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Exploratory study on offshore aquaculture suitability and co-location with marine renewable energy in Portugal

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ABSTRACT

The increasing global demand for seafood, coupled with the urgent need of transition to renewable energy sources, has led to a growing interest in innovative and sustainable uses of marine space trough the development of Marine Spatial Planning protocols. Offshore aquaculture and renewables are two sectors poised for significant growth along the Portuguese coast, a country with outstanding potential for both sectors. Therefore, this paper seeks to assess the technical and environmental feasibility of co-locating these two industries along the continental coastline.

The study focused on identifying suitable sites for the farming of 3 key species – *Dicentrarchus labrax* (European Seabass), *Mytilus galloprovincialis* (Mediterranean Mussel) and *Laminaria hyperborea* ("curvie" Kelp) - by generating multicriteria suitability indexes and evaluating their compatibility with areas allocated for marine renewable energy deployment. Metocean data was obtained from the Copernicus database, with particular emphasis on seawater temperature, salinity and chlorophyll concentrations. The species' tolerance and ideal growth limits for these values were obtained from literature references. Lastly, suitability maps were generated through Python scripts and QGIS.

Results indicated that several areas along the Portuguese coast, mainly so in the Northwest, may offer adequate suitability for the target species, also overlapping with zones identified as appropriated for offshore wind and/or wave energy deployment. In addition, technical and environmental considerations, as well as potential conflicts with other activities and protected areas, were identified. Moreover, the potential influence of climate change was explored. These remarks suggest that co-location should be studied and improved in-depth, not only to bolster co-location synergies and minimize local conflicts and impacts, but also to provide robust information for proper decision-making processes.

1. Introduction

Given the rapid growth of the world's population, the demand for food production is progressively increasing. As seafood consumption offers significant health benefits, such as providing essential nutrients, from protein to omega-3 fatty acids, aquaculture has been one of the fastest-growing food production sectors in the world. Thus, it plays a fundamental role in meeting human demand (Golden et al., 2021).

According to Fig. 1a, global capture fisheries production has remained relatively stable since the late 1980's. This is greatly attributed to the depletion of explored populations and strict fishing quotas. On the other hand, aquaculture has experienced significant growth over the same period, although at a slower pace in the last two decades. The average annual growth rate was 6.1% in the 2000's, 4.4% in the 2010's, and 3.7% in the 2020's (FAO, 2024). In fact, aquaculture, has expanded across marine and freshwater environments and is now producing more fish than wild capture. This activity, once traditional and localized, is now a high-tech sector facing both challenges and new opportunities (Buck and Langan, 2017).

The aforementioned slower pace of aquaculture can be explained by

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several factors. These include recent environmental policy changes and the decreasing availability of land, water, and suitable sites for aquaculture in key production regions. These aspects have contributed to the increasing demand for offshore aquaculture (OA) systems, which help overcome some of the challenges associated with coastal operations. However, they also introduce some new adversities, such as high cost of maintenance, monitoring and operations. To this adds the risk of structure and juvenile loss during high energy weather events (Miranda et al., 2025). Another risk resides in marine spatial planning, as conflicts with other offshore activities may arise. Nonetheless, there are also opportunities to explore, such as co-location with marine renewables.

With wind energy becoming a crucial contributor to the global energy mix, Europe is expected to accelerate the expansion of wind power capacity between 2024 and 2030. It is expected that 29 GW of new wind farms will be installed annually. However, to meet its 2030 climate and energy targets, Europe actually needs to install 33 GW per year (WindEurope, 2024). Given this, the EU's total installed wind capacity is anticipated to reach 393 GW, which is still below the 425 GW target. Additionally, and according to Fig. 1b, the EU's commitment to wind energy is evident, extending towards an increasing investment in offshore structures.

Furthermore, wave energy also emerges as a promising co-location option with OA systems. This has been evaluated in various regions, such as the European Union (Clemente et al., 2021; Clemente et al., 2022; Karathanasi et al., 2022; Ocean Energy Systems, 2022), the United States (Garavelli et al., 2022; Garavelli et al., 2025), and China (Long et al., 2024; Cao et al., 2025). As addressed in (Karathanasi et al., 2022), the severe wave, current and wind climates at offshore sites imply greater structural loads onto the aquaculture structures, such as cages. This leads to higher risks of system fatigue and/or failure, requiring better operation and maintenance planning – including feeding –, namely in terms of accessibility during weather windows and avoidance during severe events. Intense action from the aforementioned climate factors can also cause cage volume reductions and increment the farmed population's density (Abrahamsen et al., 2025). This can increase the individual's stress levels and the risk of collisions with the netting. Wave Energy Converters (WECs) can harness a resource with greater persistency and lower intermittency than offshore wind (Veerabhadrappa et al., 2022), whilst potentially providing an artificial barrier to aquaculture systems by attenuating incoming waves. Simultaneously, WECs

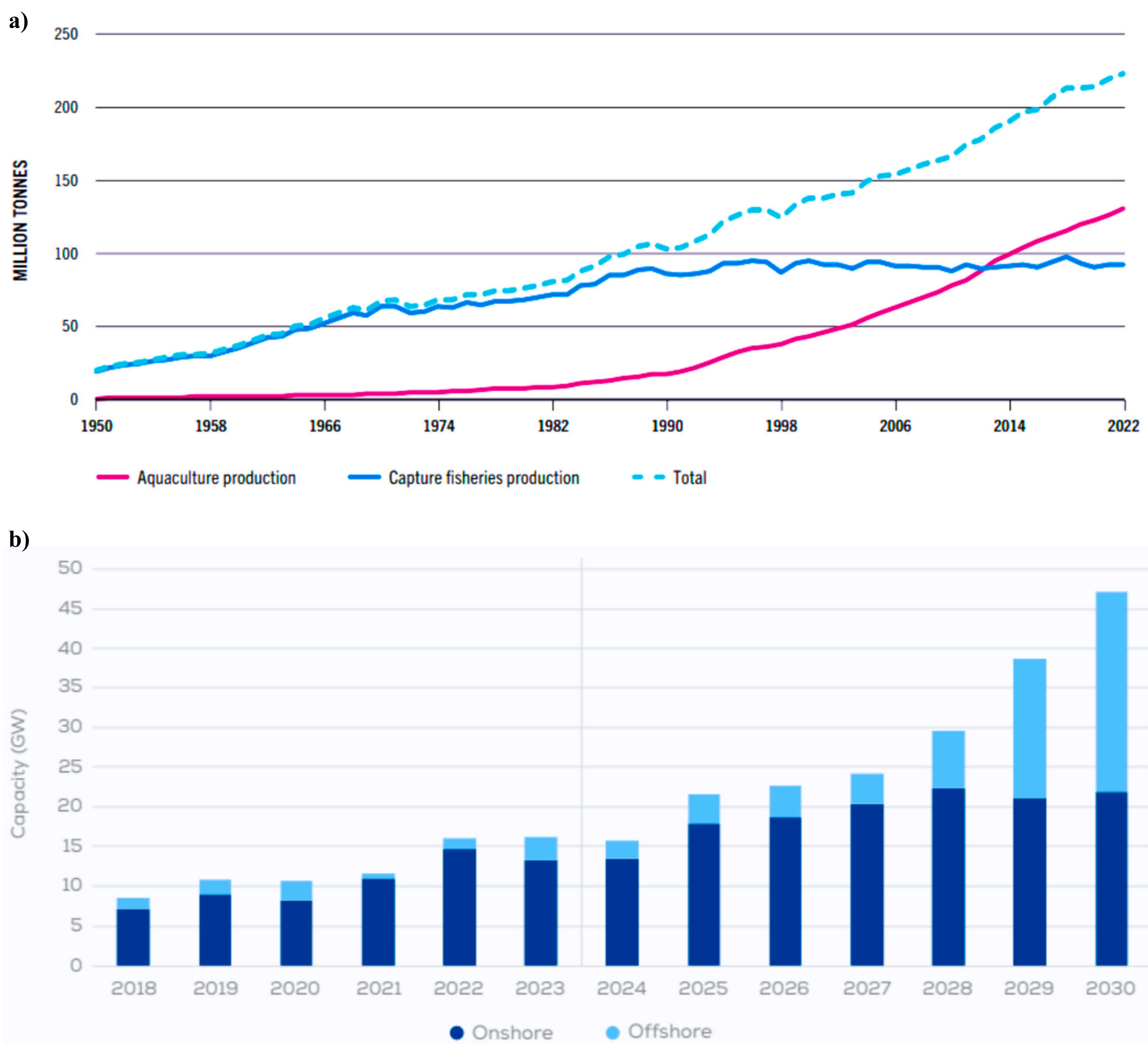

Fig. 1. a) World fisheries and aquaculture production, and b) 2024–30 annual onshore and offshore wind power installations in the EU. *Sources*: (FAO, 2024; WindEurope, 2024).

convert wave energy into useful electricity that can later be applied in various operations associated with aquaculture. These include electric boats, feeding units and even "intelligent" sensors, in order to increase productivity and product quality. The latter incorporates key information systems that enhance the automation capabilities of OA, and enable better control and monitoring of the farmed species (Wei et al., 2020). The Penghu platform and MoorPower WEC are prime examples of OA vessels integrating wave energy (Abaei et al., 2025; Yue et al., 2023). In (Ewig et al., 2025), the correspondence between WEC scale, which is generally smaller than its offshore wind counterparts, and the energy needs of OA farms is also highlighted. Still, feasible co-location requires several requirements, being operational compatibility (e.g., water depth range and energy transfer connections) and proximity between WECs and aquaculture sites key factors. An adequate overlap, in both space and time, between a WEC park's wake field and the OA facilities is crucial, so that the WECs' "shielding" effect can take effect. This can be achieved through numerical modelling with wave propagation models and sea-trials, though the former are generally robust and more accessible for assessing near and far-field effects of WEC parks (Fanti, 2019). A situation where the two sites are too close, very far apart and/or misaligned with regards to the most intense wave climates can greatly diminish the co-location benefits.

Co-locating these offshore industries is a relatively unexplored, yet potentially advantageous strategy. It maximizes marine space and brings benefits in terms of more sustainable management for both systems. All this considering that, besides promoting synergy, it contributes to the reduction of costs supported by the sharing of services related to the installation and transport (Miranda et al., 2025). Consequently, marine spatial data holds pivotal importance towards planning priorities and strategies, and to support the selection of potential farm sites for offshore systems, based also on suitable environmental conditions (Nunes et al., 2011; Caldow et al., 2015). This data is equally necessary for conducting the aforementioned numerical verifications of the WEC park wake fields.

A prime location for exploring co-location of the two offshore sectors is Portugal's continental coastline. Portugal holds the top position in Europe and represents the third place in the world ranking when it takes to fish consumption (only behind Iceland and Japan) (Almeida et al., 2015): around 60 kg of fish/year per capita (Clemente et al., 2023). As a result, aquaculture has become an activity of interest to this country, reaching 14,336 tons in 2019. This corresponds to an increase of 2.5% compared to the previous year (Mosqueira et al., 2022). In parallel, the need for energy transition enhances the possibility of co-locating these systems with renewable energy production stations, in this case, marine ones (MRES). With a target of 2 GWs of installed capacity by 2030, offshore wind and wave energy emerge as great options in Portugal. The higher velocity of wind on the open sea and the "hot-spot" of wave energy resource in the North Atlantic may generate sufficient power to meet the energy demands of aquaculture systems (Clemente et al., 2023). However, the available space for nearshore systems is limited, often leading to conflicts between different economic and tourist activities (Santjer et al., 2024). Accompanied by this, the interest in both OA and MRES has been rising in Portugal: it can help to reduce its dependency on imported products, decarbonize coastal activities, and boost its "blue" economy, creating jobs and investment opportunities along the coast.

Building upon this, the aim of this study consists of processing, analysing and integrating metocean, meteorological and spatial data, in order to identify suitable locations along the Portuguese coast for the installation of OA systems. To that end, reliable sources such as Copernicus, the National Laboratory of Energy and Geology (LNEG) and the Portuguese "Diário da República" were consulted. Additionally, it is also intended to explore the possibility of co-locating these structures with MRES, promoting an integrated and sustainable approach to the use of maritime space.

For this purpose, an intuitive simple, and easily replicable OA suitability index (SI) framework was developed. This framework integrates metocean data with species-specific tolerance thresholds to generate suitability maps for selected species (e.g., fish, bivalves and macroalgae) and can be readily applied on a national level by aquaculture practitioners and marine spatial planners to different coastal regions. Suitability maps generated for the Portuguese coast were analysed using geospatial techniques to identify potential co-location opportunities with MREs.

In terms of structure, Section 2 details the methodology used in this work, describing the study area, criteria for species selection and the development of a SI model. The SI is implemented in Python scripts that generate maps for visualization in QGIS. Section 3 focuses on presenting and discussing the main outcomes. This includes SI maps for the selected species and their integration with MRES deployment sites along the Portuguese coast. In addition, complementary remarks on technical and environmental aspects, including long-term factors (i.e., climate change), are provided. Lastly, Section 4 presents the main conclusions of the study, as well as recommendations for future work.

2. Materials and methods

2.1. Portugal's maritime spatial planning and offshore renewables

2.1.1. Overview

Portugal has a maritime continental border of approximately 1000 km, in addiction to 900 km of coastline corresponding to the Madeira archipelago and 400 km associated with the Azores islands (Pacheco, 2024). As a result, Portugal's maritime space covers an area of approximately 2 million km^2 and encompasses three distinct legal statuses: the exclusive economic zone (EEZ), territorial waters and internal maritime waters. This represents the largest EEZ within European waters, granting Portugal access to vast marine areas that must be strategically managed. Consequently, the proposed extension of the continental shelf beyond 200 nautical-mile limit is of even greater significance (Pacheco, 2014). By contrast, it entices higher requirements in terms of marine spatial planning.

Portugal's Situation Plan (PSOEM) was approved under the Resolution of the Council of Ministers No. 250/2019, and is currently accessible in geoportal format (DGRM, 2025a), Fig. 2. Several institutions played a role in its development, including the Directorate-General for Natural Resources, Safety and Maritime Services (DGRM), the Regional Directorate for Spatial Planning and the Regional Directorate for the Environment and Sea. The DGRM is responsible for coordinating the work of all these entities to ensure consistency in the criteria and methodologies applied in maritime spatial planning.

In addition, the PSOEM is supplemented by the characterization reports for specific areas, as well as environmental reports. The geoportal also provide in-depth, updated information about local offshore activities, including OA and MRES (DGRM, 2025a). Thus, the PSOEM is defined as an economic, social and environmental development tool. It serves as an instrument for spatial management, legal consolidation and geopolitical positioning of Portugal in the Atlantic basin. This document addresses the challenges posed by the National Maritime Strategy, promoting the spatial organization of economic activities while ensuring the protection of common uses, and the preservation of the environmental quality of marine waters (DGRM, 2025b).

2.1.2. Allocation of offshore marine renewable energy areas

With the publication of the European Joint Action REPowerEU, EU member states were required to identify the land and maritime areas needed to meet their national contributions towards the 2030 European renewable energy targets. In this context, the Plan for Allocating Renewable Energy (PAER) plays a key role in addressing this challenge. Resulting from a collaboration between LNEG, DGRM and other institutions, the PAER identifies the areas with the highest potential for the implementation of renewable energy production units (LNEG, 2020).

Fig. 2. Offshore aquaculture (red) and MRES areas (blue) identified in the PSOEM geoportal (DGRM, 2025a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Among its many objectives, the PAER also aims to contribute to national energy independence, thereby facilitating the energy transition and the decarbonization of the economy. Accompanied by an area characterization plan, the PAER is also subject to frequent environmental impact assessments and both public and stakeholder participation. This promotes the sustainable development of activities while protecting marine ecosystems and mitigating conflicts with other activities (DGRM, 2025b; LNEG, 2020).

Currently, the PAER establishes an offshore pilot zone – Aguçadoura – and 4 offshore sites – Viana do Castelo, Leixões, Figueira da Foz and Sines – for deployment of MRES conversion technologies (2 GW targeted by 2030), based on multiple criteria. These include horizontal wind speed (m/s), the incident wind power flux (W/m^2), wave conditions (wave height, period and direction – m, s and °), the wave power per metre of wave front (kW/m), the number of equivalent full-load hours (h/year), and other technical and environmental factors (LNEG, 2020).

2.1.3. Offshore co-location

Traditional marine activities, such as fisheries and tourism, frequently compete for space and resources with emerging industries, namely aquaculture and MRES (Jouffray et al., 2020). Therefore, the growing and often conflicting use of marine resources has driven the search for tools and approaches that can address these challenges. The tools and approaches combine technology and sustainability to enable the co-location of multiple activities (Griffin et al., 2015), which can also promote cost reductions and infrastructure/resource sharing (Schupp et al., 2019), Fig. 3. Given the importance of the "blue" economy, maintaining economic growth while conserving marine habitats is a key goal of the EU and its member states, including Portugal (Stockbridge et al., 2025).

Co-locating aquaculture with wind farms holds many benefits related to the reduction of high initial costs, mainly associated with building an offshore facility, which highlights the benefit of sharing infrastructures (Kam et al., 2003). In addition, several long-term synergetic advantages were identified, such as shared maintenance and operation costs, marine space optimization, reduced impact on coastal activities and alternative livelihood for decaying fisheries (Buck and Langan, 2017). Similar advantages can be obtained from co-location with wave energy, to which adds the creation of a wake field that attenuates the local wave climate, namely wave heights, known as the "shadow" or "shielding effect" (Clemente et al., 2023; Astariz and Iglesias, 2015a). This is particularly important as OA moves further away from the coastline, becoming more exposed high-energetic wave conditions. A similar trend is seen in offshore wind, with floating technologies being preferred at depths of 60 m or more (Miranda et al., 2025). Certain WECs can also be incorporated into farming systems by sharing the aquaculture net pen moorings or anchors, or be anchored separately by a barge feed, while providing power to the culture facilities (Garavelli et al., 2022).

Nevertheless, despite all the benefits, co-locating aquaculture and MRES still implies several practical and environmental challenges (Billing et al., 2022). These encompass cost competitiveness (Astariz and Iglesias, 2015b), survivability at sea (Tiron et al., 2015), technology maturity (Magagna et al., 2018), unclear insurance policy on co-location (Onyango et al., 2020), and risks of injury and/or damage (e.g., caused by mooring failure or collisions between structures) (Miranda et al., 2025; Williams et al., 2017). It is also necessary to verify if areas allocated for MRES exploitation provide suitable metocean conditions for aquaculture species farming, which is analysed in the next sub-section.

2.2. Aquaculture species

2.2.1. Dicentrarchus Labrax (European seabass)

As a highly appreciated fish in Portugal, the species selected to represent the finfish group is the European seabass (*Dicentrarchus labrax*), Fig. 4. The European seabass is a predatory fish who feeds from prawns, crabs, cuttlefish and smaller fish in the wild. Across its geographic range – which includes the Atlantic Ocean region in which Portugal is situated –, this species tends to occur primarily within coastal and estuarine waters in the summertime, and, subsequently, in offshore sites during the colder seasons (European Comission, 2025).

In Europe, the demand for fresh seabass has been increasing due to its taste, aroma, value, and overall quality. These characteristics make this fish one of the most important species in European aquaculture (Kousoulaki et al., 2015), being the most farmed fish among the Mediterranean territory (Kyrana and Lougovois, 2002). In addition, the European Maritime and Fisheries Fund allocated 1.2 billion EUR (2014–2020) to modernize aquaculture, including technologies for species such as the seabass. This provides a great driving factor for the expansion of the *Dicentrarchus labrax* farming.

The species selection process must consider their tolerance limits and optimal growth requirements, mainly in terms of water quality. Hence, the species must be compatible with the environmental conditions of the study area, thus promoting its welfare and product quality. To that end, information was collected regarding the survivability limits and optimal growth conditions of the *Dicentrarchus labrax*, Table 1.

2.2.2. Mytilus galloprovincialis (Mediterranean mussel)

The Mediterranean mussel (*Mytilus galloprovincialis*), Fig. 5, was selected mainly based on the national consumption of bivalves such as this one, as well as the long ranges of survival and optimal growth, Table 2. Such ranges align well with the conditions found in the Portuguese marine environment. In terms of commercial value, Europe

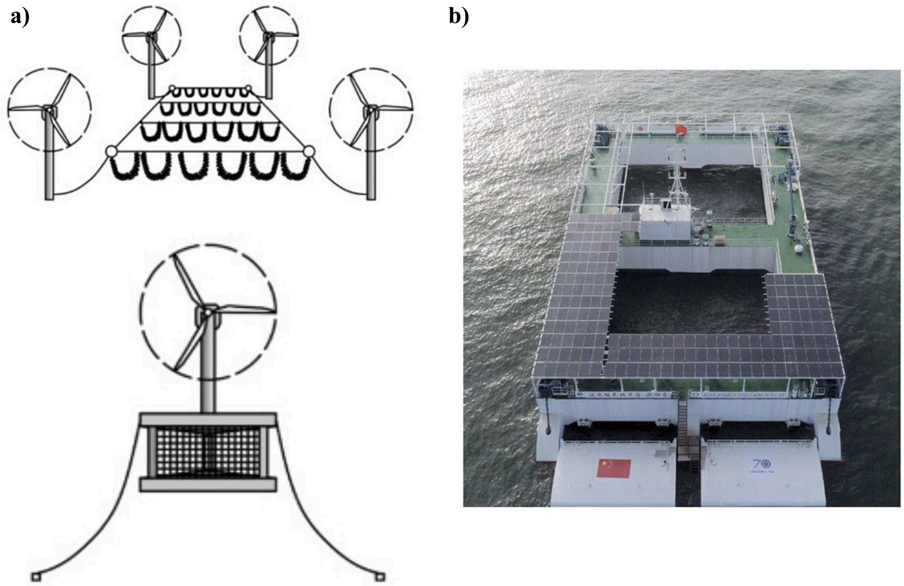

Fig. 3. a) Co-located offshore wind and aquaculture schematic and b) the Penghu wave energy-powered aquaculture platform. Adapted from (Miranda et al., 2025; IEA-OES, 2022).

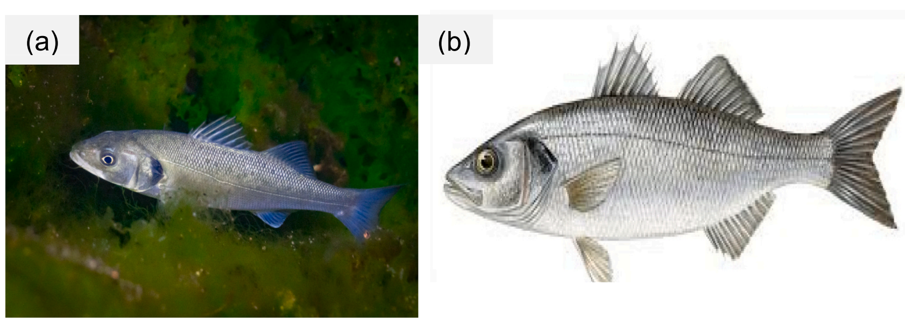

Fig. 4. (a) *Dicentrarchus labrax* representation in the wild, (b) *Dicentrarchus labrax* species illustration. *Sources*: (European Comission, 2025; Fishipedia., 2025).

Table 1
Tolerance and optimal growth conditions for European Seabass.

	Tolerance		Optimal Growth		References
	Min.	Max.	Min.	Max.	
Temperature (°C)	11	32	22	24	(Claridge and Potter, 1983)
Salinity (PSU)	8	36	25	30	(Elaraby et al., 2018)
Nitrate (mmol/m^3)	Not specified	Not specified	–	8.06	(Yilmaz et al., 2020)
Dissolved O_2 (mmol/m^3)	> 188	Not specified	> 219	Not specified	(Stathopoulou et al., 2021)
pH (–)	Not specified	Not specified	8.0	8.2	(Yilmaz et al., 2020)

supplies over a third of the world's mussel production, being aquaculture responsible for over 90% of it (EMFAF, EUMOFA, 2022). Next to *Mytilus edulis, Mytilus galloprovincialis* represents one of the main mussel species, and can be sold as a fresh or processed product. Nonetheless, most of them are destined to process treatments for subsequent export and domestic consumption (FAO, 2014). Additionally, this species is fast growing, being the production cycle established between a year and a half and two years (Peharda et al., 2007). Furthermore, and given the high consumption of mediterranean mussel in Europe, this species can generate a great economic value. Recent retail prices (excluding VAT) were about 2.65 EUR/kg in Italy, 2.82 EUR/kg in Spain, and 3.60 EUR/kg in France (EMFAF, EUMOFA, 2022).

2.2.3. *Laminaria hyperborea (brown kelp)*

Laminaria hyperborea, known as “tangle” or “curvie”, is a large, perennial brown seaweed that grows up to 3.6 m in length forming large kelp forests, Fig. 6. This species dominates rocky shores, most of them on the Northeast Atlantic (Chemello et al., 2025). *Laminaria hyperborea* is commercially harvested in several European countries, being a major source of alginates. This species support over 25% of the world's alginate production, a market that is valued at 200 million dollars annually. This market encompasses food, pharmaceutical, biotechnological and cosmetic industries (Araújo et al., 2021).

Though mostly found naturally in the Northwest of Portugal, this species' commercial potential warrants an exploratory analysis towards OA cultivation along the coast, whilst accounting for its tolerance and ideal growth conditions, Table 3. It should be noted that the ideal values for PO_4 are not mentioned, due to the lack of information in the existing literature. However, this parameter is, in fact, relevant for these algae cultivation, especially regarding to the process of biomass synthesis and photosynthesis (Franke et al., 2024).

2.3. *Suitability index*

To assist decision-making processes on potential OA sites along the Portuguese continental coast, it was decided to create a suitability index

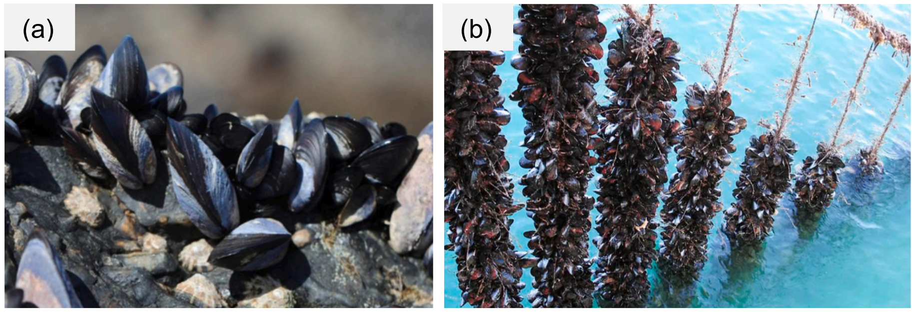

Fig. 5. (a) *Mytilus galloprovincialis* in its natural environment, (b) Mediterranean mussel culture in Greece. *Sources*: (Shinen and Morgan, 2009; Theodorou and Tzovenis, 2011).

Table 2
Tolerance and optimal growth conditions for Mediterranean Mussel.

	Tolerance		Optimal Growth		References
	Min.	Max.	Min.	Max.	
Temperature (°C)	5	30	15	25	(Keskin et al., 2020; Kamermans and Saurel, 2022)
Salinity (PSU)	15	40	30	35	(Meloni et al., 2022; His et al., 1989)
Nitrate (mmol/m^3)	0,21	10	0,5	2	(Kamermans and Saurel, 2022; Karayucel et al., 2010)
Dissolved O_2 (mmol/m^3)	63	Not specified	> 125	Not specified	(Bayne, 1976)
pH (–)	Not specified	Not specified	8.1	8.2	(Keskin et al., 2020)

for OA systems. Afterwards, this information was combined with maps for wind and wave energy.

The SI for the installation of OA systems was built from the detailed analysis of oceanographic data obtained through the Copernicus Marine Service, namely the reanalysis (physical data) and hindcast (biological data) series. The data refers to the parameters of temperature, salinity, nitrates (NO_3), phosphates (PO_4), dissolved oxygen (O_2), current velocity and chlorophyll-a concentration. Table 4 shows all the indicators initially analysed, as well as the name of the associated variables, the units of measurement and the data source. The data covers a period from 1993 to 2021, with a uniform spatial resolution of 0.083°. For each parameter, the monthly average was calculated over the years, resulting in 12 different files for each variable. Subsequently, these monthly data were grouped into seasons, calculating the mean and standard deviation for each season. Additionally, to capture vertical variations, the analysis considered three specific depths: 0.5 m, 10.0 m and 20.0 m, following (Gimpel et al., 2015). In this way, NetCDF files corresponding to the mean, mean plus standard deviation and mean minus standard deviation were generated at each depth.

For the 3 species from different representative groups of marine organisms that were selected – finfish, bivalve and macroalgae - the environmental tolerance limits and optimal growth conditions were taken from literature. Furthermore, specific suitability indices were defined, namely: a thermohaline index for fish and algae, and an index that integrates temperature, salinity and chlorophyll-a for bivalve, Table 5 and Table 6. In addition, is important to note that parameters such as dissolved oxygen, *pH*, phosphates and nitrates are relevant from an ecological point of view. However, a preliminary quantitative screening of the Portuguese coast data showed that these parameters remain within acceptable limits for all species studied, not justifying their inclusion in the SI. By contrast, each of the temperature, salinity and chlorophyll-a parameters exhibited ranges that would significantly impact the suitability of at least one species, as evident from the ensuing results and discussion.

To proceed with the calculation of the index, a series of Python scripts were developed on the platform of Jupyter Notebook. The aim was to process the spatial data, and compare the mean values and the respective standard deviations with the tolerance and optimal growth intervals of each species, depth and season of the year. Furthermore, logical conditions were established to reflect the rules implemented in

Table 3
Tolerance and optimal growth conditions for *Laminaria Hyperborea*.

	Tolerance		Optimal Growth		References
	Min	Max	Min	Max	
Temperature (°C)	5	19	10	15	(Bolton and Lüning, 1982)
Salinity (PSU)	16	50	30	35	(Tyler-Walters, 2025)
Nitrate (mmol/m^3)	1–2	Not specified	Not specified	Not specified	(Lüning, 1986)
pH (–)	Not specified	Not specified	8.1	8.2	(Chemello et al., 2025)

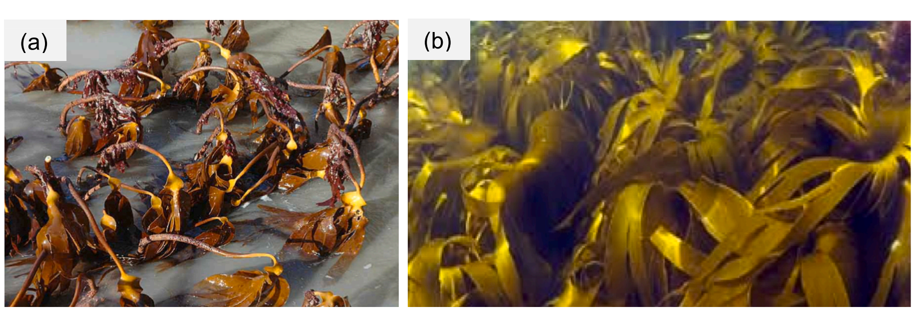

Fig. 6. (a) *Laminaria hyperborea* on shore, (b) Kelp Forest composed by *Laminaria hyperborea*. *Sources*: (Tyler-Walters, 2025; Seaweed Solutions, 2025).

Table 4
Tolerance parameters and data sources.

Parameters (variables)	Unit of measurement	Copernicus data source
Temperature (*thetao*)	°C	Global Ocean Physics Reanalysis
Salinity (*so*)	PSU	Global Ocean Physics Reanalysis
Currents-U and Currents-V* (*uo & vo*)	m/s	Global Ocean Physics Reanalysis
Chlorophyll-a (*chl*)	mg/m^3	Global Ocean Biogeochemistry Hindcast
Nitrate (*no3*)	$mmol/m^3$	Global Ocean Biogeochemistry Hindcast
Phosphate (*po4*)	$mmol/m^3$	Global Ocean Biogeochemistry Hindcast
pH (*ph*)	–	Global Ocean Biogeochemistry Hindcast
Dissolved Oxygen (*o2*)	$mmol/m^3$	Global Ocean Biogeochemistry Hindcast

* Currents-U corresponds to Eastward sea water velocity and Currents-V to Northward sea water velocity, combining these values through the expression $\sqrt{uo^2 + vo^2}$ we obtain the total speed of the current (magnitude).

Table 5
Description of the SI developed for each species.

SI Conditions	Classification	Description
0	Not suitable	Mean values fall outside the minimum or maximum tolerance limits for the species
1	Marginally Suitable	Mean values are within tolerance limits, but standard deviations exceed them
2	Suitable	Mean and standard deviation values are within tolerance, but outside the optimal range
3	Excellent	All values (means and standard deviations) fall within the optimal range for the species

the code for the construction of the SI. These conditions are represented by Eqs. (1) to (4), being applied at the level of each spatial grid cell of the study area.

Table 6
Nomenclature adopted for the survivability and ideal growth.

T_{tmin}	Minimum tolerance temperature	S_{tmin}	Minimum tolerance salinity	C_{tmin}	Minimum tolerance cholorophyll
$T_{tmáx}$	Maximum tolerance temperature	$S_{tmáx}$	Maximum tolerance salinity	$C_{tmáx}$	Maximum tolerance cholorophyll
T_{imin}	Minimum ideal temperature	S_{imin}	Minimum ideal salinity	C_{imin}	Minimum ideal cholorophyll
$T_{imáx}$	Maximum ideal temperature	$S_{imáx}$	Maximum ideal salinity	$C_{imáx}$	Maximum ideal cholorophyll
T_{mean}	Mean temperature obtained	S_{mean}	Mean salinity obtained	C_{mean}	Mean cholorophyll obtained
$T_{mean+std}$	Mean temperature plus the standard deviation obtained	$S_{mean+std}$	Mean salinity plus the standard deviation obtained	$C_{mean+std}$	Mean cholorophyll plus the standard deviation obtained
$T_{mean-std}$	Mean temperature minus the standard deviation obtained	$S_{mean-std}$	Mean salinity minus the standard deviation obtained	$C_{mean-std}$	Mean chlorophyll minus the standard deviation obtained

$$If,\ T_{mean} < T_{tmin} or\ T_{mean} > T_{tmáx}\ or\ S_{mean} < S_{tmin} or\ S_{mean} > S_{tmáx}\ or\ C_{mean} < C_{tmin} or\ C_{mean} > C_{tmáx},\ then:\quad \boldsymbol{SI} = \mathbf{0} \tag{1}$$

$$If,\ T_{tmin} \le T_{mean} \le T_{tmáx}\quad S_{tmin} \le S_{mean} \le S_{tmáx}\quad C_{tmin} \le C_{mean} \le C_{tmáx}, then:\quad \boldsymbol{SI} = \mathbf{1} \tag{2}$$

$$If,\ T_{tmin} \le T_{mean+std} \le T_{tmáx}\quad T_{tmin} \le T_{mean-std} \le T_{tmáx}\quad S_{tmin} \le S_{mean+std} \le S_{tmáx}\quad S_{tmin} \le S_{mean-std} \le S_{tmáx}\quad C_{tmin} \le C_{mean+std} \le C_{tmáx}\quad C_{tmin} \le C_{mean-std} \le C_{tmáx}, then:\quad \boldsymbol{SI} = \mathbf{2} \tag{3}$$

$$If,\ T_{imin} \le T_{mean+std} \le T_{imáx}\quad T_{imin} \le T_{mean-std} \le T_{imáx}\quad S_{imin} \le S_{mean+std} \le S_{imáx}\quad S_{imin} \le S_{mean-std} \le S_{imáx}\quad C_{imin} \le C_{mean+std} \le C_{imáx}\quad C_{imin} \le C_{mean-std} \le C_{imáx}, then:\quad \boldsymbol{SI} = \mathbf{3} \tag{4}$$

*This index corresponds to the one utilized for *Laminaria Hyperborea*. As previously mentioned, for the fish and bivalve species, a thermosaline SI was developed.

After generating the code corresponding to each species, season and depth, numerous NetCDF files were obtained. These files, when imported into QGIS as a raster layer, allow the spatial visualization of the different suitability classes through a coloured symbology. Therefore, the visual identification of the most promising areas for the installation of OA systems is facilitated, as exemplified from Fig. 7 to Fig. 9. The figures correspond to the maps of mean salinity and temperature distributions at a 10 m depth in Spring, the standard deviations, and the SI for the European Seabass, by said order. (See Fig. 8.)

3. Results and discussion

This section presents the resulting suitability index maps and a critical discussion of their spatial overlap and potential co-location with other maritime uses, including marine renewable energy areas, marine protected areas, and proximity to ports. In addition, the potential effects of climate change on species suitability are assessed.

To maintain clarity and readability, only representative maps per species are included in the main text. Additional analyses were conducted separately to avoid overloading the figures and impairing their interpretability. Maps generated under alternative conditions and scenarios are provided in the Supplementary Material.

3.1. Suitability areas

3.1.1. European seabass

The production cycle of European seabass starts in controlled environment until individuals reach around 2.5 g, typically after 75 days. At this point, fish is transferred to open-sea cages for the grow-out phase and remain there until reaching commercial size of around 400 to 500 g (FAO, 2024). Cages are generally positioned at an average depth of 10 m (Chen et al., 2023; Izzabaha et al., 2020), with vertical dimensions ranging from 9 to 10 m depending on site conditions and culture practices (Chen et al., 2023). As a result, seabass typically occupy the water column between 10 m and 20 m. Fig. 10 presents the SI results for seabass aquaculture at 10 m depth. The SI at 0.5 m and 20 m depth, are presented in Supplementary Material (Annex A).

In Spring, a large area along the Northwestern coast is classified as "suitable". This classification reflects local environmental conditions with temperatures between 14 and 15 °C, which are within the tolerance range though below the optimal 22–24 °C, and stable salinity values between 35 and 36 PSU. In contrast, suitability is null along the Southern and Southwestern coast. Although temperatures remain

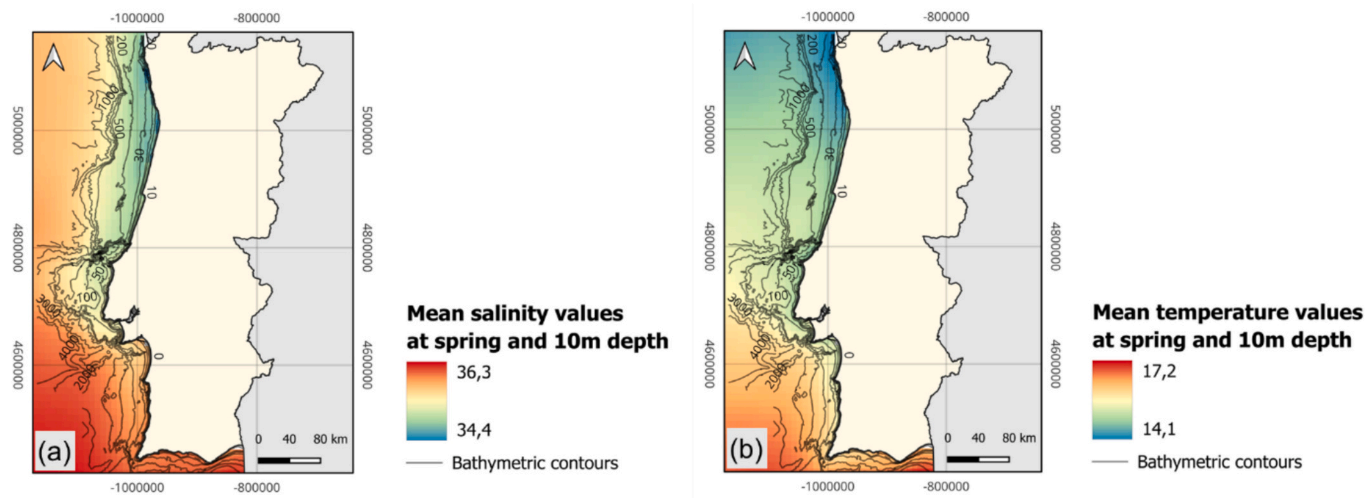

Fig. 7. (a) Mean salinity (b) and temperature values in Spring, at 10 m depth.

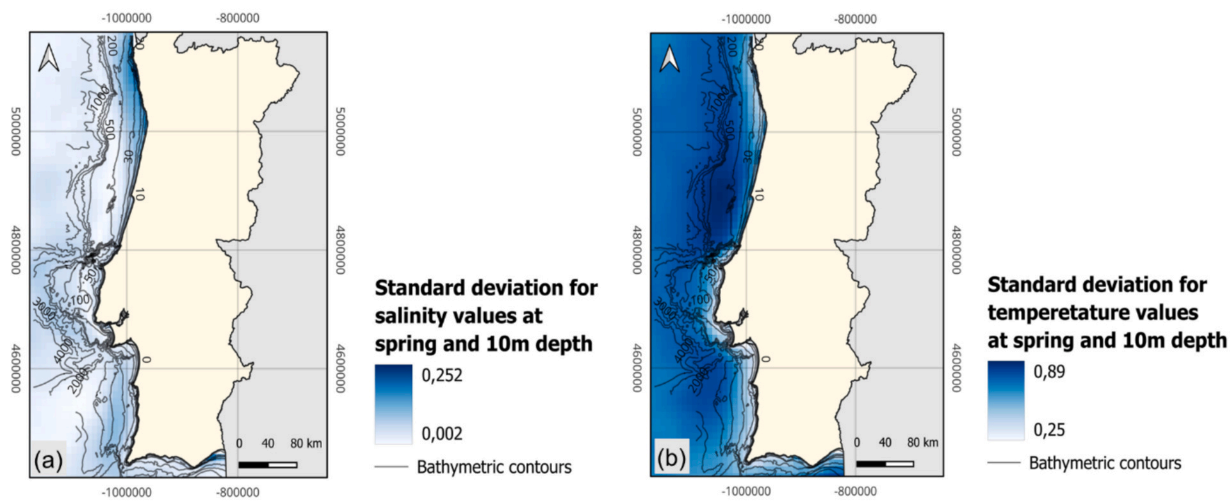

Fig. 8. (a) Standard deviation for temperature, (b) and for salinity in Spring, at 10 m depth.

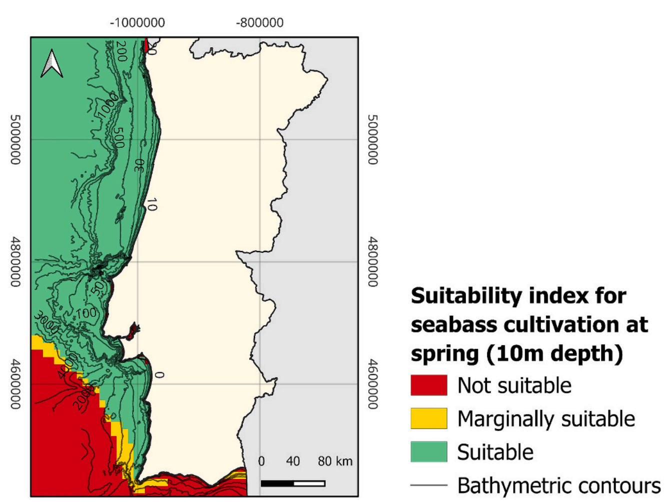

Fig. 9. Suitability index for European Seabass (*Dicentrarchus labrax*) in Spring, at 10 m depth.

acceptable (16–17 °C), salinity values exceed 36 PSU, surpassing the upper limit.

In Southern Portugal, specifically the Algarve, existing seabass aquaculture systems operate on land or in estuarine environments areas (lower salinity compared to open ocean waters). As a result, no oceanic sites in the region were classified as suitable according to the SI, in accordance to what is equally identified in the PSOEM. A deeper verification of existing aquaculture exploration titles further confirms these observations (e.g., edict PT20241TAA008317103), with few facilities being identified and mostly in the always "suitable" Figueira da Foz area.

In Summer, suitability increases slightly, particularly along the Southwestern and Southern coasts. Northern waters remain within the tolerance limits (17–19.5 °C), while Southern regions record surface temperatures between 18.5 and 20 °C. This seasonal expansion of suitable areas is primarily due to reduced salinity levels, now falling within the acceptable 35–36 PSU range. In the Autumn, suitable zones contract, mostly restricted to the North and a narrow coastal band extending to western Algarve. Temperature remains within acceptable limits, but elevated salinity once again becomes the main limiting factor. An increase in the 'marginally suitable' category (yellow band) indicates that although average values fall within tolerance, the inclusion of standard deviation exceeds defined salinity thresholds. In Winter, despite lower

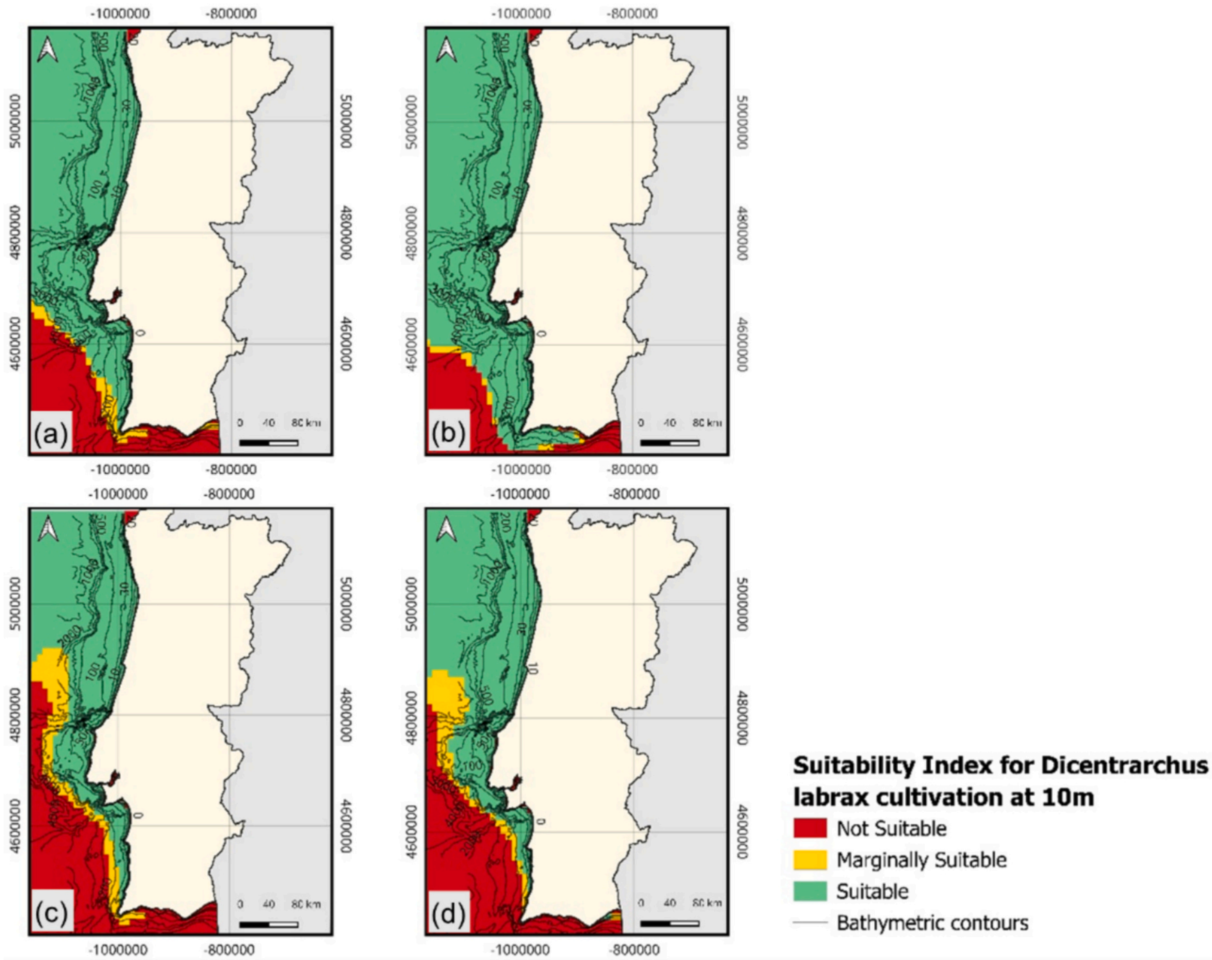

Fig. 10. Suitability index for the offshore production of European seabass (*Dicentrarchus labrax*) at: (a) Spring, (b) Summer, (c) Autumn and (d) Winter, at 10 m depth.

temperatures (13–17 °C), all values remain within the broad tolerance range (11–32 °C) for seabass. As in Autumn, salinity remains the primary constraint on site suitability.

3.1.2. Mediterranean mussel

The production cycle of the mediterranean mussel begins with the seed collection during low tides. This activity occurs in Spring and Summer with calmer sea conditions. At this stage, juvenile mussels reach a length of approximately 20 mm and are ready to be attached to the grow-out ropes, either on land or offshore. The mussels are then suspended on longlines at depths up to 20 m (Gimpel et al., 2015). It takes around 8 to 13 months, depending on factors such as water temperature, cultivation depth, and phytoplankton availability to reach commercial size (8 to 10 cm).

Given the mussel's reliance on phytoplankton, the SI was developed using the parameter of chlorophyll-a concentrations as a proxy for food availability, in line with standard practice (Huot et al., 2007). Fig. 11 presents the SI for water depth of 10 m. The SI at 0.5 m and 20 m depth, are presented in Supplementary Material (Annex A).

In the Spring season, the SI identifies a broad area, stretching from the North to the South, as suitable for the Mediterranean mussel. Water temperatures range from 14 to 16 °C in the North/Centre and 16–17 °C in the South, all within the species' tolerance range (5–30 °C), though below the optimal growth window (20–25 °C) (Keskin et al., 2020; Kamermans and Saurel, 2022). Salinity values also fall within acceptable limits (15–40 PSU), ranging from 34.40 to 36.30 PSU across the study area.

Thus, chlorophyll-a concentration emerges as the limiting factor. Values range from 0.13 to 1.58 mmol/m^3. Sites classified as "not suitable" and "marginally suitable" correspond to areas with chlorophyll-a below the tolerated range for *Mytilus galloprovincialis* (0.21–10 mmol/m^3). Red zones reflect values between 0.13 and 0.20 mmol/m^3, while yellow zones, with averages between 0.20 and 0.30 mmol/m^3, fall below threshold limits when accounting for standard deviation.

In Summer and Autumn, the suitability pattern remains largely unchanged, though areas classified as "marginally suitable" decrease slightly, particularly in the North. Winter brings an improvement, particularly along the North and centre areas. This may be attributed to stronger winds and currents promoting vertical mixing, which homogenizes phytoplankton distribution and improves overall suitability in some regions.

Looking at existing facilities, the production is concentrated in the South, where the wave climate is also more benign. It was observed that, by overlapping Fig. 11 with the OA sites from the PSOEM, there is a very good agreement. The bulk of Southern OA occurs within less than 10 km away from the coastline, and within the "suitable" areas. Only one OA site was clearly identified in a red zone, which was a fish farm, and not a blue mussel one.

3.1.3. "Curvie" kelp

The production cycle of *Laminaria hyperborea* begins with the collection of sori (reproductive structures of this algae), which are stimulated to release spores. The spores are then developed in the laboratory, where over a period of 45 days, turn themselves into juveniles

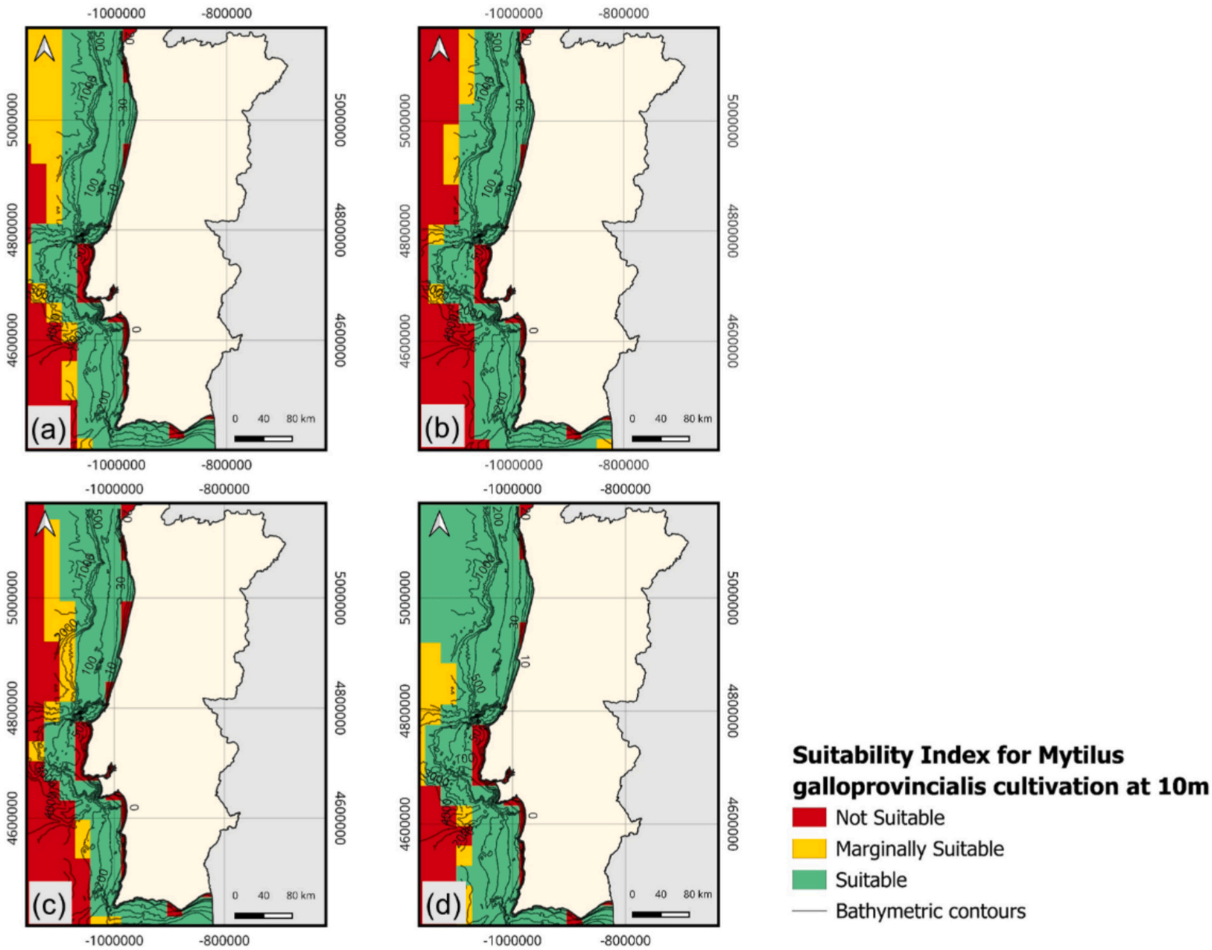

Fig. 11. Suitability index for the offshore production of Mediterranean mussel (*Mytilus galloprovincialis*) at: (a) Spring, (b) Summer, (c) Autumn and (d) Winter, at a 10 m depth.

(sporophytes). Once the juveniles are ready, they're transferred to the longlines, where the grow-out phase continues for around 6 to 7 months until commercial size is reached (Purcell-Meyerink et al., 2021). Harvesting typically occurs in late Spring or early Summer (Tyler-Walters, 2025), which may be useful for avoiding heatwave periods.

Literature indicates that most seaweed cultivation systems are deployed between 5 and 12 m, ensuring both protection from wave action and sufficient light availability (Tyler-Walters, 2025). Fig. 12 presents the SI for water depth of 10 m. The SI at 0.5 m and 20 m depth, are presented in Suplementary Material (Annex A).

As presented in Fig. 12, *Laminaria hyperborea* is the only species in this study with areas classified as "excellent" (SI = 4) for OA. As a cold-water species with a thermal tolerance range of 5–19 °C and an optimal range of 10–15 °C, *Laminaria* adapts well to the thermal conditions of Northern Portugal. Its high salinity tolerance (16–50 PSU) further supports excellent suitability in this region during Autumn and Winter. This is in agreement with its natural distribution, mostly found in the Northern coast.

Given the broad salinity tolerance, water temperature becomes the primary limiting factor. In Winter and Spring, the entire study area is classified as suitable, with Northern nearshore regions rated as "excellent". However, during Summer and Autumn, rising temperatures cause a significant reduction in suitable areas, narrowing suitability to a coastal band wider in the North and thinner towards the centre and South. A "marginally suitable" (yellow) zone also appears along the boundary between "suitable" and "not suitable" offshore areas. This highlights the sensitivity of the species to extreme events, such as heatwaves, and the necessary cares that come with it from an operational perspective. Though the authors did not, at this point, identify concrete *Laminaria* production sites, literature and ongoing forest restoration efforts (Chemello et al., 2025) do focus on the North of Portugal, which aligns well with the distribution patterns seen in Fig. 12.

3.2. Potential co-location with marine renewable energy

The selection of the PAER offshore energy sites was based on numerous factors such as the slope, depth and type of soil of the seabed, as well as the availability of resources like average wind speed and wind incident power flow. As a result, five areas were identified as suitable locations for renewable commercial projects: Figueira da Foz (0), Aguçadoura (1), Sines (2), Viana do Castelo (3), and Leixões (4) (Ewig et al., 2025).

Fig. 13 represents the spatial distribution of wind incident potential and average annual wave energy density along the Portuguese coast, as well as the areas delimited by the PAER. Wind incident potential, also known as Wind Power Density (WPD), is a critical metric for assessing offshore wind energy resources. This parameter, typically measured in watts per square meter (W/m^2) quantifies the kinetic energy available in wind per unit area, that is, it defines the power that is to be utilized by the turbine blades at any given area, (Abbas et al., 2025). Wave resource or wave power per meter of wave front (kW/m) is a critical metric for assessing wave energy resources and designing wave energy converters (Clemente et al., 2023).

According to the analysed data in the development of the PAER

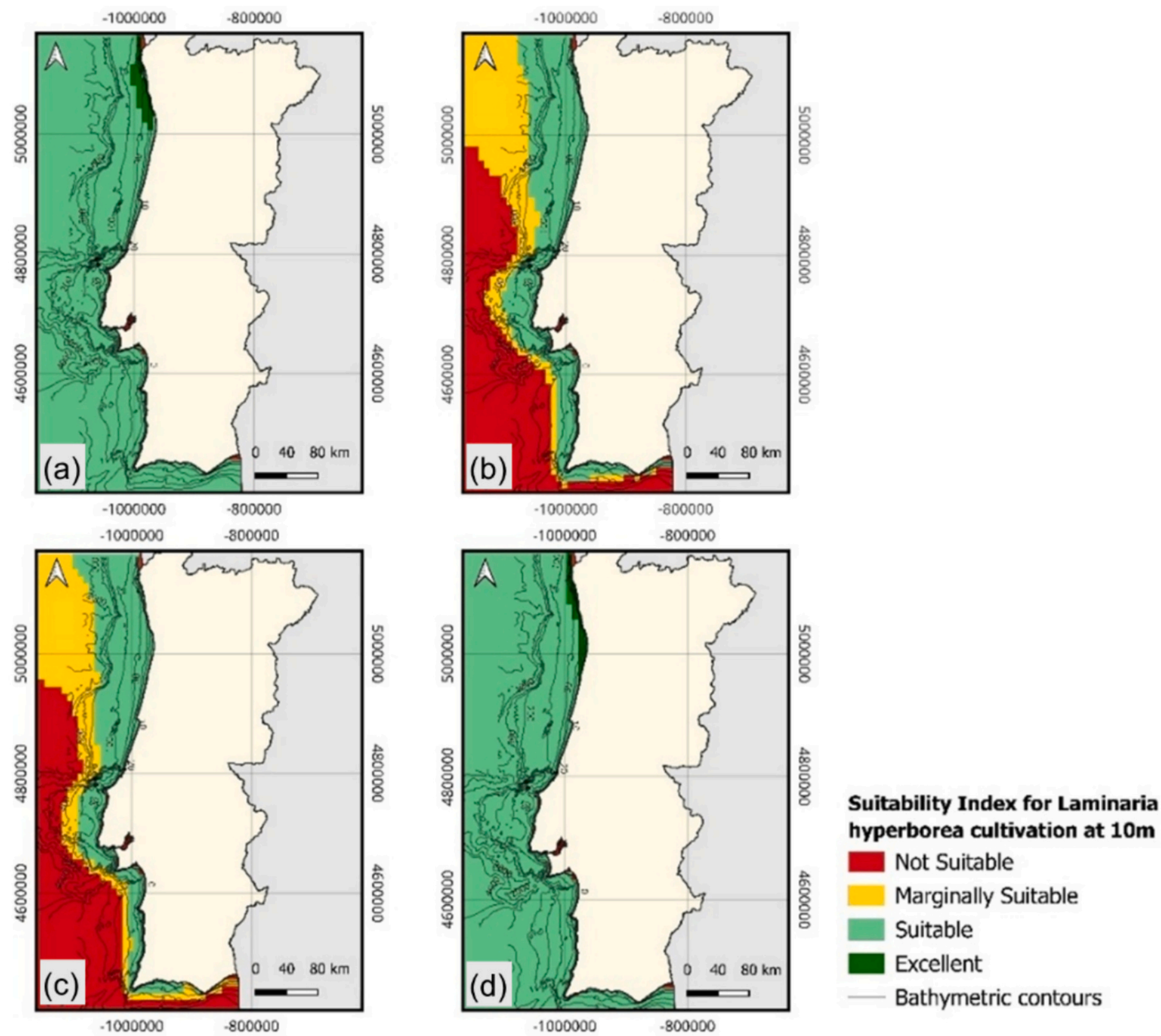

Fig. 12. Suitability index for the offshore production of *Laminaria hyperborea* at: (a) Spring, (b) Summer, (c) Autumn and (d) Winter, at a 10 m depth.

(LNEG, 2020), the average annual wind speed at 100 m high on the Portuguese coast varies between 4.83 and 8.72 m/s. It is known that regions with annual wind speeds that are superior to 7 m/s at a 100 m height are considered viable for commercial offshore wind projects (The World Bank, 2025). In addition, it is known that the energy production is optimal at areas with an average wind speed of 12 m/s (European Agency for Safety and Health at Work (EU Body or Agency), 2013), a value that is not recorded along the Portuguese coast. However, there is a vast area that represents average speeds above 7 m/s, with special emphasis on the regions adjacent to Porto, Viana do Castelo and Lisbon, which mostly represent speeds above 8 m/s, while the coastal area between the South of Lisbon and Faro, have much lower speeds (4.83 and 6.78).

The Northwest of the country has the highest values of wave energy, representing densities above 35 kW/m, and peaking at 42.25 kW/m. In addition, there is a clear energy gradient from North to South, since the central region of the country already presents intermediate to low values (14–21 kW/m) and the extreme South of the coast has the lowest recorded values ranging between 0.5 and 7.5 kW/m. This gradual decrease in energy from North to South reflects the typical pattern of the wave regime in the North Atlantic, influenced by the North Atlantic Oscillation (Clemente et al., 2023; Ramos et al., 2017).

In this context and considering the previous analysis on the suitability indices for the aquaculture, the maps that presents the overlapping between areas identified in the PAER and the SI's carried out for each species at a 10 m of depth are further discussed (Fig. 14 to Fig. 16).

As shown in Fig. 14, PAER zones (0), (1), (3), and (4) are located within areas classified as "suitable" for the offshore cultivation of European seabass. In contrast, Sines (2) transitions from "suitable" in Spring and Summer to "marginally suitable" in Autumn and becomes "not suitable" in Winter. Regarding Mediterranean mussel cultivation, all zones are considered "suitable", except for a small section of Aguçadoura (1), which lies within a Northern coastal area classified as "not suitable" for mussel farming, Fig. 15.

Fig. 16 shows the overlap between PAER zones and the SI for *Laminaria hyperborea*. During Winter and Spring, all PAER zones fall within areas classified as "suitable" for aquaculture, with Aguçadoura (1) standing out as "excellent." However, in the warmer months of Summer and Autumn, suitability decreases notably, with Figueira da Foz (0) and Sines (2) falling into areas classified as "marginally suitable." As such, the zones of Viana do Castelo (3), and Leixões (4) emerge as the areas within the PAER with greater potential for the co-location of aquaculture and offshore renewables in Portugal, considering the SI for all three species analysed. Aguçadoura (1) appears in locations considered "excellent" for the *Laminaria Hyperborea*, "suitable" for the European seabass, and "not suitable" for the Mediterranean mussel. Sines (2) demonstrates good potential for co-location with the Mediterranean

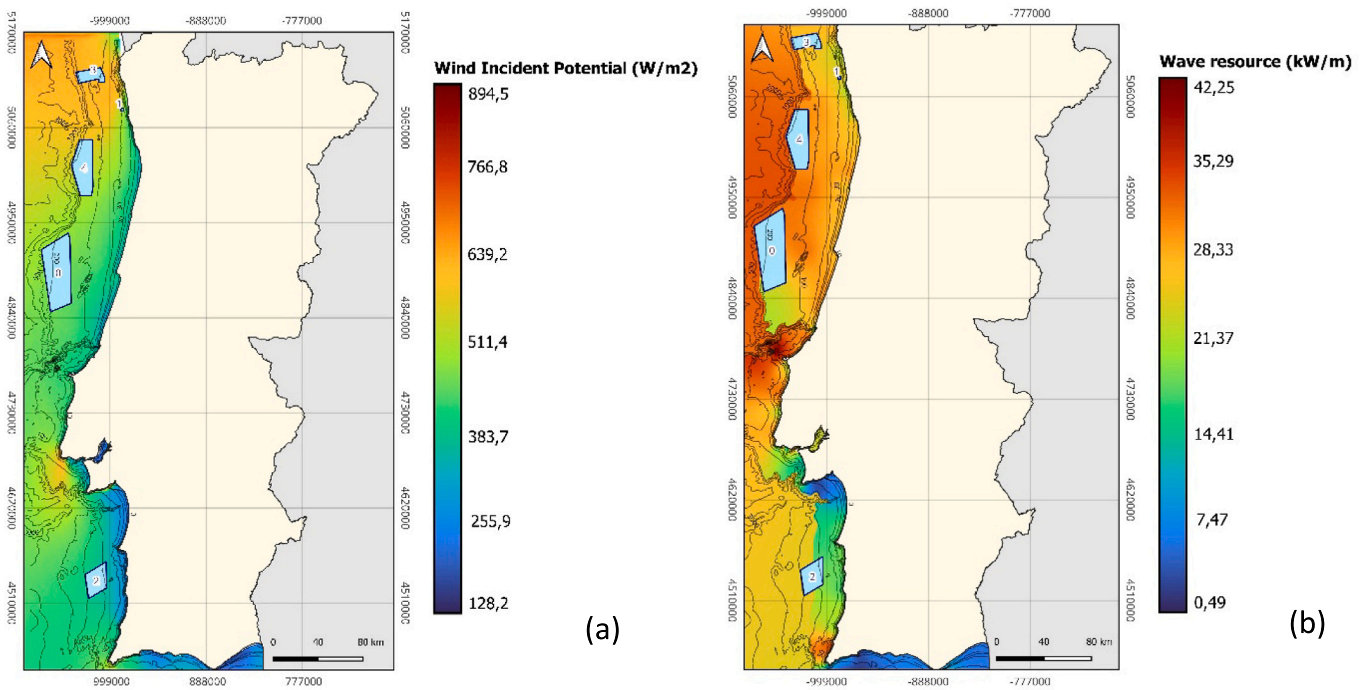

Fig. 13. (a) Wind incident potential (W/m^2) and (b) Annual average wave energy density (kW/m) along the Portuguese coast. Data extracted from (LNEG, 2020).

mussel. However, it is situated in areas classified as "not suitable" and "marginally suitable" for extended periods in relation to both *Dicentrarchus labrax* and *Laminaria hyperborea*. Figueira da Foz (0) presents favourable conditions for co-location with European seabass, but it partially overlaps with areas identified as "marginally suitable" for the Mediterranean mussel during the Autumn season, and for *Laminaria hyperborea* during both Summer and Autumn.

As highlighted in the Introduction, local compatibility is crucial to ensure that the co-location benefits are harnessed. According to the PSOEM geoportal, all PAER zones fall within water depths close to or above 100 m, while existing OA sites operate at depths around 50 m or less. This also implies relatively large distances between them, usually above 30 km. Furthermore, the PAER zones are facing the Atlantic Ocean, but many OA sites can be found in the South, between Sagres and the Spanish Border. As such, currently, there is a noteworthy mismatch between the marine renewables and OA sites, which restricts proximity and alignment. This would likely dilute the "shielding" effect provided by WEC parks, whose wake field dissipates with distance, as well as complicate any interconnections and accessibilities that can be established between the sites (e.g., more expensive and longer setups of electric cables, and longer travel times from one site to the other). While OA is expected to move further into offshore areas, it may take some time to fully exploit the synergies with marine renewables, particularly WEC parks. Nonetheless, hybridization is already being developed, as is the case for the AquaWind project (Aquawind, 2025).

Installing and operating marine renewables can interfere with the local marine environment. Noise propagation, seabed dredging, vessel traffic and electromagnetic fields are some of the hazards to be taken into account. Recent projects in Portugal, such as SAFEWAVE (SafeWave Consortium, 2021) and WindFloat Atlantic (Principle Power, 2020), seek to identify and propose mitigation measures. Furthermore, this type of projects is subjected to environmental impact assessments, as stated previously, forcing them to comply with strict rulings. Lastly, given the distance between existing OA sites and the PAER zones, the direct negative impact of MRES onto the OA operations is expected to be rather limited.

The potential co-location areas must, therefore, be subjected to detailed and multidisciplinary evaluation, taking into account a wide range of environmental, technical, and regulatory factors that may limit or prevent their effective implementation. The next section addresses some, from the overlap with marine protected areas to long-term changes in metocean conditions.

3.3. *Complementary environmental and practical remarks*

3.3.1. *Marine protected areas*

According to the European Environment Agency, Natura 2000 is a network composed of directives that cover the most vulnerable ecosystems around the continent. In the Portuguese coast, two main protected areas are represented, namely the Special Protection Areas (SPAs), that are focus on the well-being of wild birds, and the Sites of Community Importance (SCIs), that host natural habitats of countless species, Fig. 17.

Despite the fact that the marine Natura 2000 network is not yet complete, it presents significant ecological and regulatory challenges to the allocation of offshore structures in the Portuguese coast. The impacts caused by offshore installations must be considered, especially regarding the wind turbines. Regardless, their installation into these protected areas has been subjected to scrutiny at a national level, both from stakeholders and the general public (DGRM, 2025b).

In 2020, a document published by the European Union emphasized the impacts caused by wind turbines and pointed out that structures with fixed foundations, such as monopiles and jackets, have a more negative impact on the surrounding environment, as they produce impulsive noise through hammering operations, vibrations and drilling works into the seabed, which cause proven negative effects on marine mammals and the benthic environment (European Court of Auditors, 2023). On the other hand, wind turbines supported by floating platforms appear to represent a lower impact on the marine biodiversity (LNEG, 2020). Lastly, despite the current incompleteness of Natura 2000 marine directives, governmental bodies are actively working towards the implementation of a new and more comprehensive marine management framework.

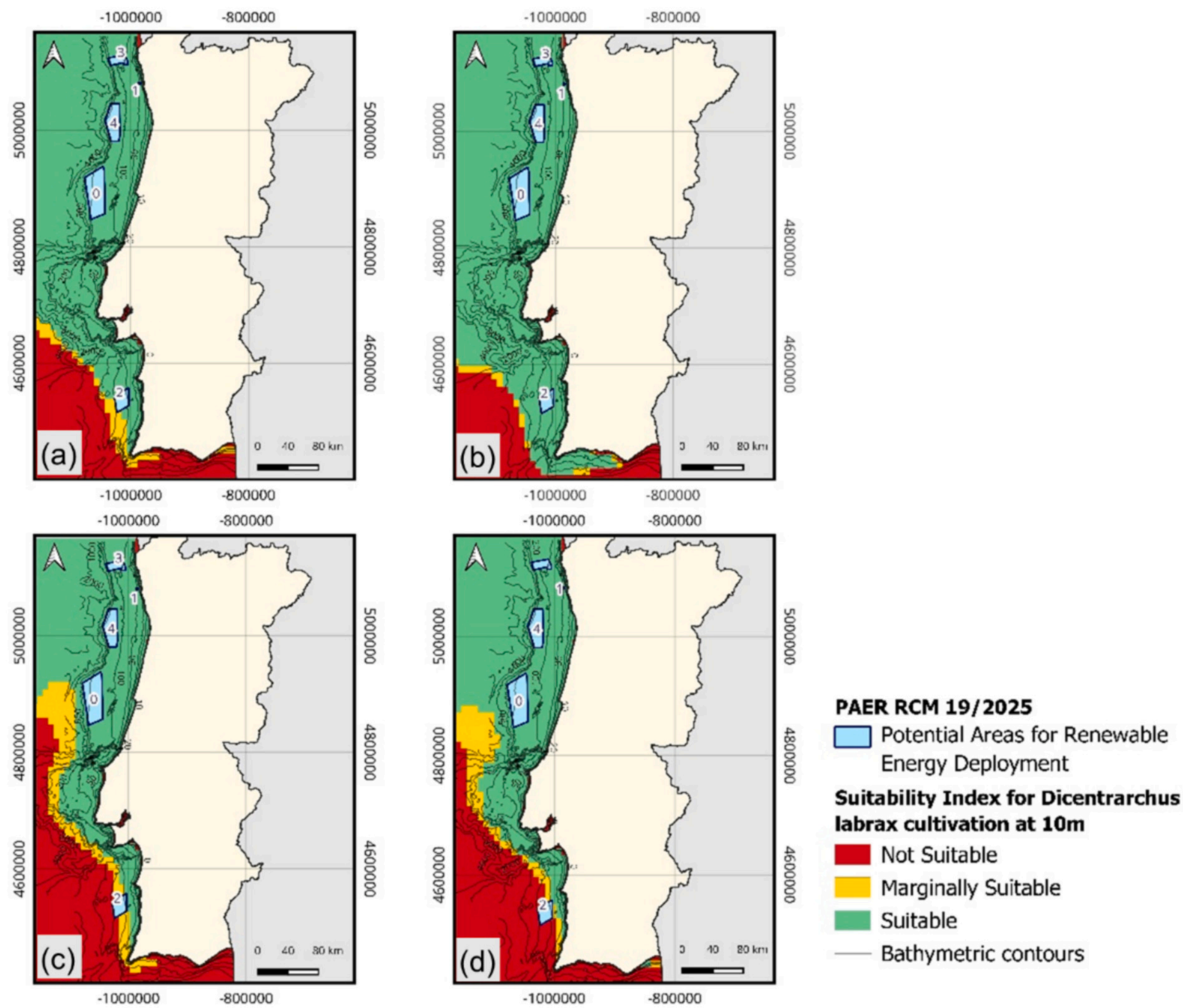

Fig. 14. Overlapping between PAER and SI for European seabass (*Dicentrarchus labrax*) at: (a) Spring, (b) Summer, (c) Autumn and (d) Winter, at a 10 m depth.

3.3.2. Distance to ports and collision risks

Accessibility to both offshore renewables and aquaculture is pivotal for both product handling (seeding, harvesting, etc.) and maintenance operations. Personnel typically depart from a port, and costs associated with vessels increase the further offshore facilities are from the coast (Ren et al., 2021). Therefore, choosing a location that is relatively close to a port may prove to be crucial. As an example, Fig. 18 combines the SI of *Dicentrarchus labrax*, *Mytilus galloprovinvialis* as well as *Laminaria hyperborea* (water depth of 10 m) alongside the locations of major Portuguese ports.

Fig. 18 provides a better perception of how far offshore structures can be from the Portuguese coast. In this context, by combining the information on the suitability indices of each species, it is possible to realize that, although a large maritime area is classified as “suitable” for the cultivation of these organisms, the distance to the ports may limit the operational feasibility. Currently, OA facilities are relatively close to the coastline, as shown beforehand in Fig. 2.

Additionally, Fig. 18 shows the navigational approach cones in an area delimited by black lines (PSOEM). These areas are critical for keeping shipping routes safe and efficient, as they minimize the risk of collision and ensure smoother access for commercial and service ships. Therefore, when aquaculture facilities, wind turbines or WECs are sited near these areas, the vessel's movement may be constrained and the transit times increased (European Commission et al., 2021), to avoid damage and collisions. For instance, accidents in offshore wind farms commonly involve collisions between commercial or maintenance vessels and wind turbine structures (Ren et al., 2021). When aquaculture systems are co-located with offshore wind farms, the risk of vessel collisions may increase due to a greater number of vessels operating within the same area. Additionally, the excessive proximity of aquaculture installations to renewable energy infrastructure can raise the risk of impact between aquaculture cages and the foundations, structures and/or moorings of wind turbines or WECs (e.g., aquaculture structures detaching and drifting into the offshore renewable systems, or entanglement or collision of aquaculture units with the structural base or moorings). As stated beforehand, though, excessive distancing is equally detrimental, and it seems to be the prevailing scenario at the present time.

3.3.3. Weather conditions and climate change

Extreme weather conditions (wave heights, current velocities, and wind) gusts are often responsible for the failure of offshore structures (Ren et al., 2021). Additionally, weather conditions limit the accessibility of offshore facilities such as aquaculture systems and offshore renewable energy devices, affecting the work of the maintenance teams and service vessels, as they require adequate weather windows to operate.

For instance, safety regulations prohibit climbing wind turbines when wind speeds exceed 20 m per second. For vessel-based maintenance involving lifting operations, wave heights must remain below 1.5 m (Maldonado et al., 2022), and wind speeds should not surpass 10 m per second. Helicopter operations are similarly restricted, with wind

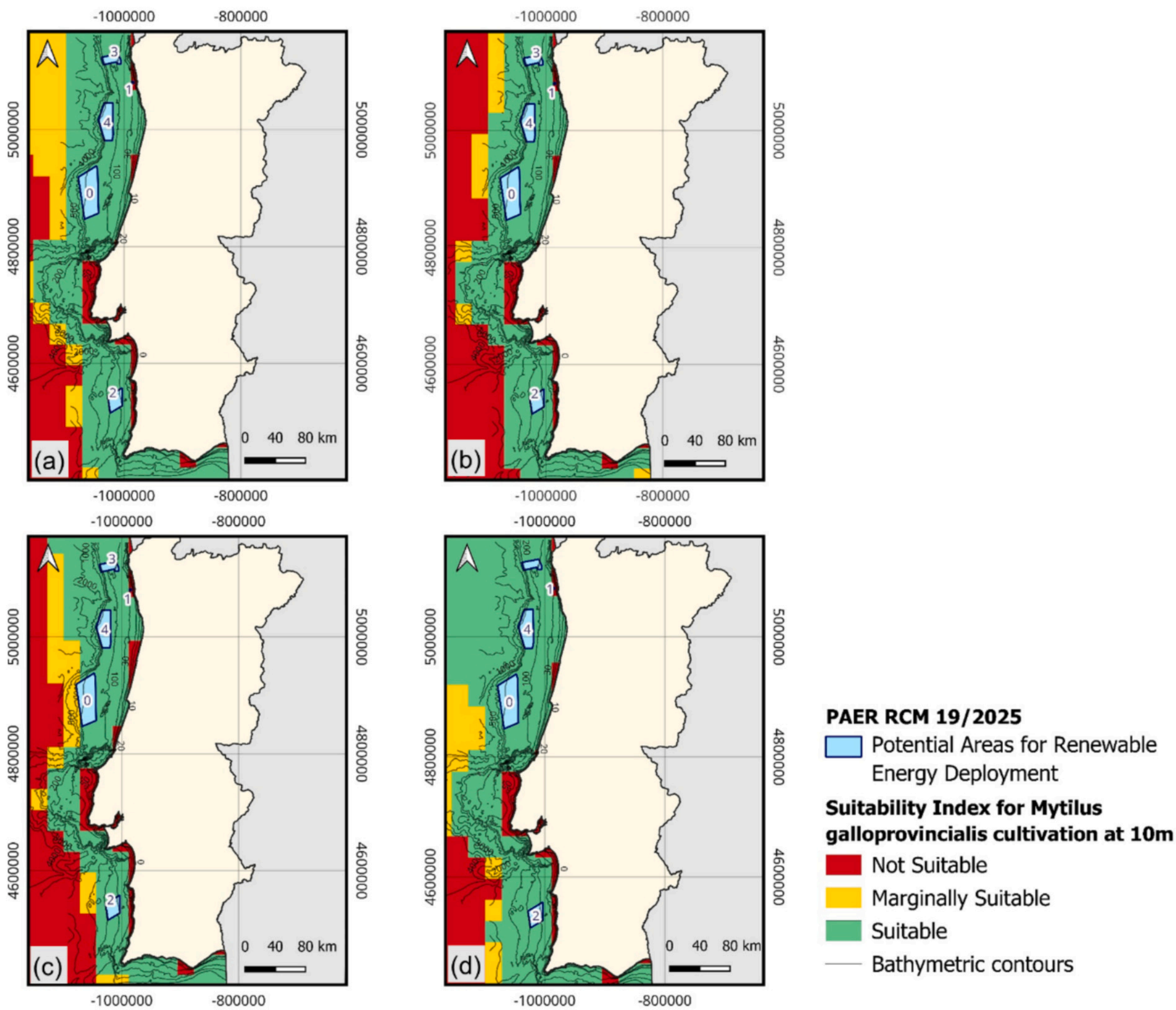

Fig. 15. Overlapping between PAER and SI for Mediterranean mussel (*Mytilus galloprovincialis*) at: (a) Spring, (b) Summer, (c) Autumn and (d) Winter, at a 10 m depth.

speeds required to be under 20 m per second (Ren et al., 2021).

These limitations pose a significant challenge for offshore industries along the Portuguese coast, especially in the Northern region, where wind gusts can reach up to 40 m per second and waves frequently exceed 1.5 m in height (Majidi et al., 2025). Climate change can also have profound impacts, such as the increase in sea surface temperature. This warming trend alters the productivity of aquatic ecosystems and affects the geographical distribution of numerous marine species (Prakash, 2021). A study by Batista et al. (Baptista et al., 2018) concluded that, along the Portuguese coast, surface water temperatures have risen by approximately 0.5 °C per decade in Summer and 0.1 °C per decade in Winter. Assuming this warming trend continues over the next 50 years, projections indicate an estimated increase of about 2.5 °C during the Summer and 0.5 °C during the Winter. Based on these estimates, new suitability indices were developed for the species analysed in this study, incorporating the projected thermal conditions expected along the Portuguese coast in both seasons. By comparing these new SI with those previously presented, it is possible to see how changes in the surface temperature of the water could impact the viability of aquaculture over the next 5 decades.

As shown in Fig. B.1 and B.2 in Supplementary Material (Annex B), the increase in sea surface temperature has no apparent impact on the areas suitable for the optimal growth of European Seabass and Mediterranean Mussel. This is primarily because the thermal tolerance ranges of these species are centred around higher temperatures, making them less vulnerable to the projected warming scenarios.

On the other hand, Fig. 19 reveals a significant impact on the suitable areas for the cultivation of *Laminaria hyperborea*, in line with its natural retreat to colder water in the North. During the Winter, the primary difference between the present and projected scenarios is a reduction in areas classified as “excellent”, particularly in the nearshore zones between Figueira da Foz and Peniche. However, in the Summer, the effect is dramatic, and practically the entire coastline becomes “not suitable”.

Therefore, cold-water species like *Laminaria hyperborea* could face severe habitat loss, potentially driving them towards local extinction (Prakash, 2021). In contrast, this analysis suggests that, for species naturally adapted to warmer waters, such as seabass and mussels, climate change may not worsen environmental suitability. However, one should also consider that there are interactions between sea surface temperature and other factors, such as dissolved oxygen content, disruption of ocean gradients and current patterns, and chlorophyll-a concentration. These interactions are not captured in the analysis made in this section, Fig. 19, which solely focuses on sea temperature variation. Combined with the increasing frequency of extreme weather events, such as storms and heatwaves, these factors may further restrict suitable areas for offshore aquaculture, even for species adapted to warmer waters.

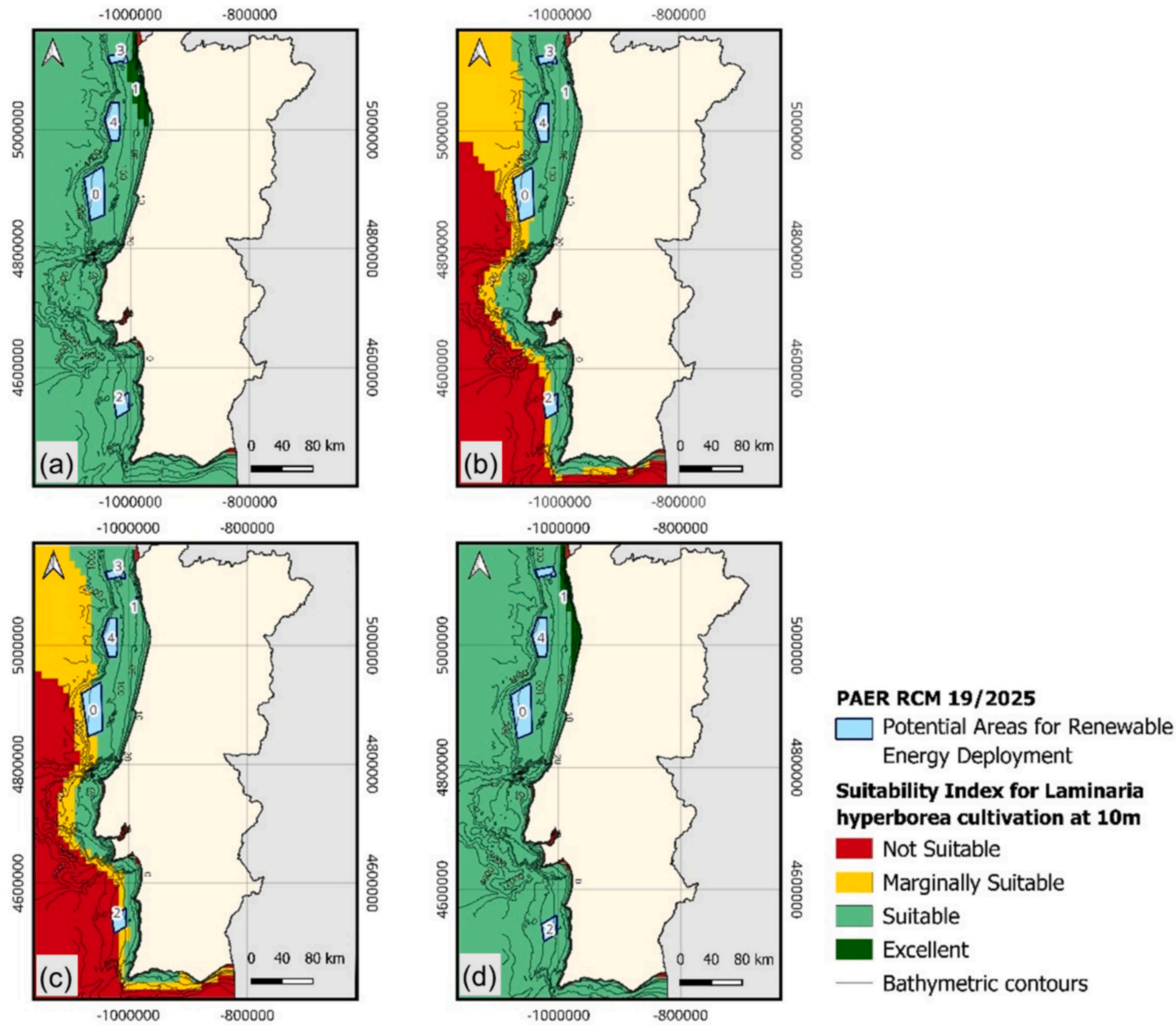

Fig. 16. Overlapping between PAER and SI for *Laminaria hyperborea* at: (a) Spring, (b) Summer, (c) Autumn and (d) Winter, at a 10 m depth.

3.4. Study limitations

This work prioritizes a careful and reduced selection of key variables, with direct standardization, thus ensuring a simple and practical application. In this way, the use of the proposed SI allows the direct incorporation of critical limits and optimal growth zones, providing a result that is immediately applicable in the national context. However, and despite the efforts to guarantee the results viability, this study presents some limitations which are important to recognise.

The environmental parameters selection was based on the available data of CMS, which may condition the scope of the results. The same applies to the seasonal arrangement of the standard deviation, which may omit short-term variations. The resolution of the dataset restricts the identification of extreme events of either upper or lower threshold exceedance for the survival limits of the species. For instance, heatwaves are a major concern for marine species, leading to potentially high mortality rates among farmed populations. Though this is dependent on their life-cycles and harvesting periods (e.g., collect the product prior to warmer periods, such as the Summer), the continued exploitation of the aquaculture farms may require persistent presence of populations, which will be subjected to such extreme events. There can also be interactions between variables, such as the influence of seawater temperature on dissolved oxygen content. As such, even at a SI of 2, the suitability can be conditioned. This becomes a management and economic matter beyond the scope of this paper, but must be accounted for.

In addition, the biological limits of each species were supported by research of the existing literature. This further increments the uncertainty in the analysis, given the individual variability of tolerances and ideal growth within a population. The farmed species may also be affected by diseases, pollution, and even harassed by natural predators. As an example, natural *Laminaria Hyperborea* forests are overgrazed by subtropical fish species like Salema that are moving North, given the increase of seawater temperature associated with climate change (Chemello et al., 2025; de Azevedo et al., 2023). Hence, other stressors are not effectively imbued into the current SI version, though future ones may be capable of handling new stressor input. Therefore, all of these factors do not invalidate the results, but must be mentioned. Lastly, there are specific environmental aspects to be taken into account. For instance, Portugal's DGRM has a dedicated online platform with rulings and guidelines on OA activities (DGRM, 2025c). In order for companies to operate, they must be granted a unique title and follow strict rules on periodical monitoring of water quality, farmed species welfare and other relevant restrictions.

4. Conclusions

This study aimed to assess the viability of OA systems along the Portuguese coast and their potential co-location with MRES. This analysis was carried out through the processing and analysis of available metocean data from Copernicus Marine Service and LNEG. By

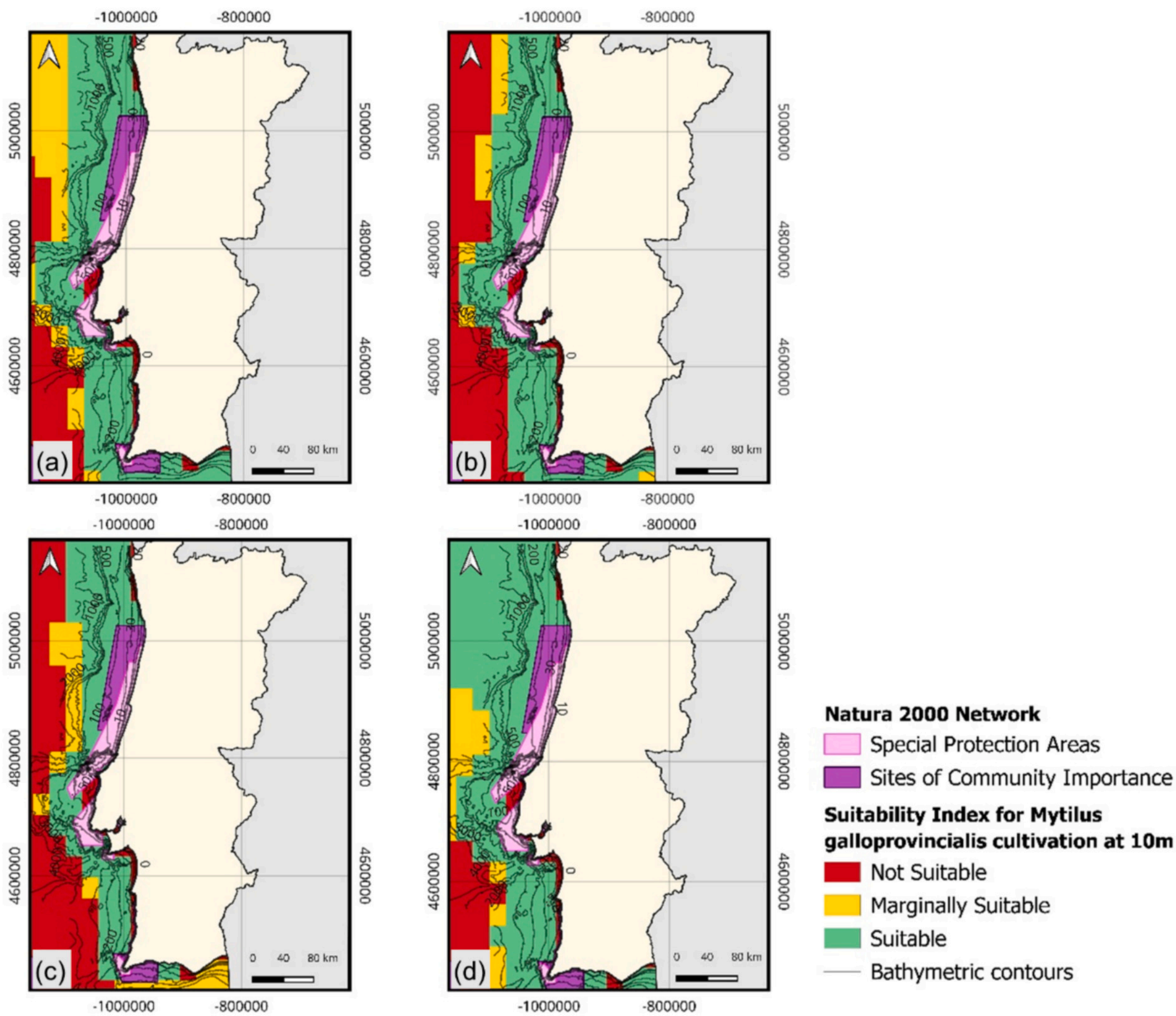

Fig. 17. Natura 2000 maritime areas combined with the 10 m depth SI of *Mytilus galloprovinvialis* at (a) Spring, (b) Summer, (c) Autumn and (d) Winter.

comparing these environmental parameters with the ideal biological limits of the species *Dicentrarchus labrax* (European Seabass), *Mytilus galloprovincialis* (Mediterranean mussel), and *Laminaria hyperborea* (Kelp), suitability indices were generated for different seasons and depths.

These indices were spatially processed using GIS tools, resulting in a series of maps that identified promising areas for the cultivation of each species in Portugal. Furthermore, the overlapping of these suitable zones with the areas defined by the PAER was explored to assess the feasibility of co-locating aquaculture installations with offshore renewable energy. Though there are inherent limitations to the current SI, particularly data concerning actual environmental interactions and impacts, its structure enables a preliminary evaluation of opportunities and restrictions. It also permits future updates, as new information and regulations are made available.

Based on the results of this study, the following conclusions can be drawn regarding the suitability of the three species analysed:

- The North of Portugal appears to be a favourable location for OA of the three species analysed. The European seabass is most suitable in areas to the North of Lisbon (Fig. 10), while the Mediterranean mussel shows suitability for a broad strip parallel to the coastline, wider in the North and narrower in South (Fig. 11). The suitability of *Laminaria hyperborea* presents the highest seasonal variability, which may restrict their suitability to Northern coastal zones (Fig. 12).
- The limiting parameter varies by species. The European seabass is primarily constrained by salinity levels, the Mediterranean mussel by chlorophyll-a concentration, and the *Laminaria hyperborea* by water temperature. More detailed surveys with greater resolution are required for a more specific identification of suitable sites, as well as the assessment of ecological variables interactions. MRES activities and their impacts, from noise limits to seabed dredging, may also be converted into additional SI constraints, if justifiable. The implementation of binary "exclusion zones" may also be pertinent for qualitative criteria, which extends to other complex interactions (e.g., overlap between WEC park wake fields and OA sites).

Regarding their potential co-location with marine renewable energy, the overlap analysis revealed that:

- Viana do Castelo (3) and Leixões (4) are promising areas for the co-location of aquaculture and offshore renewable energy systems, showing suitability for all three species analysed. The generally large distance between existing OA sites and PAER areas, as well as the distinct local water depth ranges, may compromise co-location synergies, such as "shielding" wake fields. By contrast, the negative impacts of MRES-related activities should be mitigated by the spatial distancing;
- Aguçadoura (1) is highly suitable for *Laminaria hyperborea* and suitable for European seabass but not suitable for Mediterranean

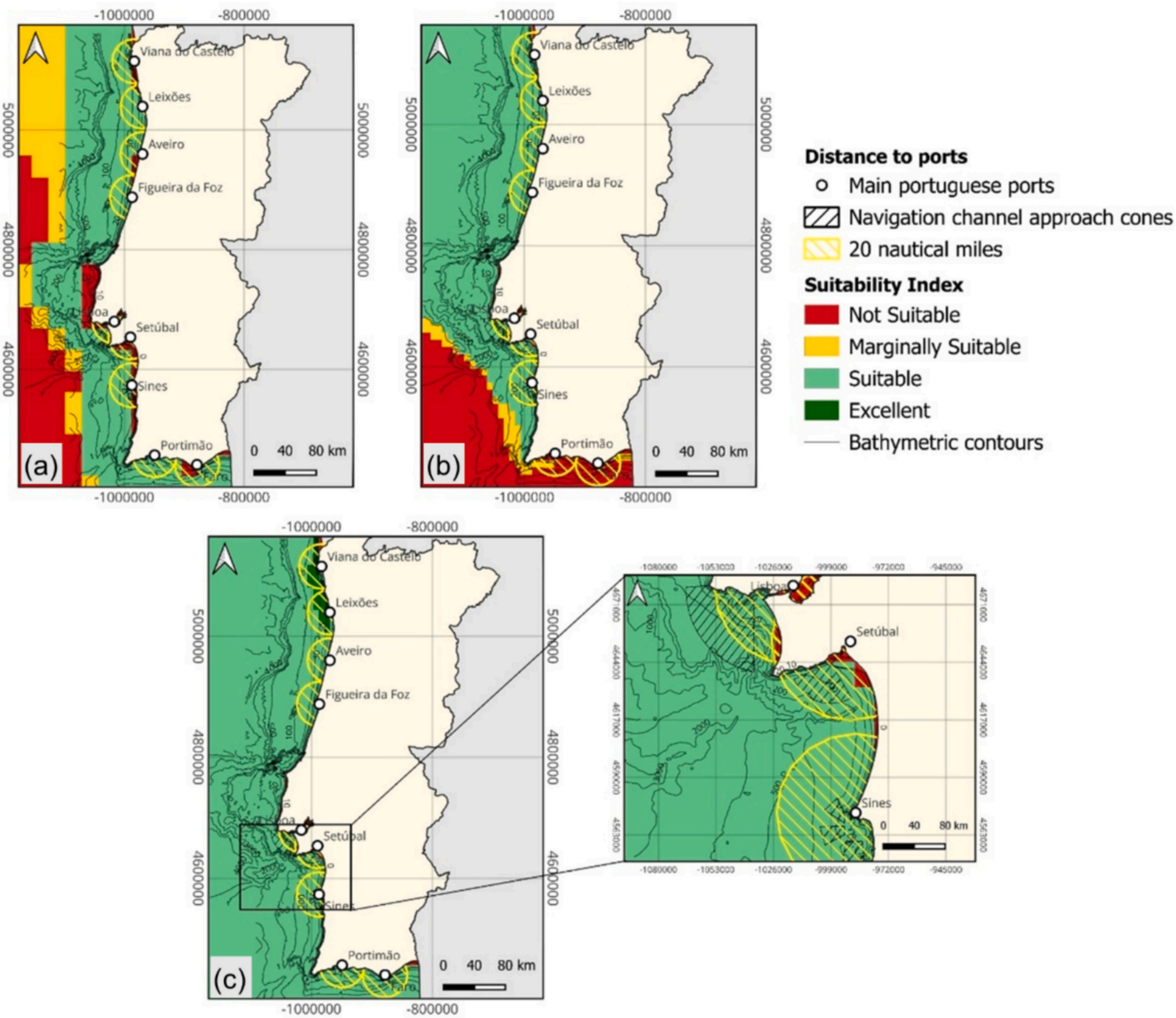

Fig. 18. Suitability indices of *Mytilus galloprovinvialis* (a), *Dicentrarchus labrax* (b) as well as *Laminaria hyperborea* (c) at a 10 m depth, combined with the main Portuguese ports.

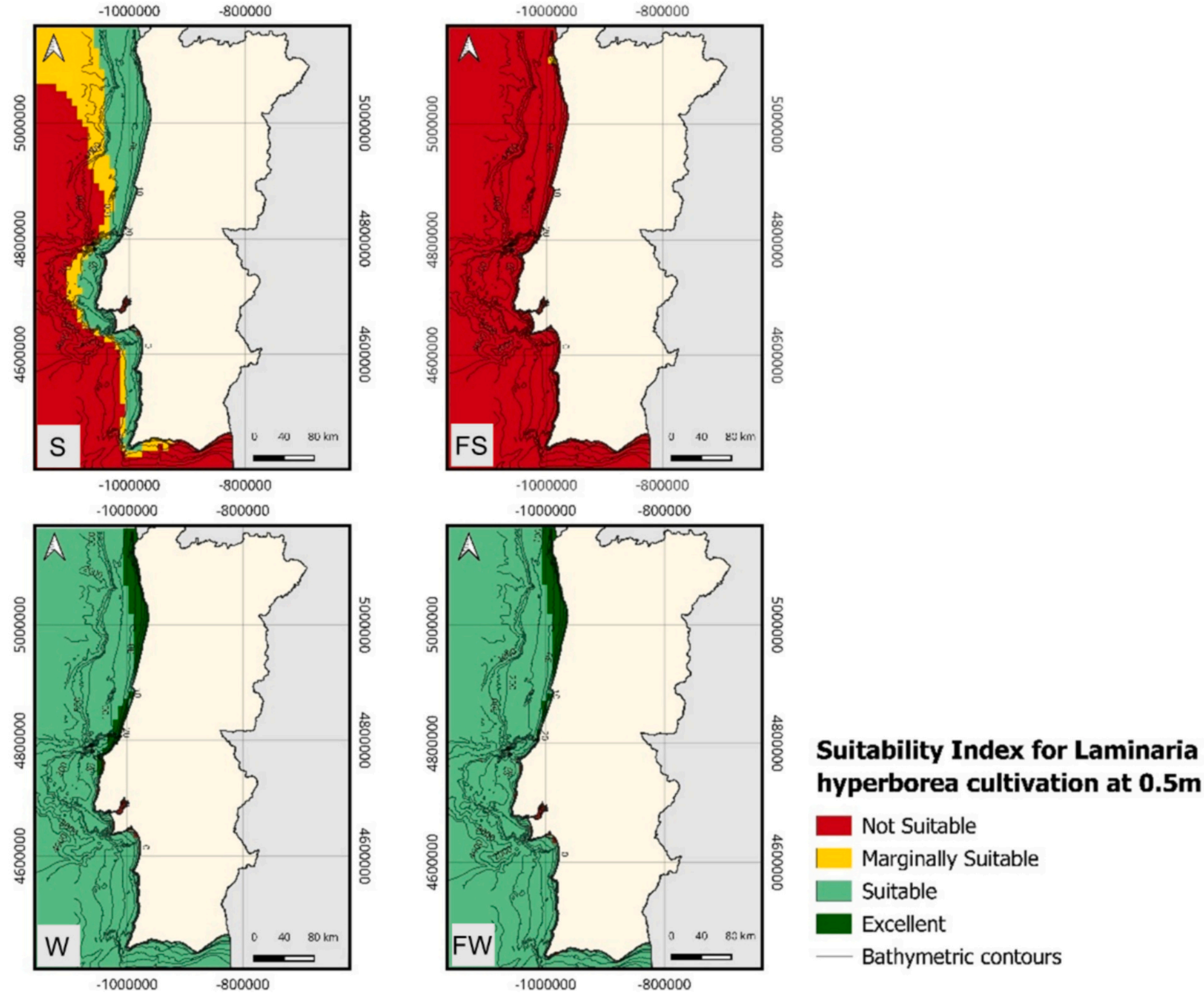

Fig. 19. Comparative analysis of the suitability indices of *Laminaria hyperborea* at surface in the (S) current Summer situation, (FS) in the Summer within 5 decades, (W) in the current Winter, and (FW) 50 years from now Winter.

mussel, while Sines (2) shows good potential only for the Mediterranean mussel and is less suitable for the other two species. Given its "pilot zone" status, it may also provide a controlled, small-scale environment for assessing potential negative impacts and synergy viability under co-location scenarios;

- Figueira da Foz (0) could be viable for the aquaculture of European seabass but presents seasonal limitations for both Mediterranean mussel and *Laminaria hyperborea*. Similar remarks to those made for Leixões and Viana do Castelo are made here, with regards to operational compatibility and impacts. Regardless, further studies like the ones carried out in SAFEWAVE and WindFloat Atlantic, but adapted to the reality of co-located MRES with OA, will be crucial to get more realistic data on these matters. This will enable upgrades to the SI, in order to better reflect reality and provide better decision-making insights for the stakeholders.

Future versions of the SI will seek to incorporate constraints enhancements, practical concerns and innovative approaches. This includes fitting distribution functions to the environmental datasets, from which alternative parameters can be obtained for the SI constraints; further investigating long-term trends and their impacts on the SI distribution and variability over time; and implementing "exclusion zones", based on local marine space restrictions.

CRediT authorship contribution statement

Cristiana Costa: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Filipe Miranda:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Clemente:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Paulo Rosa-Santos:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Francisco Taveira-Pinto:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Tiago Fazeres-Ferradosa:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Daniel Clemente reports financial support was provided by the European Union through Interreg ATLANTIC AREA 2021–2027 Programme. Filipe Miranda reports financial support from FCT.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2026.743888.

Data availability

Data will be made available on request.

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