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Research article

Ocean multi-use for the transition to sustainable energy and aquaculture developments in the Mediterranean Sea

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ABSTRACT

The suitability of the Mediterranean Sea for offshore wind and wave energy, aquaculture, and multi-use developments is examined considering the human and environmental dimensions. The human dimension analysed marine renewable energy, aquaculture and multi-use developments, and described the current cumulative impact of existing marine uses and activities on marine ecosystems. A Suitability Index was applied to assess technical, structural, operational, and biological factors for wind and wave energy and aquaculture developments across 3632 cells in the Mediterranean (0.2°). Aquaculture potential was evaluated for 22 species, selected based on their farming history, biomass, economic importance and future market potential. The environmental dimension analysed the marine protected areas and biodiversity conservation status. The study highlights that seventeen Mediterranean countries have potential for multi-use development, but southern countries have a unique advantage in combining wind, wave and aquaculture. However, it also underscores a limited ecological capacity of these regions to tolerate additional anthropogenic activities. One of the main challenges when developing new activities in complex socio-ecological systems, such as the Mediterranean, is ensuring biodiversity conservation. Thus, the main contribution of this study is to provide interested parties and administrations with the necessary information and criteria for informed decision-making, guided by precautionary and preventive principles. The results of this study can be visualized in the following link: https://msp.ihcantabria.com/#/tool.

1. Introduction

The UN Decade on Ecosystem Restoration 2021–2030 underscores the urgent need to fight the climate crisis, improve food security, and protect biodiversity. These challenges are becoming increasingly critical, as global energy and food demands are projected to rise in response to a growing population, expected to increase by nearly 2 billion people by 2050 (United Nations, 2019), and the ongoing development of emerging economies (IEA-International Energy Agency, 2020).

In this rapidly changing context, the ocean is poised to play a pivotal role in addressing climate change, sustainable energy production, and food security challenges (United Nations, 2019). Particularly, offshore renewable energy and marine aquaculture are emerging as key marine resources to achieve these goals. The large unexploited energy potential of marine environments offers a promising avenue for sustainable energy production, while marine aquaculture, one of the least freshwater-dependent food sectors, is expected to expand significantly to meet future food demands (Troell et al., 2014; Ottinger et al., 2016; Weiss et al., 2020; Majidi et al., 2024).

However, despite the timeliness and necessity of promoting marine renewable energy and aquaculture, several challenges must be overcome to enable their sustainable deployment (Maar et al., 2023). Given the vast expanse of the ocean and the relatively small area currently occupied, spatial limitations alone are unlikely to constrain growth (Hofherr et al., 2015; Dalton et al., 2019). However, most existing facilities are located in coastal waters, and future expansion will likely extend into offshore areas (Medeiros et al., 2024). In these zones, competition for space, driven by established coastal economic activities and overlapping environmental protection priorities, such as marine protected areas and biodiversity hotspots, may become a critical factor

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(Fernandes et al., 2018; Wilson et al., 2025).

One of the major challenges when developing new marine activities is to ensure the conservation of biodiversity. Ecosystem functioning is essential to the provision of goods and services that support human health and well-being (Lloret et al., 2023). But, the full delivery of these services depends on the maintenance of ecosystem integrity. With oceans under increasing pressure from human activities, the preservation of marine ecosystems has become more critical than ever (Fernandes et al., 2018). Fortunately, the expansion to the ocean cannot bypass the EU's Nature Restoration Regulation (Regulation , 2024/1991), and today the development of integrated economic models that accommodate emerging ocean activities, while maintaining ecological integrity is a scientific and political imperative.

In the next few years, we will witness an enormous change in the ocean. We will see the gradual development of new activities and the installation of new infrastructure. Thus, it is time to think about how we want to do this and how we should do it. It is time to seek solutions that balance the nature conservation and economic development, and optimize the use and exploitation of ecosystems. This is why the future expansion of new activities in the ocean should be accompanied by solutions that are socially, environmentally and economically sound.

This is precisely the basis of multi-use. Multi-use is defined as the shared use of resources in close geographical proximity by one or multiple users (Bocci et al., 2019). The concept of 'multi-use' space represents a shift from exclusive resource rights to a collaborative sharing of resources by multiple users (Schultz-Zehden et al., 2018). These solutions combine compatible activities to share infrastructure and technologies, increase resource efficiency, optimize space usage, generate synergistic benefits and reduce ecological impact (Buck and Langan, 2017; Pascual and Bocci, 2018; van den Burg et al., 2020).

The integration of multi-use marine activities has been considered essential for future growth since early policy discussions. Key policy instruments, including the Marine Spatial Planning Directive (Directive, 2014/89/EU), the marine renewable energy strategy (European Commission, 2020), or the sustainable blue economy framework (European Commission, 2021), have consistently endorsed multi-use. While, the EU's Blue Growth strategy particularly supports the promotion of wind energy and aquaculture (European Commission, 2012). From a marine spatial planning perspective, multi-use is increasingly promoted in national plans (Rezaei et al., 2024; Schultz-Zehden et al., 2018) and is recognised not only as a sustainable planning tool, but also as a central component of the planning (Calado et al., 2019).

Despite the urgency and opportunities presented by European regulations, comprehensive studies exploring the combined potential of renewable energy and aquaculture, particularly in the context of the Mediterranean Sea and its ecosystems, remain limited (e.g., Weiss et al., 2018a, b, c; Zanuttigh et al., 2021; Depellegrin et al., 2024). This study aims to address this gap by assessing the potential for offshore wind, wave energy, and aquaculture in the Mediterranean, with a particular emphasis on evaluating the feasibility of integrated multi-use developments. The study incorporates ecologically relevant data to contrast potential multi-use developments with marine protected areas (hereafter MPAs) and biodiversity hotspots. Moreover, the ecosystem tolerance to new activities is assessed by an impact coefficient that compares the cumulative anthropogenic pressures with the conservation status of marine biodiversity.

2. Methodology

2.1. Study site

The Mediterranean is a semi-enclosed sea connected to the Atlantic Ocean by the Strait of Gibraltar. It encompasses three continents (Africa, Asia and Europe) and is bordered by 22 countries. It has a surface area of about 2.51 million km^2 and a total coastline of 46,000 km. Its coasts are home to more than 150 million inhabitants, which doubles during the tourist season. The Mediterranean basin also hosts more than 450 ports and terminals which together account for approximately 30 % of the global sea-borne trade (European Commission, 2017). It is an oligotrophic sea and a hotspot of marine biodiversity, holding between 4 and 18 % of the world's natural wealth. It hosts more than 8500 macroscopic marine species, with a high level of endemism, accounting for over a quarter of the entire Mediterranean biota (Bianchi and Morri, 2000). Remarkably, all of this biodiversity is found within just 0.3 % of the ocean's total volume (UNEP, 2024). One of the greatest challenges in developing marine activities is ensuring the conservation of this vast biodiversity within a highly complex social ecological system. The analysis at Mediterranean scale adopted a holistic approach, looking at both the human and environmental dimensions.

2.2. Human dimension

The human dimension examined marine renewable energy, aquaculture and multi-use developments, and described the current cumulative impact of existing marine uses and activities on marine ecosystems.

2.2.1. Assessment of marine renewable energy potential

A Suitability Index (hereafter *SI*), based on the approach developed and applied across various temporal and spatial scales by Weiss et al. (2018a, b, (Weiss et al., 2020), (Weiss et al., 2023), was used to assess the potential for wind and wave developments. A threshold of $SI \geq 0.5$ was applied to identify areas suitable for wind and wave energy developments, considering the limit defined by Weiss et al. (2018c) between low and moderate suitability. The *SI* is calculated by integrating four suitability factors through the critical value method: wind and wave energy production (I_{we}, I_{wve}), structural integrity (I_{wss}, I_{wvss}), operation and maintenance (I_{os}) and energy transmission (I_{et}). Each suitability factor is independently evaluated (0–1), according to international standards, reference wind turbines and generic wave devices (Table 1).

Table 1
Variables and thresholds used to calculate the four suitability factors integrated into the Suitability Index (SI) for (a) wind and (b) wave marine renewable energies

Marine renewable energies	Thresholds
a) Wind Energy potential	
Wind production suitability	
Mean wind speed (hub-height- 150m) (W_s,m/s)	3 < W < 25
Available wind potential (W_p,Kw/m^2)	>400
Significant wave height (H_s,m)	Hs < 5
Structural suitability	
Wind speed 50-yr ($W_{s\text{-}50yr}$,m/s)	<40
Significant wave height 50-yr ($H_{s\text{-}50yr}$,m)	<15
Bathymetry (m)	<300
Operational suitability	
Distance from ports (km)	<60
Mean wind speed (hub-height- 150m) (Ws,m/s)	<15
Significant wave height (H_s,m)	<2
Energy transport	
Distance from consumer centers (km)	<80
b) Wave Energy potential	
Wave production suitability	
Wave energy flux (Ef)	>15
Significant wave height (H_s,m)	1 < Hs < 6
Peak Period (T_p, s)	5 < Hs < 14
Structural suitability	
Peak Period (T_p, s)	<25
Significant wave height 50-yr ($H_{s\text{-}50yr}$,m)	<15
Bathymetry (m)	<300
Operational suitability	
Distance from ports (Km)	<60
Mean wind speed (10m high) (Ws,m/s)	<15
Significant wave height (H_s,m)	<2
Energy transmission	
Distance from consumer centers (km)	<80

The resulting value, expressed as the probability (in percentage) of encountering optimal conditions, reflects how closely the environment aligns with the required conditions for each suitability factor.

For *wind power production* suitability (I_{we}), wind speed (Ws), available wind potential (W_P) and significant wave height (H_s) were considered. Ws and Wp were measured at 150m hub-height, and the maximum Hs is the limit at which the turbines can interrupt power production for safety reasons. The wind production was evaluated as a function of the percentage of time in which the Ws and Wp remain within the production thresholds. The Ws was distributed according to the power curve of the IEA- 15 MW turbine referenced by DTU (Fig. 1a, Gaertner et al., 2020).

$$I_{we} = (3Ws + 2Wp + 1Hs) / 6 \tag{1}$$

For the *wave energy production suitability* (I_{wve}), the available energy flux (E_f), wave peak period (T_p) and H_s were considered. The production index for wave energy was calculated by integrating each element through the weighted mean, with more height assigned to the availability of the resource against the site severity.

$$I_{wve} = \left(3H_s + 2E_f + T_p\right) / 6 \tag{2}$$

The *structural suitability* was characterized based on the severity of the met-ocean conditions (*i.e.* 50-year return period for *Ws*-50yr*, Hs*-50yr*, Tp*-50yr) and the bathymetry (Bat). The structural suitability index (*Iwss*) for wind energy was defined based on the weights reflected in the following equation:

$$I_{wss} = \left(W_{50yr} + H_{s,50yr} + 4Bat\right) / 6 \tag{3}$$

For wave energy exploitation (*Iwvss*), the integration of the index was done according to the following equation:

$$I_{wvss} = \left(T_{p,50yr} + H_{s,50yr} + 4Bat\right) / 6 \tag{4}$$

The extreme conditions (i.e., *Ws*-50yr*, Hs*-50yr*, Tp*-50yr*)* and the Bat were parameterised according to specific distribution functions (Fig. 1b–e).

Operational suitability (Ios) was assessed based on the availability of annual 8-h weather windows for Ws and Hs (i.e., Win) and the distance to ports (D). The study area was considered fully accessible if it has 1095 windows of access. For wind energy, the Ws corresponds to a height of 150 m. For wave energy, the Ws corresponds to a height of 10 m.

$$Ios = (2D + 3Win)/5 \tag{5}$$

Energy transmission (*Iet*)for wind and wave suitability was assessed by calculating the Euclidean distance to the nearest urban areas (i.e., consumer centers). Euclidean distance was parameterized assuming a radius of 80 km of distance (Fig. 1f).

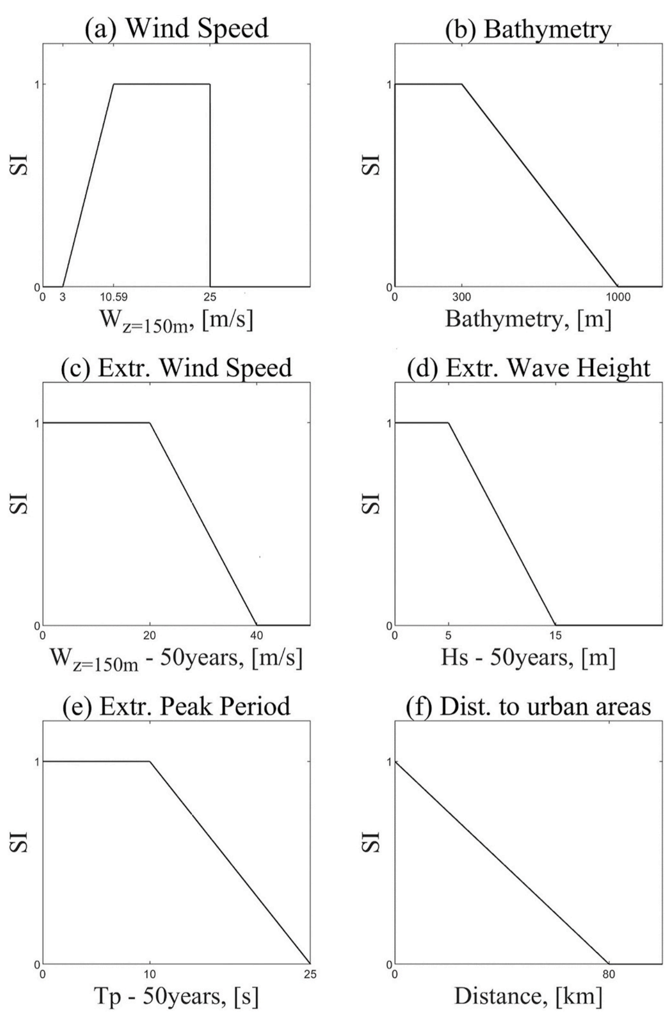


Fig. 1. Distribution functions used to parametrise the indicators used to assess the opportunities for marine renewable energy: (a) wind speed; b) bathymetry; c) 50-year return period for wind speed – 150m (Ws-50yr); d) 50-year return period for significant wave height (Hs-50yr); e) 50-year return period for peak period (Tp-50yr); (f) distance to urban areas.

2.2.2. *Assessment of aquaculture potential*

The potential of the Mediterranean Sea for offshore aquaculture was addressed through the methodological approach developed by Weiss et al. (2018b). The *SI* was calculated for aquaculture from three suitability factors: biological, operational and structural requirements. *SI* calculations were performed similarly to the marine renewable potential assessment. The *SI* was assessed for 22 species, including fish, cephalopods, bivalves and macroalgae, although only species with $SI \geq 0.5$ were included in the results. The selection of these species considered factors such as their history as farmed species, biomass, economic value, and future market potential (Table 2). The selection was made in collaboration with the Spanish aquaculture sector and included species currently in production (i.e., blackspot seabream, meagre, gilthead seabream, European seabass), and new species with future market potential in which the sector is now interested (i.e., wreckfish, common dentex, dusky grouper, flathead grey mullet, common dolphinfish, red porgy, or greater amberjack).

Biological suitability assessed how closely the environmental conditions resemble the requirements of the species (e.g. temperature, salinity, chlorophyll *a*), defined through their optimum growth requirements. The environmental conditions were compared with the species' requirements and the probability of meeting optimal conditions was calculated concomitantly for the variables influencing their growth (Table 2), based on the entire historical time series of available data (Table 3).

Structural suitability, similar to the approach used for renewable energies, assessed the severity of met-ocean conditions and their influence on the long-term integrity of aquaculture structures. This assessment considered factors such as bathymetry, seabed slope, extreme waves, and currents, as well as survival conditions, to parameterize the study area (cf. Weiss et al., 2018b).

Operational suitability, similar to the approach used for renewable energies, evaluated the possibility of carrying out the O&M (operations and maintanance) activities (feeding, fishing, cleaning, maintenance, etc.) and was determined by met-ocean conditions and by the distance to ports (cf. Weiss et al., 2018b).

To complement the *SI*, the probability of *species survival against extreme events* caused by marine cold or heatwaves was analysed. An extreme event is a period of unusual conditions that could result in mortality or stress for the species. In this study, an extreme event was defined as a period of more than seven consecutive days during which

Table 2
Variables and thresholds to define the optimum growth conditions for the 22 species of interest: fish, cephalopods, bivalves and macroalgae.

Common name	Scientific name	Temperature (°C)	Salinity (UPS)	PAR (Einstein/m^2 day)	Chlorophyll *a* (mg/m^3)	Current velocity (m/s)
Fish in production						
Blackspot seabream	*Pagellus bogaraveo*	12–21	34.5–37.8			
Meagre	*Argyrosomus regius*	14–28	29.5–39.1			
Gilthead seabream	*Sparus aurata*	14–28	30.0–40.0			
European seabass	*Dicentrarchus labrax*	4.1–30	5.0–50.0			
Rainbow trout	*Oncorhynchus mykiss*	6–18	10.0–38.0			
Fish with future market potential						
Atlantic Bluefin tuna	*Thunnus thynnus*	15–30	30.0–38.0			
Wreckfish	*Polyprion americanus*	12–20	32.4–37.8			
Common dentex	*Dentex dentex*	15–28	35.4–38.8			
Dusky grouper	*Epinephelus marginatus*	14–23	33.2–37.2			
Flathead grey mullet	*Mujil cephalus*	15–30	30.0–38.0			
Common dolphinfish	*Coryphaena hippurus*	20–30	16.0–36.4			
Red porgy	*Pagrus pagrus*	15–26	31.6–38.0			
Greater amberjack	*Seriola dumerilii*	14–28	30.0–38.0			
Cephalopods						
Octopus vulgaris	*Octopus vulgaris*	10–20	27.0–35.5			
Sepia officinalis	*Sepia officinalis*	20–30	25.0–38.0			
Bivalves						
Mediterranean mussel	*Mytilus galloprovincialis*	10–25	20.0–38.0		>1	<0.35
King scallop	*Pecten maximus*	8–17	28.0–35.0		>1	<0.35
Queen scallop	*Aequipecten opercularis*	8–16	>26.0		>1	<0.35
Variegated scallop	*Mimachlamys varia*	8–18	25.0–35.0		>1	<0.35
Macroalgae						
Laver	*Porphyra* sp	10-15 °C	30.0–40.0	6.05–43.2		
Velvet horn	*Codium tomentosum*	10-16 °C	30.0–40.0	6.05–17.3		
Irish moss	*Chondrus crispus*	10-15 °C	28.0–40.0	5.62-34.6		

Table 3
Data sources, spatial resolution, temporal resolution and time period available for met-ocean and physiographic variables.

Variable	Source	Period	Temporal resolution	Spatial resolution
Sea temperature (°C)	Copernicus	1982–2024	Daily mean	0.05° × 0.05°
Salinity (UPS)	Copernicus	1987–2024	Daily mean	0.042° × 0.042°
Chlorophyll *a* (mg/m^3)	Copernicus	1999–2024	Daily mean	0.042° × 0.042°
Wind (m/s)	IHData	1985–2022	1 h	0.312°
Wave (m)	IHData	1985–2015	1 h	0.125°
Currents (m/s)	IHData	1985–2015	1 h	0.114°
Bathymetry	EMODnet, DTM	2020		1/16x1/16arcmin
PAR (Einstein/m^2 day)	Aqua/MODIS	2002–2022	Daily	4 km
Ports	World Port Index-NGA	2019		Polygon
Consumer centers	Eurostat; World Bank Open Data; United Nations Data Portal	2023		Points
MPAs	MAPAMED	2019		Polygon
SPAMIs	MAPAMED	2016		Polygon
National designated areas	EEA	2023		Polygon
Marine Natura 2000 sites	EMODNET	2022		Polygon
Seagrass beds	Green and Short; O'Keefe and Lillis	2023, 2019		Polygon
Coralligenous habitats	EMODNET	2023		Polygon

sea surface temperatures are either above or below the optimal growth range for the species (Table 2). The probability was calculated using the entire historical dataset, and species survival was considered at risk if the likelihood of extreme events exceeded 50 %. Thus, regardless of the *SI* values, study areas where species survival was at risk were classified as unsuitable for aquaculture.

2.2.3. Assessment of multi-use potential

The *SI* for multi-use potential in the Mediterranean Sea was determined by combining SI_{Wind}, SI_{Wave}, SI_{Aqua}, either collectively or in pairs. The assessment used the minimum value (*i.e.* the critical value method) for the study area. Only study areas with $SI > 0.5$ for all three activities were included in the calculations. For aquaculture, particularly, only areas with more than 5 species with $SI > 0.5$ were considered. As an example, multi-use potential for the three activities was obtained from Eq. (6):

$$SI_{MU} = min(SI_{Wind}, SI_{Wave}, SI_{Aqua}) \tag{6}$$

2.2.4. Cumulative pressures

Pressures caused by marine economical activities can stress marine ecosystems and compromise their conservation status. Single impacts may be insignificant when considered individually. However, when all pressures and impacts are considered together, the effect on ecosystems may become significant, especially when introducing new marine activities. The cumulative pressure index was used to translate human activities into ecosystem-impacts (Halpern et al., 2008). The 2023 data for Mediterranean countries in the Economic Exclusive Zone (hereafter EEZ) were obtained from the Ocean Health Index scenarios (Ocean Health Index, 2023). The index evaluates the cumulative pressures acting on the biodiversity of habitats and species. Pressures included both ecological and social pressures. Ecological pressures fall into five broad categories (i.e. pollution, habitat destruction, species introductions, fishing and climate change) and were weighted equally to social pressures (i.e. poverty, political instability and corruption). The overall pressure on each country was based on the relative sensitivity of biodiversity to each stressor and the magnitude of the stressor. The score to evaluate this indicator ranges from 0 to 100, with 0 indicating the lowest stress and 100 the highest stress. To provide a single value for each country, the average cumulative pressure value of habitats and species was calculated.

2.3. Environmental dimension

The environmental dimension examined the status of Mediterranean ecosystems and biodiversity combining the regional and the national scale. The regional scale addressed the Mediterranean Sea as a continuous system of interconnected MPAs and functioning ecosystems. The country's EEZ scale explored how its policies affect the biodiversity conservation status.

2.3.1. Marine protected areas

Following Agnesi et al. (2020), the inventory of MPAs included those legally designated by EU Nature Directives, National designations, and Regional Sea Conventions, including Protocol concerning Specially Protected Areas and Biological Diversity in the Mediterranean (SPA/BD Protocol). Under the umbrella of MPAs, the Natura 2000 network, national protected areas, and Specially Protected Areas of Mediterranean Importance (SPAMIs) were integrated. In a second step, habitats and species with stricter conservation objectives and restrictions for biodiversity were inventoried under the category of biodiversity hotspots. National Parks and Sanctuaries for the Conservation of Marine Mammals and Cetaceans (under the Barcelona Convention), coralligenous habitats and the species *Posidonia oceanica* were considered as part of this classification. The interactions between multi-use opportunities and MPAs in the Mediterranean basin followed two approaches. The top-down approach analysed multi-use suitable areas that may have the potential to overlap with MPAs. The bottom-up approach explored the MPAs that may be affected by multi-use developments.

2.3.2. Biodiversity conservation status

The Biodiversity Conservation Status Index developed under the Ocean Health Index (Halpern et al., 2012) was used to provide an overview of the conservation status of habitats and species. The 2023 data for Mediterranean countries (EEZ) were obtained from Ocean Health Index scenarios (Ocean Health Index, 2023). The Biodiversity Index assesses how successfully the richness and variety of marine life is being conserved through the assessment of species and habitats. Species biodiversity measures the conservation status of all marine species, including endangered species and species in relatively good conditions. Habitat's biodiversity measures the status of marine habitats that support large numbers of marine species ($n = 8$ habitats), and it is as a proxy for the condition of the broad suite of species that depend on them. Values range from 0 to 100. A score of 100 indicates that all species are at very low risk of extinction and that all habitats are conserved. The score was calculated separately for species and habitats and then combined (average value) to obtain a unique conservation status value for the Mediterranean countries EEZ.

2.4. The impact coefficient

In the EEZ of Mediterranean countries with suitable areas for multi-use, biodiversity conservation status and cumulative human pressures were assessed to derive an impact coefficient. This coefficient serves as an indicator of ecosystem tolerance to additional activities.

The Impact coefficient was calculated as the ratio between the cumulative pressure and the conservation status of marine biodiversity. As outlined in Sections 2.2.4 and 2.3.2, cumulative pressure and biodiversity conservation status were assessed using indices developed by Halpern et al. (2008 (Halpern et al., 2012); The cumulative pressure index and biodiversity conservation index quantify independent anthropogenic impacts and status on species and habitats. Thus, to obtain a single cumulative pressure and biodiversity status score for each Mediterranean country's EEZ, the average values for habitats and species were calculated. The score of the impact coefficient ranges from 0 to 1, with 0 indicating a high biodiversity conservation status, with respect to the cumulative pressures and 1 a high cumulative pressure score, in relation to the conservation status of marine biodiversity. The closer the score of the impact coefficient is to 0, the less saturated the system is, and *vice versa.*

Ideally, the optimal conditions for the ecosystem would correspond to minimum cumulative pressures and maximum conservation status (Impact factor = 0). Conversely, high cumulative pressures and low conservation status would indicate saturated ecosystems (Impact factor = 1).

2.5. Data sources and analysis

The spatial resolution of the grid cell for the Mediterranean Sea was 0.2° (20 km), from 0 to 2000 m depth. Long-term data series with spatial resolutions between 0.04° (≈4 km) and 0.3° (≈30 km) and temporal resolutions of hours and days were used (Table 3). To account for the different resolutions of data sources for each variable, the closest point to each grid cell was used. Regarding temporal resolution, the use of hourly or daily data from different sources was determined by the specific requirements of each parameter included in the *SI* formula. If a variable was available hourly but needed daily, the daily average was calculated to enable its integration with other daily data. Finally, the temporal period was adjusted to each *SI*, based on the overlapping temporal coverage of all relevant variables. Thus, to ensure consistency and coherence in the final *SI* calculations, a common time frame was selected, even at the expense of excluding longer time series from individual variables. This temporal window varies between groups (fish and cephalopods, bivalves, and macroalgae) because each needs different variables for their *SI*.

SI analysis were conducted at each cell of the grid (3632 cells) using MATLAB R2023b. The spatial data was analysed using a Geographic Information System (ArcGIS Desktop 10.8 by ESRI), employing the Pan-European projection system ETRS89 Lambert Azimuthal Equal-Area (LAEA).

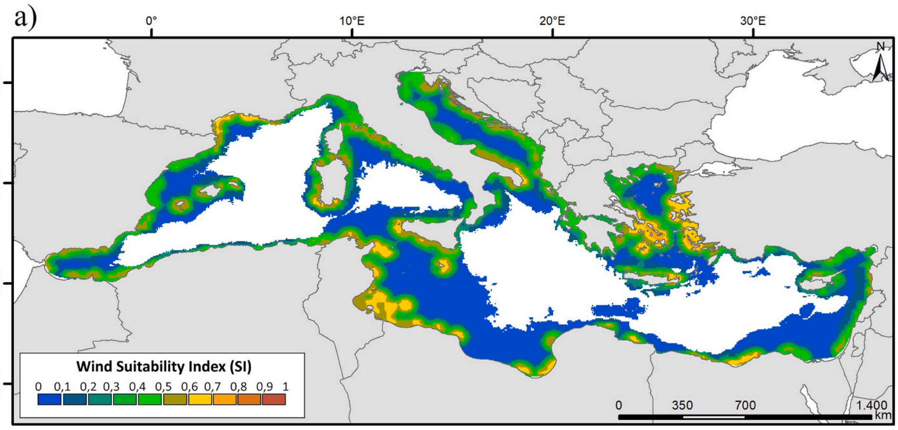
3. Results

3.1. Marine renewable energies and aquaculture opportunities

The Aegean Sea (*SI*~0.7) has the highest wind *SI* in the Mediterranean Sea, with maximum values recorded in the Cycladic archipelago and on the Island of Mykonos ($SI > 0.75$; Fig. 2a). Six countries register *SI* values above 0.6: Tunisia (0.67), France (0.67), Libya (0.6 5), Egypt (0.63), Malta (0.63) and Italy (0.62). The wind resource in these countries is noticeable and the main limiting factor in the suitability analysis is the distance from urban areas (i.e., energy transmission).

The highest *SI* values ($SI > 0.6$) for wave energy are found along the North African coasts of Tunisia (0.63), Libya (0.64), Egypt (0.64) and Morocco (0.63), together with regions in Malta (0.62) and southern Italy (0.6; Fig. 2b). The southern Mediterranean regions are the most energetic with a noteworthy availability of wave resources. Greece, Spain and France have notable wave energy potential; however, current conditions for O&M activities, structural suitability and energy transmission in these areas present a series of constraints. These limitations have also restricted suitable areas for wave energy developments to coastal regions, due to harsh offshore met-ocean conditions and the long distance from ports and consumer centers outside these areas. The maps for each of the suitability factors considered in the Suitability Index (*SI)* for wind and waves (*i.e.* energy production, structure, operation and energy transmission) are available in the Marine Spatial Planning Viewer (https://msp.ihcantabria.com/#/tool).

Out of the twenty-two finfish species originally considered, eleven have suitable areas for aquaculture in the Mediterranean Sea ($SI > 0.5$). Looking for synergies between different aquaculture productions, we find that the Adriatic Sea, the Aegean Sea, the west coast of Italy, the north-east coast of Spain and the east coast of Tunisia are suitable areas ($SI > 0.7$) for farming at least four species. European seabass is the species with highest *SI* values (Fig. 3a), the Aegean and the Adriatic Sea ($SI \sim 0.9$) representing the regions with the highest suitability for cultivating it. Other suitable areas for this species ($SI > 0.85$) are found in Turkey's west coast; Greece, Aegean Sea; Montenegro, Albania, Italy,



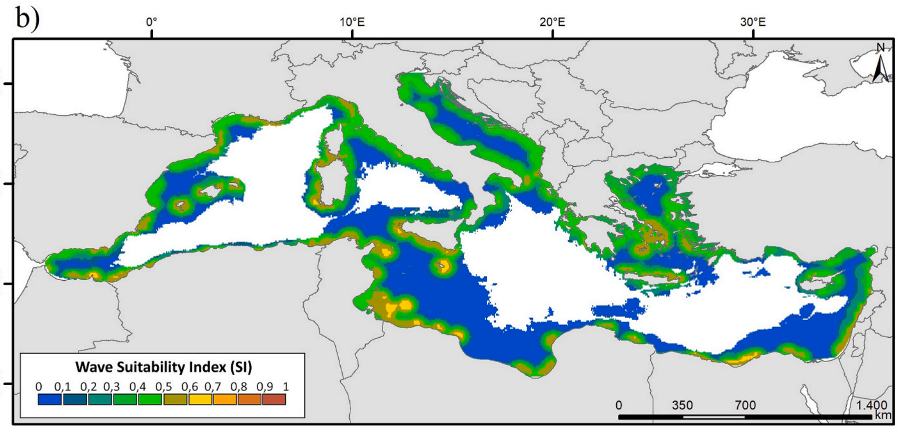


Fig. 2. Suitable areas for marine renewable energies in the Mediterranean Sea: a) Suitability index, *SI* (0–1) for wind energy. b) Suitability index, *SI* (0–1) for wave energy.

the west and south coasts and Sicily; and Spain, east coast and Balearic Islands. Similar spatial distribution patterns and *SI* values are observed for gilthead (Fig. 3b), meagre (Fig. 3c) and common dentex (Fig. 3d). Moreover, greater amberjack (Fig. 3e), Atlantic bluefin tuna and flathead grey mullet (Fig. 3f), and red porgy (Fig. 3g) also share suitable areas due to similar biological requirements and limitations in operational and structural suitability (Table 2). Tunisia (east coast), Spain (Mediterranean coast and Balearic Islands) and Morocco have suitable areas ($SI \geq 0.8$) for these species. The last group of species sharing suitable areas are wreckfish (Fig. 3h), dusky grouper (Fig. 3i) and blackspot seabream (Fig. 3j). For these species suitable areas are located along the coasts of Spain, Morocco and Tunisia. Of these three species, the dusky grouper has the smallest available suitable area in the Mediterranean, although its *SI* is up to 0.8 along the southeast coast of Spain. Suitable areas for blackspot seabream and wreckfish (>0.75) are also found in the southeast coast of Spain.

Wreckfish, dusky grouper and blackspot seabream are the only species likely to experience the effects of seawater heat waves for more than 7 consecutive days (i.e., extreme temperature event). The inner Adriatic, Tunisia, Libya, Egypt, Israel, Lebanon, and Syria have the highest probability to register extreme events. High probability areas for heatwaves only affect areas suitable for wreckfish ($SI > 0.5$) in certain areas of Tunisia (Fig. 3h). The maps for each of the suitability factors considered in the Suitability Index (SI) for aquaculture (i.e. biological, structure and operation) maps obtained for each species of interest are available in the Marine Spatial Planning viewer (https://msp.ihcantabria.com/#/tool).

3.2. Multi-use opportunities

Multi-use opportunities examine the combination of wind energy, wave energy and aquaculture in the Mediterranean, considering suitable areas with a $SI > 0.5$ for the three activities and the cultivation of 5, or more, finfish species (Fig. 4).

The main added value for multi-use in the Mediterranean is related to the simultaneous development of wind and wave renewables (100,029 km^2). Libya (23,069 km^2), Italy (18,096 km^2) and Tunisia (15,472 km^2) account for 56 % of the suitable areas for the combined exploitation of renewable energies. Wind energy and finfish species farming could potentially be combined across 32,551 km^2, with three countries accounting for 66 % of the total available area. Tunisia has the largest area (10,951 km^2), followed by Spain (6141 km^2) and Italy (4446 km^2). Compared to the other multi-use combinations, the combined use of wave energy and aquaculture has the smallest area available in the Mediterranean (24,830 km^2). Tunisia (7930 km^2), Spain (5096 km^2) and Libya (5030 km^2) are the countries with the most extensive areas, and together account for 72 % of the total available area in the Mediterranean, where up to 21,596 km^2 are suitable for the joint development of the three activities (wind, wave and aquaculture; Fig. 4). Wind and wave are compatible in large areas of the Mediterranean (100,029 km^2), but when aquaculture is taken into account multi-use compatible areas are reduced by 80 %. These areas are mainly located in the southern and western Mediterranean. Around 78 % of the multi-use opportunities for the combination of the three activities are concentrated in three countries: Tunisia (7930 km^2), with the best conditions for all possible multi-use combinations, Libya (5030 km^2) and Spain (4005 km^2). Under the heading of aquaculture, the species with suitable areas ($SI > 0.5$) vary according to the multi-use

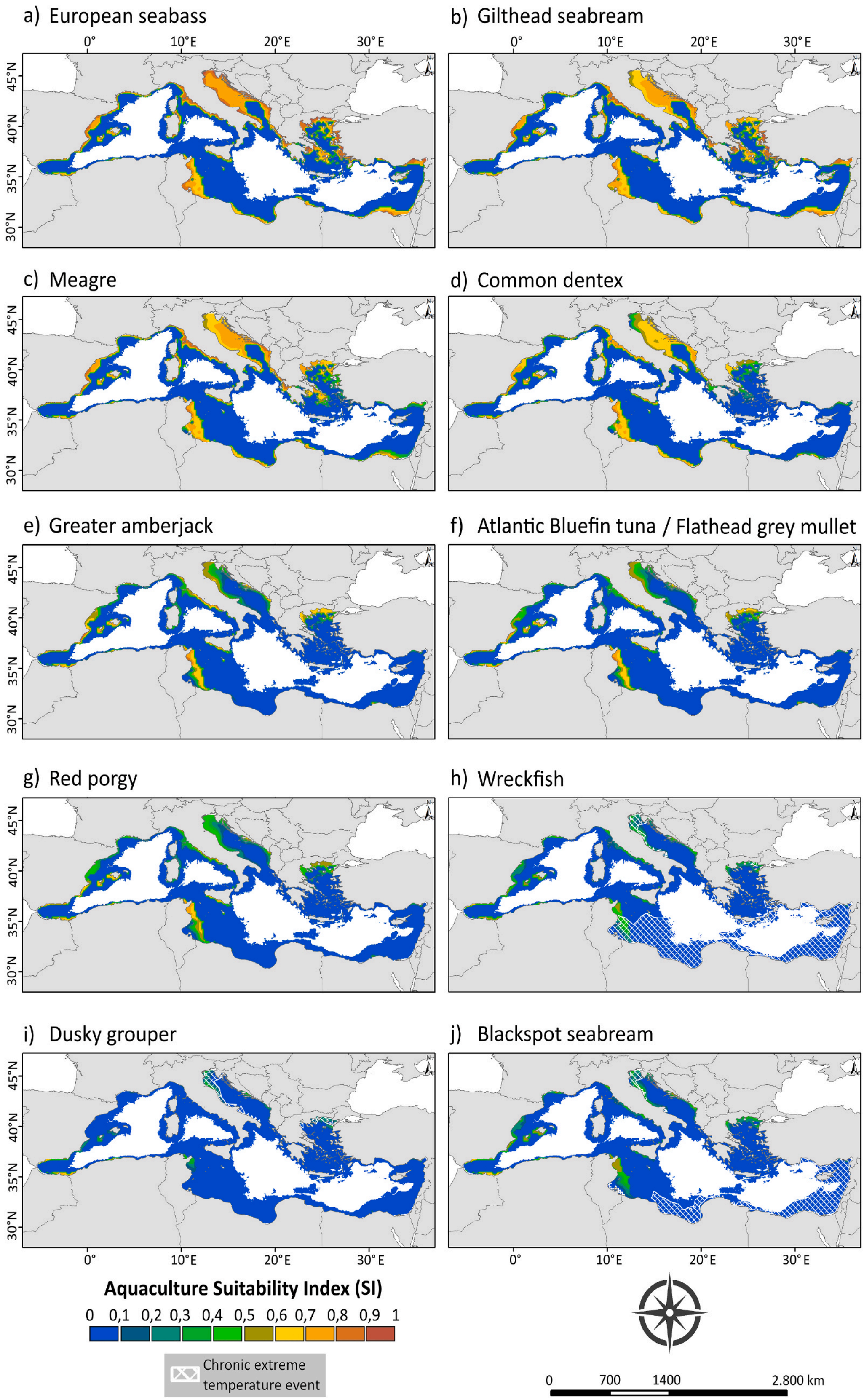


Fig. 3. Suitability index, *SI* (0–1) for aquaculture of: **a)** European seabass; **b)** Gilthead seabream; **c)** Meagre; **d)** Common dentex; **e)** Greater amberjack; **f)** Atlantic Bluefin tuna and flathead grey mullet; **g)** Red porgy; **h)** Wreckfish; **i)** Dusky grouper; **j)** Blackspot seabream. Extreme events, heatwaves (striped pattern) for more than 7 consecutive days were identified for 3 species: wreckfish, dusky grouper and blackspot seabream.

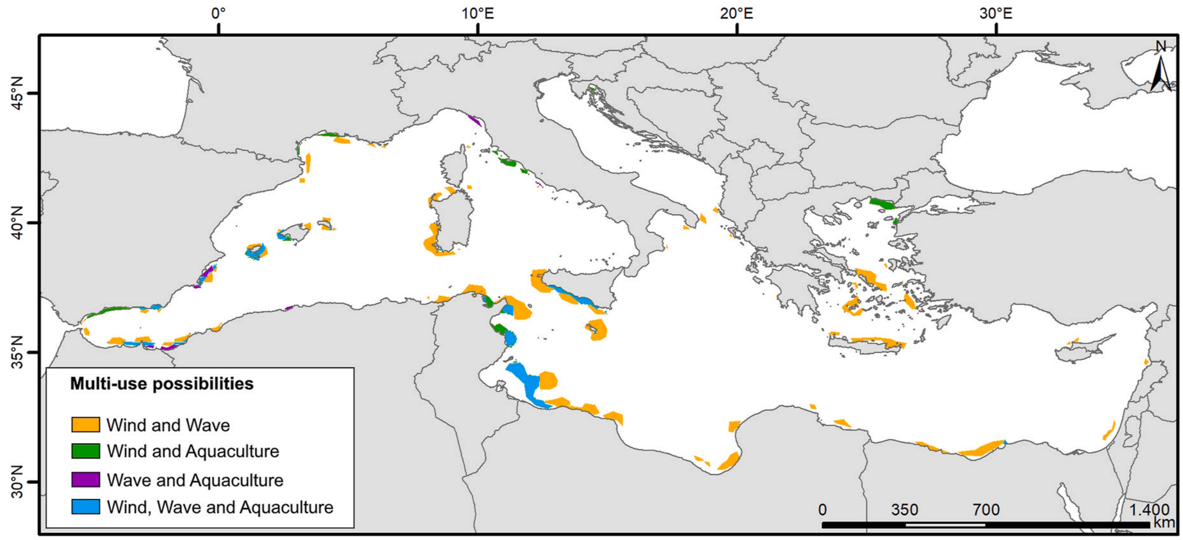


Fig. 4. Suitable areas for multi-use in the Mediterranean Sea ($SI > 0.5$ for wind, wave and aquaculture). Four possible multi-use combinations are shown: wind and wave; wind and aquaculture; wave and aquaculture; and wind, wave and aquaculture.

combination. However, six species, European seabass, Gilthead seabream, Meagre, Common dentex, and Greater amberjack, are present in all four combinations, though no clear spatial distribution pattern is identified.

Seventeen Mediterranean countries have opportunities for multi-use developments, and eight countries in the north of Africa (i.e. Algeria, Egypt, Libya, Malta, Morocco and Tunisia) and south of Europe (i.e. Spain and Italy) have suitable areas for the development of the 4 possible combinations of multi-use (Fig. 5). Overall, Italy (20,463 km^2), Libya (23,087 km^2), Tunisia (18,493 km^2), Spain (13,034 km^2) and Greece (14,066 km^2), have the largest suitable areas for multi-use. But in relation to their EEZ, Morocco (15 %) and Tunisia (12 %) have the highest percentage. The impact coefficient in the EEZ is calculated as the ratio between the cumulative pressure and the conservation status of marine biodiversity and pretends to infer the ecosystem tolerance to new activities. Spain and France have the lowest scores (0.47), while Tunisia or Libya are above the average score across countries (≥0.65). These last two countries have optimal conditions for the exploitation of natural resources (e.g. wind, waves, sea temperature, etc.), but the high score in the impact coefficient suggests that the pressures already accumulated in the EEZ may be affecting the conservation status of marine biodiversity. But the main anomaly is Syria. In this country, the cumulative pressure is higher than the conservation status score, indicating that the system is highly impacted. When focusing on the environmental dimension, it is outstanding that France (73,031 km^2; 60 %) and Spain (52,779 km^2; 28 %), account for the largest MPAs, and are between the countries with a higher score in the conservation status of marine biodiversity (Fig. 5).

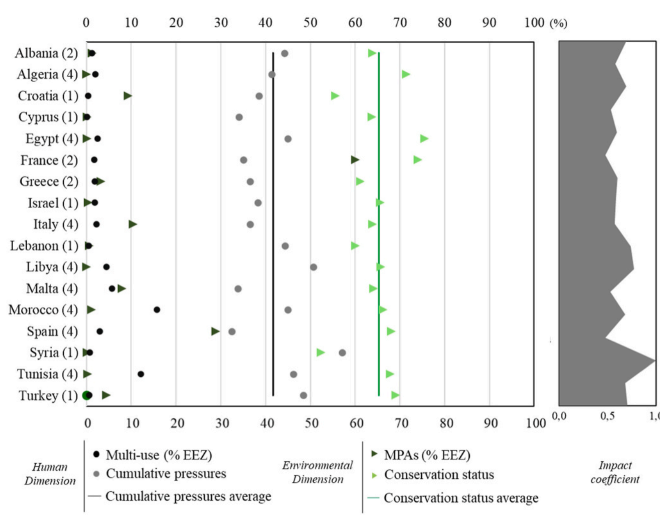


Fig. 5. Factors of the human dimension (circles) and environmental dimension (triangles) in the EEZ of the Mediterranean countries with areas suitable for multi-use. The number of multi-use combinations with suitable areas is given in brackets next to the country name. Suitable areas for multi-use and MPAs are expressed as a percentage (%) of the EEZ. Cumulative pressure and conservation status in the EEZ are expressed as a dimensionless value (0–100). Solid lines are the average value of conservation status (green) and cumulative pressures (black) considering the countries with suitable areas for multi-use. The graph on the right shows the impact coefficient (0–1) calculated as the ratio of cumulative pressure to conservation status for each country.

3.3. Interactions with marine protected areas

In the Mediterranean basin, around 16 % of the suitable areas for wind energy and aquaculture and wave energy and aquaculture overlap with MPAs (top-down approach) and whatever the combination of multi-use, the main interaction is with the Natura 2000 (Fig. 6a). Focusing on biodiversity hotspots, the maximum overlap is with wind energy and aquaculture (6.3 % of suitable areas), and again, regardless of the combination of multi-use, the main overlap is with the Pelagos sanctuaries.

When the interactions are analysed from an ecosystem perspective (bottom-up approach), *Posidonia oceanica*, a biodiversity hotspot, is the most affected ecosystem by multi-use developments (Fig. 6b). The main interactions occur in shallow waters (less than 300 m) and 12 % of seagrass beds may be affected by the multi-use of wind and wave energy. In contrast, deep-water ecosystems such as the Pelagos Sanctuaries which cover 88 % of the Mediterranean biodiversity hotspots (134,121 km^2), are only affected by multi-use developments in 2.5 % of the area.

4. Discussion

4.1. Renewable energies and aquaculture opportunities

Despite the limited number of studies carried out in the Mediterranean Sea to assess the spatial expansion of marine aquaculture and energy production, the results obtained in this study highlight the

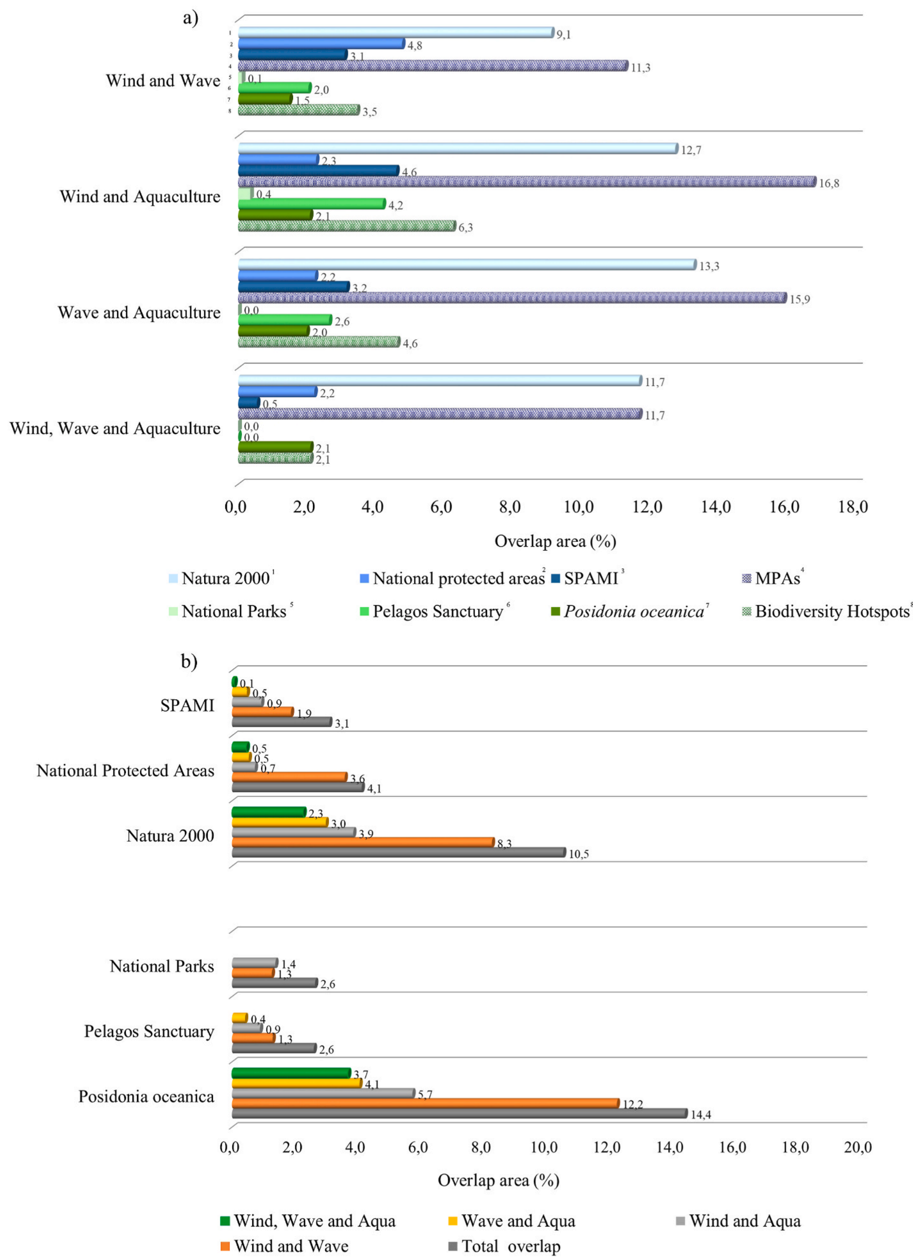


Fig. 6. a) Multi-use suitable areas combining wind, wave and aquaculture, overlapping with MPAs (1–4) and biodiversity hotspots (5–8). b) MPAs (i.e. SPAMI, National Protected areas, Natura, 2000) and Biodiversity hotspots (i.e. National Parks, Pelagos sanctuary, *Posidonia oceanica*) in the Mediterranean Sea that are overlapped by different combinations of multi-use suitable areas (%).

suitability of the Mediterranean Sea for the individual and joint development of these activities. The current study explores the potential of the Mediterranean Sea for multi-use combinations of renewable energies and aquaculture. The novelty of the multi-use analysis conducted lies in its probabilistic, standardised, quantitative, and scalable nature. It holistically assesses environmental, technical, operational and biological aspects providing an overview of potential opportunities for the combined or individual development of wind, wave and aquaculture. This study also analyses the interactions between the human and environmental dimensions taking into account the potential multi-use developments, the distribution of MPAs and the current cumulative pressures, together with biodiversity's conservation status.

The Mediterranean basin is characterised by narrow continental shelves. Extensive shelf areas only occur in the northern half of the Adriatic and on the east coast of Tunisia, where the shelf extends for about 300 km. This geomorphology of the Mediterranean basin strongly determines the search for opportunities and the availability of suitable areas for renewable energy and aquaculture developments, which are scarce and close to the coast. However, the Mediterranean has a unique advantage for combining the development of offshore wind and wave renewable energies due to its energy production and connection to the electricity transmission grid. Our analysis highlights that the best opportunities for wind energy developments are in the Aegean Sea, between Greece and Turkey ($SI \sim 0.7$) and in the North African coasts of Tunisia, Libya, Egypt and Morocco, together with regions in Malta and southern Italy, for wave energy developments ($SI > 0.6$). Nevertheless, when the opportunities for wind energy obtained in this study are compared with the location of the real projects, we observe that today, there are no fully commissioned projects in most of these regions. The Aegean Sea is a development zone (4COffshore, 2023). Italy has more than 160 offshore wind projects in concept or early planning stages in the EEZ. Most of them are planned in the three areas identified as highly suitable (4COffshore, 2023). The first and, so far, only completed offshore wind project in Italy is Beleolico (Puglia, southeast Italy) with 30 fully commissioned MW and with estimated *SI* values between 0.5 and 0.6. The North Adriatic region shows the main discrepancy between the *SI* and the planned projects. Although this region has several projects in the planning stage, the analysis shows limitations related to resource quality and energy transmission (i.e. distance from urban centers). In the Gulf of Lion (France), two wind farms are also currently in the pre-construction phase (60 MW) and four others are in development phase (1.5 GW; 4COffshore, 2023). Although suitable areas for wave energy have been identified, there are currently no operational wave farms in the Mediterranean Sea. According to Dialyna and Tsoutsos (2021), 10 WECs in the Mediterranean have achieved a technological readiness level (TRL), with at least 6 of them having been tested in real conditions. In addition to spatial and met-ocean constraints, the development of wave energy in the Mediterranean faces several technical and logistical challenges. Although the potential identified in many regions is significant, the absence of commercially viable wave energy converter (WEC) technologies, high costs related to energy storage, and limited infrastructure for grid connection and offshore maintenance continue to hinder its implementation (Magagna and Uihlein, 2015; Dialyna and Tsoutsos, 2021). Moreover, the intermittency of wave resources demands hybrid systems or advanced storage solutions to ensure a stable energy supply, which remains a key limitation for large-scale deployment. Recent studies also highlight the high seasonal and spatial variability of wave energy flux in the Mediterranean, as well as the limited predictability of swell contributions, further complicating reliable energy integration (Bozzi et al., 2018; Oikonomou et al., 2024).

Of the 22 species of fish, cephalopods, bivalves and macroalgae originally considered for aquaculture, eleven finfish species have shown to be suitable for aquaculture in the Mediterranean Sea. The European seabass achieved maximum *SI* values in the Adriatic Sea, between Greece and Turkey, and next to the coast ($SI \sim 0.9$). This species is the main commercial fish farmed in the Mediterranean, mainly by Turkey, with a production of 155,151 tonnes (live weight) and Greece, with 51,174 tonnes in 2021 (FAO, 2023). Gilthead, meagre and common dentex showed similar spatial distribution patterns and *SI* values as seabass. Gilthead seabream and meagre are currently farmed in the Mediterranean Sea and Turkey is the main producer with 133,476 tonnes and 5913 tonnes, respectively in 2021 (FAO, 2023). Common dentex was also produced by Turkey, but the last production was in 2019 with 27 tonnes.

Greater amberjack, Atlantic bluefin tuna, and red porgy are currently farmed in the Mediterranean Sea. Spain and Greece are the only producers of greater amberjack with 140 and 172 tonnes in 2021, respectively (FAO, 2023). Both countries have areas with *SI* over 0.7. The main producer of Atlantic bluefin tuna in the Mediterranean Sea is Malta ($SI \sim 0.65$), with 13,549 tonnes, followed by Spain ($SI > 0.75$) with 8399 tonnes in 2021 (FAO, 2023). Red porgy is produced in Turkey (4271 tonnes) and Greece (4 tonnes in 2021, FAO, 2023), with an *SI* of 0.6 in these countries, while flathead grey mullet farming was exploited in Greece in 2017, with a production of 6 tonnes (FAO, 2023). On the Greek coast, the suitability for farming this species is about 0.65. In addition to the areas where these four species are already farmed, Tunisia, Italy, Morocco and Algeria also have suitable conditions. The Tunisian coast has a $SI > 0.87$ for greater amberjack. Therefore, these species could be an alternative for the aquaculture market in these countries. According to FAO (2023), wreckfish, dusky grouper and blackspot seabream are not yet commercially farmed in the Mediterranean Sea, although along the coasts of Spain, Morocco and Algeria, the *SI* was >0.5. The study identified synergies for the production of multiple species, finding that the Aegean Sea, the Adriatic Sea and the west coast of Italy, the Spanish coast and Tunisia are suitable areas for farming at least four different finfish species ($SI \geq 0.7$).

4.2. Multi-use opportunities

The main question to be answered is: why multi-use?

Population is expected to increase by nearly 2 billion people by 2050, along with food and energy needs, along with the development of marine emerging economies (IEA, 2020). Oceans and seas cover 70 % of the Earth's surface and more than 65 % of the EU territory and marine ecosystems are one of the main sources of biodiversity, food and energy (European Commission, 2023).

Because in this context preserving marine ecosystems is critical, the expansion of new marine activities must be accompanied by solutions that are socially, environmentally, and economically sustainable. And, this is the basis of multi-use. Multi-use refers to the shared use of resources in close geographical proximity by one or multiple users (Bocci et al., 2019). Recent evidence indicates growing industry interest in multi-use solutions. In a recent survey of the aquaculture and offshore wind sectors in Spain, participants expressed interest in fostering synergies between the two sectors, particularly through symbiotic multi-use. (Weiss et al., accepted with minor revisions). In this use, activities share key services and infrastructure such as transport, port facilities, and monitoring systems (Schupp et al., 2019).

The feasibility of multi-use marine activities is primarily driven by economic and technical synergies. Benefits include shared infrastructure, spatial optimization and economic efficiency, reduced operational costs, and improved environmental monitoring. However, the absence of a coherent regulatory framework, regulatory fragmentation, and administrative complexity, particularly between national and regional governance, remain key barriers (Weiss et al., 2023; Dalton et al., 2019; Depellegrin et al., 2019; Ciravegna et al., 2024). Moreover, the emerging nature of multi-use technologies limits funding opportunities, as investors favor established approaches. Uncertainty around business models and insurance complicates financing due to potential cross-sector impacts and in the next few years, we will see whether this economic model is viable.

Although multi-use could improve economic and energy efficiency (Gao et al., 2021), globally, very few multi-use developments have been implemented in real sea conditions, and none of them are located in the Mediterranean. Poseidon Floating Power is a floating device located in the Baltic Sea for the combined exploitation of wind and wave. Poseidon went into real sea test in 2008 and it is the world's only offshore-proven and grid-connected combined floating wind and wave device that transform wave energy into electricity and serves as a floating foundation for off-shore windmills (https://tethys.pnnl.gov/project-sites/poseidon-floating-power-poseidon-37).

Between 2010 and 2013, the European call "The ocean of tomorrow" aimed at funding initiatives that encouraged marine and maritime research and industrial communities to come together and develop concepts and technologies with a multidisciplinary, cross-cutting approach (Collu and Bachynski, 2019). Under the topic "Multi-use offshore platforms", three projects were funded: H2Ocean, Mermaid, and Tropos. The funded multi-use initiatives included offshore floating hybrid-wind-wave energy units, aquaculture units, and several service platforms. Under the H2Ocean project, a series of techno-economic feasibility assessments, complemented by environmental impact analyses, were performed considering far offshore, multi-purpose farms in the Mediterranean Sea, North Sea, and North Atlantic Ocean. Focusing on four areas (Baltic Sea, North Sea, Atlantic, and Mediterranean), Mermaid performed a technical, environmental, and socio-economic assessment of the solutions proposed. Guidelines for the development, management and implementation of multi-purpose offshore platforms in these European scenarios were provided. As the previous ones, the Tropos project looked at multi-purpose platform systems (Collu and Bachynski, 2019).

These projects were the precursors of multi-use initiatives in the Mediterranean Sea. Since then, different projects have focused on new developments, and on the identification of areas for multi-use projects.

However, despite the comprehensiveness of these research initiatives, little attention has been paid to the assessment of multi-use considering marine wind and wave energies and aquaculture together (Weiss et al., 2018c; (Weiss et al., 2020); (Weiss et al., 2023)), and none has addressed multi-use in the Mediterranean.

4.3. Interactions between human and environmental dimensions

As previously discussed in the paper, one of the major challenges when developing new marine activities is to ensure the conservation of biodiversity within very complex socio-ecological systems. The Mediterranean Sea is a complex mosaic of countries and national jurisdictions, each with unique development priorities and environmental challenges: It supports between 4 % and 18 % of global biodiversity and accommodates up to 150 million people during the tourist season. The area covered by MPAs in the Mediterranean Sea is 228,980 km^2 (18.7 %; Agnesi et al., 2020), but it is also one of the most heavily impacted marine ecosystems due to human activities such as navigation, tourism, fishing, and other forms of exploitation. Its intercontinental character makes its sustainability a significant challenge. The potential effects of multi-use in the MPAs are diverse and depend not only on the magnitude, but also on the locations and the structure, functionality and vulnerability of the ecosystems (Lloret et al., 2023). Such effects change substantially depending on the habitats, or the species. This highlights the need to explore opportunities for marine renewables and aquaculture, while also identifying biodiversity hotspots where unique, endangered, or vulnerable habitats or species are present. Assessing the scale of impacts and establishing conservation priorities is critical in these cases.

In the framework of the EU Nature Restoration Regulation (Regulation , 2024/1991), which aims to promote the ecosystem resilience, the development of integrated economic models that accommodate emerging ocean activities, while maintaining ecological integrity is a scientific and policy imperative. This means that the development of activities in certain locations may be counterproductive, rendering its development unfeasible.

Our analysis does not determine where new activities may or may not take place, nor does it set limits or thresholds. Rather, it aims to provide information and criteria to interested parties and administrations with the necessary elements for informed decision-making, guided by precautionary and preventive principles. The application of these principles in the planning of the ocean, particularly when MPAs are affected, implies alleviating the most fragile components of marine ecosystems and avoiding their overloading.

Effective coastal and marine management should aim to provide the highest level of protection for ecosystems, natural resources, and essential ecosystem services. However, although the Mediterranean Sea functions as a continuous system of interconnected ecosystems and MPAs, it is politically fragmented, with multiple countries exercising jurisdiction over their respective national water. This geopolitical mosaic significantly influences both the conservation status of ecosystems and the formulation of conservation objectives. This is evident when we analyse the impact coefficients. Our study compares the biodiversity conservation status and the cumulative pressures to infer an impact coefficient in the EEZ of Mediterranean countries with suitable areas for multi-use. This coefficient provides an indication about the tolerance of the ecosystems to new activities. When focusing on the four countries with the largest suitable areas for multi-use developments in the Mediterranean Sea, it is evident that the impact coefficient score varies considerably among them. The scores range from the highest in Libya, followed by intermediate scores in Tunisia, Greece, Italy, and Spain, which has one of the lowest scores in the Mediterranean. These results show the potential for renewable energy and aquaculture developments in southern Mediterranean countries. However, they also reveal the impact on local ecosystems of the existing activities and suggest a limited ecological capacity to tolerate new activities. Accordingly, our recommendation is that these areas should be excluded from further development until comprehensive, site-specific assessments are undertaken and current pressures are effectively alleviated.

These findings align with those of other researchers in the Mediterranean region (Micheli et al., 2013; Paolo et al., 2024), who also identified significant impacts in the Sicilian Channel and the Tunisian Platform. The approaches to evaluate the cumulative impacts in the Mediterranean are numerous and the results are highly diverse. Micheli et al. (2013) stated that that cumulative index varies greatly across and within ecoregions and countries and highlighted that 20 % of the Mediterranean Sea and the Black Sea were subjected to high impact. More recently, Paolo et al. (2024) revealed that fishing is the most active non-public ocean industry. Although they indicated that fishing activity is causing far more depletion than other ocean industries, their results showed, for example, the high density of untracked fishing activity along the coast of Tunisia. Coll et al. (2011) mapped areas with high species diversity overlapping with areas suffering from high anthropogenic threats in the Mediterranean Sea for the first time, and concluded that those overlaps were widespread and could be used to identify priority areas for biodiversity protection.

5. Conclusions

One of the major challenges when developing new marine activities is to ensure the conservation of biodiversity within very complex socio-ecological systems. The Mediterranean Sea is a complex mosaic of national jurisdictions, each with unique development priorities and environmental challenges. It supports between 4 % and 18 % of global biodiversity and accommodates up to 150 million people during the tourist season. To integrate all these realities, this study adopts a socio-ecological approach to identify new multi-use opportunities in the Mediterranean, considering both the quality of exploitable resources and the ecosystem's capacity to tolerate additional activities.

Throughout this contribution is has been shown that seventeen Mediterranean countries have potential for multi-use development. It has been shown that multi-use opportunities, particularly for wind energy combined with aquaculture, are most promising in Tunisia, Spain, and Libya. The Aegean Sea (Greece and Turkey) has the highest wind resource and the southern Mediterranean (Tunisia, Libya) shows notable wave energy potential. Aquaculture suitability is also high, especially in the Aegean and Adriatic Seas. However, the findings also show the impact of existing activities on local ecosystems, suggesting a limited ecological capacity of these regions to tolerate new activities.

The study underlines the idea that the expansion of new activities must be accompanied by socially, ecologically and economically sound solutions. It does not determine where new multi-use activities may or may not take place in complex socio-ecological systems, nor does it set limits or thresholds. Rather, it provides interested parties and administrations with the necessary information and criteria for informed decision-making, guided by precautionary and preventive principles. These principles, when applied to the marine spatial planning imply alleviating the most fragile components of marine ecosystems and avoiding their overloading.

CRediT authorship contribution statement

Bárbara Ondiviela: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Raúl Guanche:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Elvira Ramos:** Writing – review & editing, Formal analysis, Data curation. **Lucia Meneses:** Writing – review & editing, Formal analysis, Data curation. **Carlos V.C. Weiss:** Writing – review & editing, Formal analysis, Data curation. **Jonne Kotta:** Writing – review & editing, Data curation. **José A. Juanes:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

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