aquaculture facilities in the Canary Archipelago.** *Ocean Coast Manage.* Maritime Spatial Planning, Ecosystem Approach and Supporting Information Systems (MapSIS 2017), 2018; **166**: 62–71.
Publisher Full Text

Open Peer Review

Current Peer Review Status: ✅ ✅

Version 1

Reviewer Report 03 July 2024

✅ **Aurelija Armoskaite** (iD)

Latvian institute of Aquatic Ecology, Riga, Latvia

This paper introduces a methodology for analysis to support maritime spatial planning. This methodology is demonstrated in the Catalonian region, showcasing its value. The paper is interesting, well-written and a timely, valuable contribution to the field of geospatial decision support tools and analysis techniques.

The introduction and methods sections provide a thorough overview of the planning region in focus. The introduction describes the missing component of explorative analysis and an evidence base for MSP in a region important for various maritime activities. The methods section then dives deeper into the MSP targets, open geodata availability and the chosen methods. The methods section is clear, transparent, and easily understandable for the readers.

The results section is structured according to the research objectives clearly outlined in the introduction. The results are illustrated with appropriate and well-designed figures. The results presented are insightful. They reveal current spatial conflicts and stressors and potential shifts in the future, as well as a high regional contribution towards the BST30% targets whilst raising the challenges of designating 10% for strict protection.

The discussion is engaging and well-rounded. The authors unpack the results thoroughly and discuss them in light of challenges applicable to the study region and beyond. They offer a range of suggestions on how the results and methods presented in the study can inform the decision-making process and further research.

Here are some suggestions for the authors to consider:
  ○ The abstract states: 'Potential new aquaculture sites ARE causing...' I wonder if the present tense is appropriate here, as the focus is on future activities. Consider rewording or perhaps even mentioning the results of conflict and stressor shift analyses.
  ○ Check the resolution of the figures and grammar throughout the text. For instance, there is a missing comma in the second sentence of section 2. Methods: 'In summary, this includes:...'. There are also a few missing articles (e.g. '...THE highest conflicts...' in the

abstract and 'of pivotal importance now and in THE future to perform…' in the introduction).
   ○ Consider the downsides of additive stressor/cumulative impact analysis in the discussion.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Marine spatial planning and ecosystem-based management; social-ecological systems analysis; environmental impacts assessments; geographic information systems and quantitative & qualitative social research methods.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 17 May 2024

https://doi.org/10.21956/openreseurope.18191.r39952

✅ **Humood Naser**
University of Bahrain, Sakhir, Southern Governorate, Bahrain

The paper entitled 'Addressing ocean planning challenges in a highly crowded sea space: a case study for the regional sea of Catalonia (Western Mediterranean)' provides a case study of applying marine spatial planning. It focuses on regional sea of Catalonia, Spain. Marine spatial planning is considered as an important tool to inform decision making processes related to the use and conflict of the marine environment. Therefore, the current paper topic is important and can

provide insights on the approach, methodology and applicability of marine spatial planning, especially in areas with intensive use such as the Western Mediterranean area.

The methodological approach is scientifically sound. It starts by providing a conceptual framework to highlight the overall approach and the main steps. This can provide the reader with a visual holistic view of the methods used in the study. One important thing in the method is the use of publicly available data. This can contribute to the utilization and application of the available data in marine spatial planning. The method section details the study area location and the current users, geodatabase development, marine protection targets and conflict analysis, and current and future users' analysis.

The results section generated maps of the spatial distribution of marine activities of the current and future uses of the area. The discussion provides an account for the main five challenges associated with practical insights. These insights could be very useful for planning and implementation of marine spatial planning as they are focused and based on the outcomes of the study findings.

Further, there are few notes that might be needed to be addressed:

Page 3: The last paragraph of the introduction: [Based on the results ….]. I assume this part could be with the result section, as it specifies five challenges etc. or it might be altered into an objective. The resolution of the figures in the online versions are fine, but please double check on the printed version of the paper.

Page 5 (Ca. Line 3): Please check Nature 2000 0r Natura 2000?

Page 5 (The last paragraph): What is it meant by: (The MUC is a fully novel application)? Is it developed by the study or utilized, because it is mentioned it is available in the Tools4MSP. The same for page 8 (we apply a novel QGIS plugin)?

Page 11: please check the use of the word (Surprisingly): because the outcome is negligible and that is due to the low intensity in comparison with other areas.

Is the work clearly and accurately presented and does it cite the current literature?

Yes

Is the study design appropriate and does the work have academic merit?

Yes

Are sufficient details of methods and analysis provided to allow replication by others?

Yes

If applicable, is the statistical analysis and its interpretation appropriate?

Not applicable

Are all the source data underlying the results available to ensure full reproducibility?

Yes

Are the conclusions drawn adequately supported by the results?

Yes

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of

expertise to confirm that it is of an acceptable scientific standard.