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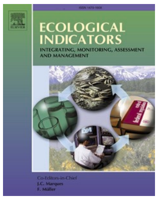

Towards sustainable marine spatial planning of aquaculture

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ABSTRACT

An efficient and adaptive strategy within the EU Marine Spatial Planning Directive has to manage the existing and increasing conflicts between human uses and habitat conservation in coastal-marine areas. Among the different human activities developed along the coasts, aquaculture occupies a primary role. In this context, the aims of this research have been: (1) to propose a conceptual model suitable for aquaculture marine spatial planning; (2) to collect and integrate indicators useful for the characterization of the study area in terms of socio-ecological-economic sensitivities and pressures; and (3) to identify and map the most suitable areas for the development of new fish and shellfish farms. The study area is the Apulia Region (Southern Italy) with a coastline of about 1,000 km, in the Adriatic and Ionian Seas, and characterized by several economic activities within a high value natural context. The evaluation of area's suitability for fish and shellfish farms have been carried out through the ecological characterization of the coastal areas, the identification of the socio-economic, ecological, cultural, and legal-military constraints and the estimate of the "Suitability Index" that, through a Weighted Linear Combination, integrates environmental variables and allows to classify areas as "Highly Suitable", "Suitable" or "Unsuitable". The "highly suitable areas" for new fish and shellfish farms are mainly located in northernmost of the Southern Adriatic Sea along the Gargano coast and in the Gulf of Manfredonia, whilst concerning the Northern Ionian Sea they are at a mean distance of 5 Km from the shoreline. The suitability maps have shown that existing fish farms are in line with their suitable areas but, surprisingly, this has seemed not to be true for shellfish farms. This can be explained by the fact that these aquaculture activities have traditionally been present in some areas (e.g., Taranto Seas), currently strongly impacted by human activities. This research has highlighted that despite aquaculture is generally conceived as an environmental impacting activity, it could be also impacted by other environmental and/or anthropic stressors (i.e., industrial ports, sewage discharges). Considering all these elements, the present research addresses decision-makers, providing information and tools necessary to plan in a more aware way, and also stakeholders interested in investing in the aquaculture sector, who could benefit from the proposed suitability maps for fish and shellfish farms for a sustainable development of this sector.

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1. Introduction

Coastal and marine systems significantly provide ecosystem services that contribute to human needs and well-being (UNEP-WCMC, 2011; Cordero-Penín et al., 2023; Van de Pol et al., 2023). However, the rates of their exploitations could exceed sustainable thresholds and, in many cases, ecosystems have been degraded beyond their resilience capacity with reduction of stability and productivity (Claudet and Fraschetti, 2010; Haghshenas et al., 2021; Halpern et al., 2012). In fact, during the last decades the increase in number and intensity of anthropogenic pressures, associated with global changes (Chimienti et al., 2020; Chimienti et al., 2021; Kyprioti et al., 2021; Patrizzi and Dobrovolski, 2018), have caused the degradation of environmental conditions on a local and wider spatial scale (Coll et al., 2012; Costanza et al., 2014; Millennium Ecosystem Assessment (MEA), 2005). This harmful condition is particularly significant in marine ecosystems due to the increase and diversification of the use of coastal and off-shore areas and their unexplored potential synergistic effects (Galparsoro et al., 2021; Guerry et al., 2012; O'Hara et al., 2021).

The existing and increasing conflicts between human uses in the coastal and off-shore areas and the conservation of marine habitats is reconnected to the indications of efficient and adaptive strategy within the EU Marine Spatial Planning Directive (Union, 2014). In this context, targeted and efficient measures of spatial planning may avoid potential conflicts as well as create positive synergies between human activities and the environment (FAO, 2014; Gimpel et al., 2013; Stelzenmüller et al., 2013), also in terms of environmental security (Müller et al., 2008).

Marine spatial planning (MSP) represents a strategic and effective tool to mitigate the growing and multiple human uses on coastal areas and to ensure their sustainable development, based on an ecosystem-based approach (Domínguez-Tejo et al., 2016; Ehler and Douvere, 2009; Flannery et al., 2018; Hammar et al., 2020; Peart, 2017). The sustainable development of complex socio-ecological coastal systems requires an adequate governance strategy, based on adaptive ecosystem-based management approach towards the integration of human activities and the conservation targets (Schaefer and Barale, 2011; Singh et al., 2021). Therefore, adaptive management is needed to ensure ecosystem sustainability by enabling stakeholders to evaluate, review and rethink their coastal planning choices.

Coastal systems are affected by strong human pressures, which can cause extensive damage and devastating impacts, such as increased erosion and sedimentation, nutrients and many forms of pollution deriving from several human productive activities (Halpern et al., 2008; Halpern et al., 2015; Nordhaus et al., 2018). However, the EU 2014/89 Directive requires the promotion of actions towards the maritime spatial planning (Union, 2014), as a suitable tool to achieve sustainable management of the coastal system (Singh et al., 2021) by considering the multiple human activities along the coasts, such as fishing, aquaculture, tourism, mining, energy, etc. (Abramic et al., 2018).

Furthermore, in the perspective of reaching the SDG 14 of the 2030 Agenda for sustainable development that aims at "*the conservation and sustainable use of the oceans, seas and marine resources for sustainable development*", sustainable marine planning can play a crucial role in supporting decision-making processes (Ntona and Morgera, 2018).

Among the different human activities along the coasts, aquaculture occupies a primary place because fish provides one of the main animal protein sources for human consumption (FAO, 2019; Maiorano et al., 2022), but the fishing industry alone cannot meet the demand without drastically depleting marine fauna (Commission, 2009a). Aquaculture would complement fishery in sustaining the ever-growing global demand for food resources (Jiang et al., 2022; Naylor et al., 2000; Subasinghe et al., 2009) through the production of aquatic organisms in artificial systems with control over habitat variables, species reproduction and feeding. In 2020, the global production of aquatic animals was estimated at 178 million tonnes, of which capture fisheries contributed 90 million tonnes (51%) and aquaculture 88 million tonnes (49%) (FAO, 2022). Aquaculture is considered the world's fastest growing activity in the field of animal production (Marino et al., 2020) due to the significant growth in production capacity with an average annual growth rate of 5,3% in the period 2001–2018 and with an increase in production of more than six hundred times since 1990 (FAO, 2020).

Traditionally managed aquaculture can be seen as environmental-friendly farm since it is based on the re-use of available production wastes and by-products (such as crop residues), coming from other activities, as nutritional inputs for farmed aquatic organisms in open water bodies (Edwards 2015; Ottinger et al., 2016). Differently, modern-managed aquaculture is based on semi-intensive or intensive production systems over a large extent, and dependent on artificial manipulation from the outside. In these production systems a high quantity of fertilizers and/or fish feed as well as antibiotics are generally used to maintain high breeding rates in short periods (Ottinger et al., 2016), leading to important environmental concerns (Naylor et al., 2000).

In this framework, the identification of suitable areas for aquaculture requires the integration of multiple socio-economic and environmental factors (von Thenen et al., 2020) that can be highly different for fish and shellfish farms. The use of an approach based on marine spatial planning can guarantee the allocation of adequate spaces for the sustainable development of different aquaculture systems (Guerry et al., 2012; Schwartz-Belkin and Portman, 2022; Stelzenmüller et al., 2017). The aims of this study have been: (1) to propose a conceptual model suitable for marine spatial planning of aquaculture; (2) to collect and integrate indicators useful for the characterization of the study area in terms of socio-ecological-economic sensitivities and pressures; and (3) to identify and map the most suitable areas for the development of new fish and shellfish farms, taking into account the carrying capacity of natural resources, and the environmental impacts of aquaculture.

1.1. *Why aquaculture needs a marine spatial planning*

To ensure structural and functional stability in marine communities as well as safety and quality in sea products, an aquaculture system must be settled in areas characterized by high environmental quality conditions (Tom et al., 2021; Walton et al., 2015). Otherwise, farmed species can become sinks for pressures coming from other nearby anthropogenic activities. Aquaculture production can be negatively affected by industrial discharges, sewage treatment systems, and the presence of commercial harbors. On the other side, human activities can have direct and indirect effects on aquaculture production (De Silva and Soto, 2009; FAO, 2018) by affecting local physical–chemical and oceanographic variables (temperature, currents intensity, sunlight, nutrient availability), as well as global change (droughts, floodings, warming, ocean acidification).

In this perspective, the analysis of the distribution of pressure sources and sensitive areas as well as an assessment of the local marine variables, through spatial planning, could help decision-makers and stakeholders alike by reducing unwanted effects of these disruptive factors on sea-water quality (Halpern et al., 2009). The increase in aquaculture production requires "environmental space" which is eroded from natural ecosystems. Thus, aquaculture, while contributing to food security, triggers inevitable potential conflicts with the natural characteristics and traditional activities already present in the area (Christie et al., 2014; Gimpel et al., 2015).

The so-called "blue revolution" (Garlock et al., 2020; Puszkarski and Sniadach, 2022) of aquaculture can be attributed to the fact that in recent years this productive sector has been characterized globally by a high growth rate in the field of food production, so much so that it has become part of the food system (Naylor et al., 2021) resulting in an ever-increasing global food reserve (Pradeepkiran, 2019) as stressed by many studies highlighting the potential of marine aquaculture at global scale (Gentry et al., 2023; Naylor et al., 2023; Weiss et al., 2018).

However, the downside of this constant growth of the aquaculture sector has often been the lack of adequate planning of the marine-coastal areas to be allocated to this use. This has led to a whole series of negative consequences, first and foremost the environmental ones (Ali, 2006; Aslan et al., 2021; Thomas et al., 2010). This has generally led to an attempt to regulate the sector through the elaboration of governance and planning guidelines aimed at regulating its development (Jayanthi et al., 2022).

Sustainable marine aquaculture needs the identification of suitable areas for its development, where this productive activity could have a lower impact on coastal-marine ecosystems (Calleja et al., 2022; Jayanthi et al., 2022). The sustainable planning of aquaculture must necessarily take into account many factors useful for an adequate zoning of this activity in coastal-marine environment. In this sense, the amount and heterogeneity of information that needs to be integrated to assess the suitability of a marine area require the use of tools that support the analysis of the several layers, such as geographic information systems (GIS) (Falconer et al., 2016; Ghobadi et al., 2021; Hossain et al., 2007; Jayanthi et al., 2022; Shunmugapriya et al., 2021; Silva et al., 2011; Wu et al., 2020; Yunis et al., 2020).

The integration of socio-ecological-economic data from heterogeneous data sources allows to carry out a spatially informed socio-ecological analysis, that is, to create a real picture of the vulnerability of the complex coastal-marine socio-ecological system capturing the overlaps between social, ecological, and economic factors that insist on these systems (Jayanthi et al., 2022).

2. Materials and methods

2.1. Study area

The study area is the Apulia Region (southern Italy, Central Mediterranean Sea) (Fig. 1), covering a coastline of about 1,000 km characterized by several economic uses and activities carried out even in natural contexts, given by natural national and regional parks, and coastal and marine Special Areas of Conservation. Given the important natural context a science-based identification of proper areas for aquaculture is a priority among stakeholders (Galparsoro et al., 2020).

2.2. Conceptual framework

2.2.1. Identification and mapping of existing aquaculture farms

The identification of suitable areas for aquaculture requires the integration of several criteria and the acquisition of social, economic, and environmental information useful for describing the study area. Thus, in the data collection process, the first step concerns the identification of aquaculture farms already present along the study areas. This has been carried out through (Fig. 2):

- The acquisition of existing data from official databases and the collection of missing data through *ad hoc* questionnaire;
- Data processing;
- Mapping the results.

Each aquaculture farm has been characterized from legal, geographic, and productive viewpoint.

2.2.2. Suitability assessment of the coastal areas

The suitability assessment is based on the following three steps.

- **Step 1 - Environmental characterization of the study areas:**

The first step is focused on the environmental characterization in ecological and hydrodynamic terms.

The ecological characterization has been based on the official Surface Water Bodies monitoring data collected by the Regional Agency for the Protection of the Environment of the Apulia Region. Data referred to the period 2016–2018 were acquired for 39 marine Surface Water Bodies (m-SWBs) and 12 transitional Surface Water Bodies (t-SWBs) along the regional coasts to evaluate:

(i) the ecological and chemical quality of coastal waters bodies, assessed according to the Water Framework Directive 2000/60/EC implemented by Italian Law n. 152/06;

(ii) the water trophic status assessed by applying the TRIX index (Vollenweider et al., 1998); this index is a combination of some variables such as dissolved oxygen, Chlorophyll "a", total phosphorus, and dissolved inorganic nitrogen, and summarizes with a numerical value ranging from 1 to 10 the trophic conditions and the level of productivity

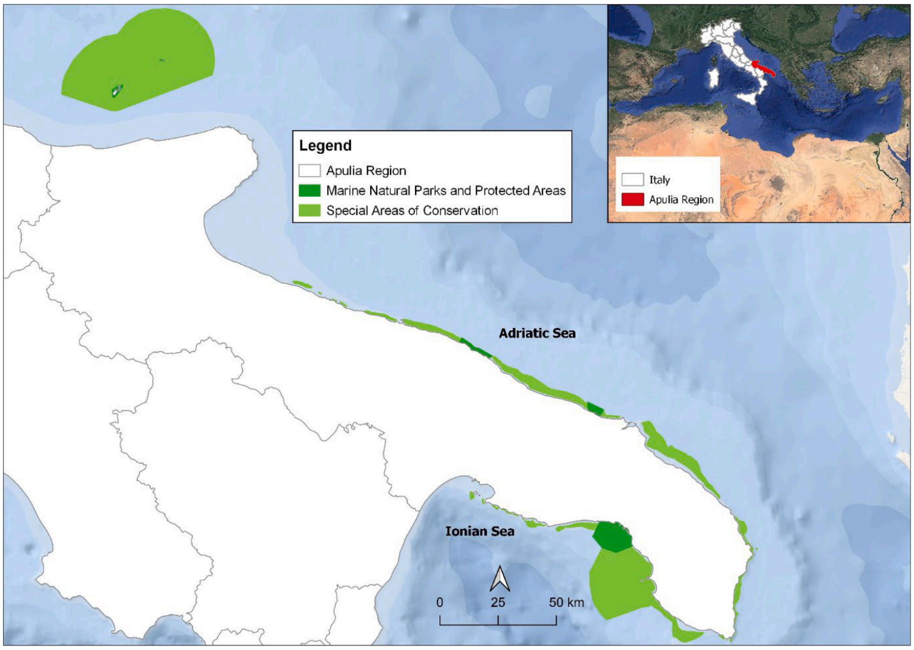

Fig. 1. Study area showing marine natural parks and protected areas and special areas of conservation according to EU Habitat Directive (92/43/EEC).

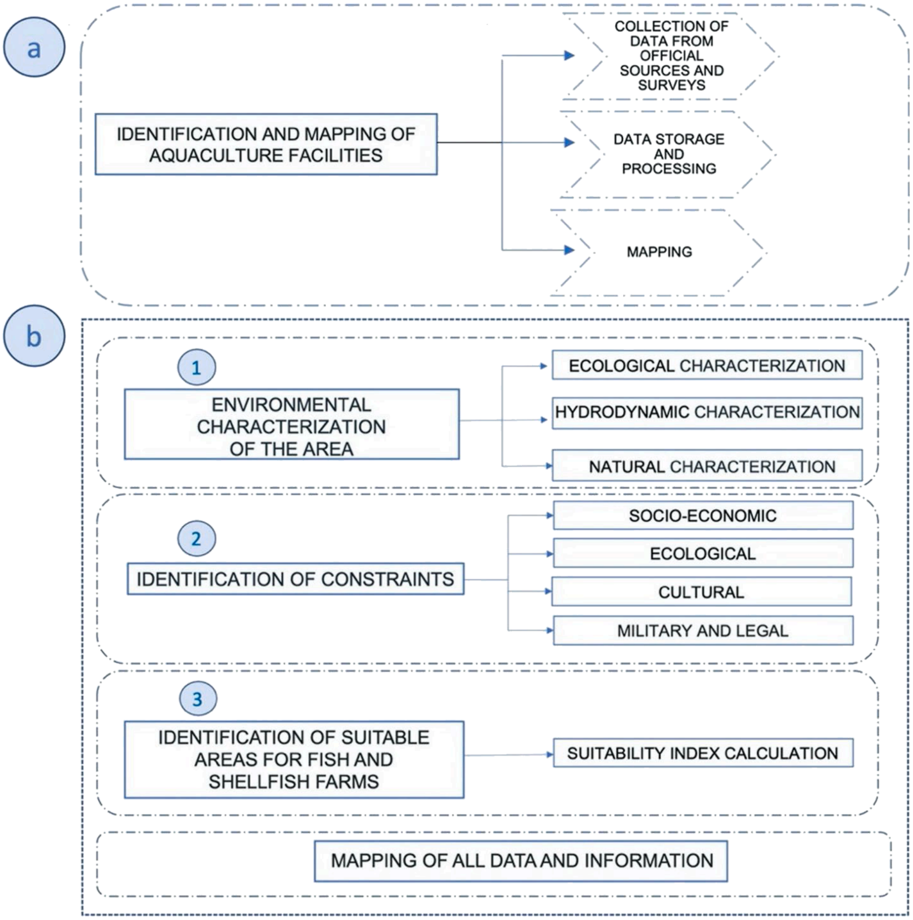

Fig. 2. Conceptual scheme for the identification of suitable areas for fish and shellfish farms: (a) identification, characterization and mapping of existing fish and shellfish farms; (b) the description of the procedure to identify suitable areas for new fish and shellfish farms.

of the coastal areas (from ultraoligotrophic condition to eutrophic-dystrophic conditions);

(iii) the phytoplankton component as a Biological Quality Element (BQE) *sensu* Directive 2000/60/EC and as an indicator of food availability for shellfishes: the abundance of phytoplankton (diatoms, dinoflagellates, and other phytoplankton) has been estimated as cell density (cell/L) in samples collected close to the sea surface.

The hydrodynamic and physical characterization of the study area, carried out on the regional scale, has examined time and space variation in:

(i) hydrodynamic current circulation (m/s);
(ii) thermohaline, i.e. temperature T (°C) and salinity S (psu), gradients.

The Copernicus Marine Environment Service (CMEMS) has been addressed to this scope and specifically the MEDSEA_ANALYSIS_FORECAST_PHY_006_013 database for the year 2019 has been selected as a reference and used (Simoncelli et al., 2019).

To get a global view of the 3D coastal circulation, three depth levels have been investigated: the surface layer (L1), the intermediate layer at 50 m depth (L50), and the deep layer at 500 m depth (L500). Nevertheless, to the aim of the present study, L1and L50 are the layers of greatest interest.

Successively a Lagrangian numerical model (Pini et al., 2018; Pini et al., 2022) has been used to simulate the dispersion of possible tracers (e.g. polluting substances or sediments) from some coastal discharges, in order to assess some reliable scenarios that could occur and eventually affect the aquaculture sites.

Finally, the natural characterization has been based on the identification of some natural habitats proposed for protection under the European Directive 92/43/EEC (e.g. seagrass beds and coralligenous bed). The map of these marine habitats has been acquired from the official web-GIS of the Apulia Region and, then, updated.

- **Step 2 - Identification of the socio-economic, ecological, cultural, and legal-military constraints**

The different socio-economic, ecological, and legal-military constraints have been acquired by the regional web-GIS (sit.puglia.it). Since the areas characterized by one or more of them are incompatible with the development of aquaculture, for each constraint, a different buffer zone has been identified for fish and shellfish farms (Table 1).

- **Step 3 - Identification of suitable areas for fish and shellfish farms.**

This step has been focused on the identification of suitable areas for fish and shellfish farms, based on the environmental characterization (Step 1) and the presence of different types of constraints (Step 2). In particular, to carry out this step the guidelines proposed by the Italian Institute for Environmental Protection and Research (ISPRA) have been followed, where a suitable methodology has been proposed by setting principles, criteria, tools, and methods for planning marine areas for aquaculture in Italy (Marino et al., 2020).

The methodology proposed in this technical guide has been used in several studies in the Mediterranean context (Castillo, 2006; Macias et al., 2019; Manca Zeichen et al., 2022). This choice stems from the

Table 1
List of marine constraints and related buffers for fish and shellfish farms.

Constraints	Buffer for fish farms (m)	Buffer for shellfish farms (m)
National defense and security (military and legal constraints)	500	500
Marine biodiversity conservation (ecological constraints)	1,000	500
Marine archeological heritage conservation (cultural constraints)	500	500
Anthropic use of the coastal system (socio-economic constraints)	1,000	1,000

Constraints and relative buffers have been identified and mapped.

opportunity to use at the national level a methodology comparable with those in use in other Mediterranean countries, with the intention of ensuring a consistent and shared methodological and decision-making approach.

The method is based on a Weighted Linear Combination (WLC) analysis (Malczewski, 2000) and assigns a weight of relevance to each environmental variable (Table 2 and Table 3). More in detail, each variable has been valued, then the variables have been integrated into a common index that applies a weighting factor to each variable according to its importance for the proper development of aquaculture. Finally, the “Suitability Index” (SIndex) has been calculated.

$$SIndex = 100*\frac{\sum_i^N WFi*Si}{\sum_i^N WFi} \tag{1}$$

where:

- WFi is the Weighting Factor giving an indication of the relevance attributed to the variable i included in the assessment;

- Si = Suitability value attributed to the different ranges of values of each variable;

- N is the total number of variables that differs for fish and shellfish farms.

In Table 2 and in Table 3 are reported the lists of variables used to measure the suitability index for fish farms and for shellfish farms, respectively. The analysis assigns three different values to each variable depending on the suitability of the intervals, noticing that optimal range values are included into suitable range values:

- −1 (critical/incompatible)
- 0 (suitable)
- +1 (optimal)

Table 2
Variables used in the assessment of area suitability degree for fish farms (modified after Marino et al., 2020) where optimal range values are included into suitable range values.

Variables	Range of values	Suitability value (S)	Weighting factor (WF)
Average speed of current (m/s)	0.03–0.1 (optimal)	1	10
	0.02–0.5 (suitable)	0	
	<0.02 or > 0.5 (critical)	−1	
Depth (m)	40–50 (optimal)	1	8
	25–80 (suitable)	0	
	<25 or > 80 (critical)	−1	
Seabed	Sand	1	6
	Others	0	
	Rocks	−1	
Swell (m)	< 0.7 optimal)	1	6
	0–2.5 (suitable)	0	
	>2.5 (critical)	−1	
Dissolved O_2 (%Sat)	90–100 (optimal)	1	8
	65–100 (suitable)	0	
	>65 (critical)	−1	
Temperature (°C)	18–26 (optimal)	1	5
	11–30 (suitable)	0	
	<11 or > 30 (critical)	−1	

Table 3
Variables used for the suitability degree for shellfish farms (modified after Marino et al., 2020), where optimal range values are included into suitable range values.

Variables	Range of values	Suitability value (S)	Weighting factor (WF)
Average speed of current (m/s)	0.03–0.1 (optimal)	1	7
	0.02–0.5 (suitable)	0	
	<0.02 or > 0.5 (critical)	−1	
Depth (m)	10–30 (optimal)	1	7
	8–40 (suitable)	0	
	<8 or > 40 (critical)	−1	
Seabed	Sand	1	6
	Others	0	
	Rocks	−1	
Swell (m)	< 0,2 (optimal)	1	7
	0–3 (suitable)	0	
	>3 (critical)	−1	
Dissolved O_2 (%Sat)	≥ 80 (optimal)	1	9
	≥ 70 (suitable)	0	
	< 70 (critical)	−1	
Temperature (°C)	10–24 (optimal)	1	7
	5–28 (suitable)	0	
	> 28 (critical)	−1	
Salinity (‰)	12–38 (suitable)	0	6
	<12 or > 40 (critical)	−1	
pH	7–9 (suitable)	0	3
	<7 or > 9 (critical)	−1	
Chlorophyll *a* (μg/l)	10–20 (optimal)	1	10
	0,5–50 (suitable)	0	
	< 0,5 (critical)	−1	

The weighting factor (K) can vary from 1 to 10, and the weight assigned to each variable is directly proportional to the significance of that variable in the case of fish or shellfish farms. Therefore, the factor K may vary on a case-by-case basis depending on the aquaculture system and technology under consideration.

Thus, by applying the equation (1), it has been possible to measure the “ Suitability Index” (SIndex), classified in three levels as illustrated in Table 4.

Finally, GIS tools are used to transform all the collected data and information into maps.

Table 4
Potential suitability classes based on the SIndex.

Suitability Index	Suitability class
50 ≤ SIndex < 100	Highly Suitable
0 ≤ SIndex < 50	Suitable
SIndex < 0	Unsuitable

3. Results

3.1. Identification and mapping of existing aquaculture farms

Fish farms are located specifically, four in the Gulf of Manfredonia, one along the Adriatic coast, one in the northern part of the Ionian Sea, and three in the Gulf of Taranto (Fig. 3). The shellfish farms are sited in three main areas: along the northern part of the Gargano (14 in the marine area and 13 in the Lagoon of Varano), in the Gulf of Manfredonia (9), and in the Gulf of Taranto (81) (Fig. 3). The fish farms occupy an overall area of 453 ha, while the shellfish farms cover a comprehensive area of about 668 ha.

As far as fish farming is concerned on preponderant breeding of sea bass and sea bream with two hatcheries. The one located in the north of Apulia Region also fattens a very small quantity of young red drum *Sciaenops ocellatus* (Linnaeus, 1766) up to the commercial dimensions required by the catering sector, while a small production of lean *Argyrosomus regius* (Asso, 1801) is carried out by facilities located in the northern Ionian Sea. In particular, the most common technique for fish farming is the use of floating cages with a diameter of around 15 m and a volume of around 2,000 m^3 per cage.

For what regards the shellfish activities some differences are needed. In the Gargano area the activities are mainly based on the rearing of *Mytilus galloprovincialis*, *Crassostrea gigas* and *Ruditapes philippinarum*. The production ranges from 3.8 to 224 q. Few quantities of oysters (*Crassostrea gigas*) are raised in suspension, both in the open sea and in the lagoon, using nursery structures for mussel farming. Unfortunately, it has been impossible to make production estimates for the shellfish farms in the Gulf Manfredonia because of the lack of data. Farms in the Gulf of Taranto base their production mainly on the breeding of *Mytilus galloprovincialis*, occupying about 250 ha with 81 shellfish production licenses. The adult mussels destined for the market come from an area of 150 ha (the second inlet of the Mar Piccolo). Production range is estimated to be between 7,000 and 8,500 tons per year.

3.2. Suitability assessment of the regional coastal areas

3.2.1. Environmental characterization of the study area

The results of the ecological characterization of the marine and transitional SWBs are shown in Fig. 4 (a-b-c): 27 m-SWBs are in the Southern Adriatic Sea and 12 in the Northern Ionian Sea, while 9 t-SWBs are in the Adriatic Sea and 3 in the Ionian Sea.

Based on the ecological quality, assessed according to the Water Framework Directive 2000/60/EC, the 53.8% of m-SWBs have been classified as "*sufficient*" while the remaining 46.2% as "*good*" ecological status (Fig. 4a). For the t-SWBs, the 92% have been classified in a "*sufficient*" state, while the 0.8% in "*bad*" state. As regards the distribution of ecological classes between the two seas, there is a higher percentage of m-SWBs classified as "*sufficient*" in the Adriatic than in the Ionian Sea (59% vs 42%). On the contrary, there is a greater presence of m-SWBs classified as "*good*" in the Ionian Sea (58%) than in the Adriatic Sea (41%). Regarding the transitional waters, all the t-SWBs of Southern Adriatic Sea have been all classified as "*sufficient*" while for the Ionian Sea 2 t-SWBs are classified as "*sufficient*" and 1 is classified as "*bad*".

The results regarding the trophic state, assessed by the application of the TRIX index (Vollenweider et al., 1998), are shown in Fig. 4b. The average value of TRIX for m-SWBs has been 3.3, ranging from a minimum of 2.6 and a maximum of 4.8. The average value of TRIX for t-SWBs has been 5.2 with a minimum of 3.8 and a maximum of 6.7. For both m-SWBs and t-SWBs, the average values of TRIX in Southern Adriatic Sea have been higher (3.41 for m-SWBS; 5.20 for t-SWBs) than the Northern Ionian Sea (3.09 for m-SWBS; 5.17 for t-SWBs).

The distribution of the phytoplankton (diatoms, dinoflagellates and other phytoplankton) cell density is shown in Fig. 4c. The average value of the cell density for m-SWBs has been 4.1E + 05, ranging from a minimum of 1.2E + 04 and a maximum of 1.4E + 06. The average value of the cell density for t-SWBs has been 3.8E + 06 with a minimum of 2.0E + 05 and a maximum of 2.3E + 07. For both m-SWBs and t-SWBs, the average values of the cell density in Southern Adriatic Sea have been higher (5.0E + 05 for m-SWBS; 4.9E + 06 for t-SWBs) than the Ionian Sea (2.2E + 05 for m-SWBS; 4.6E + 05 for t-SWBs).

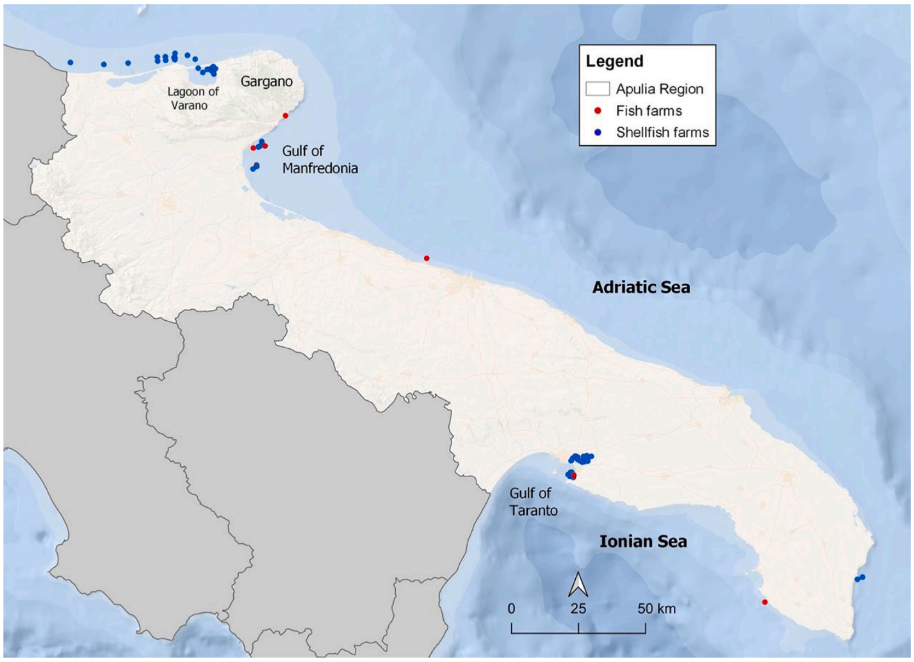

Fig. 3. Map of fish (red) and shellfish (blue) farms located along the coasts of the Apulia Region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

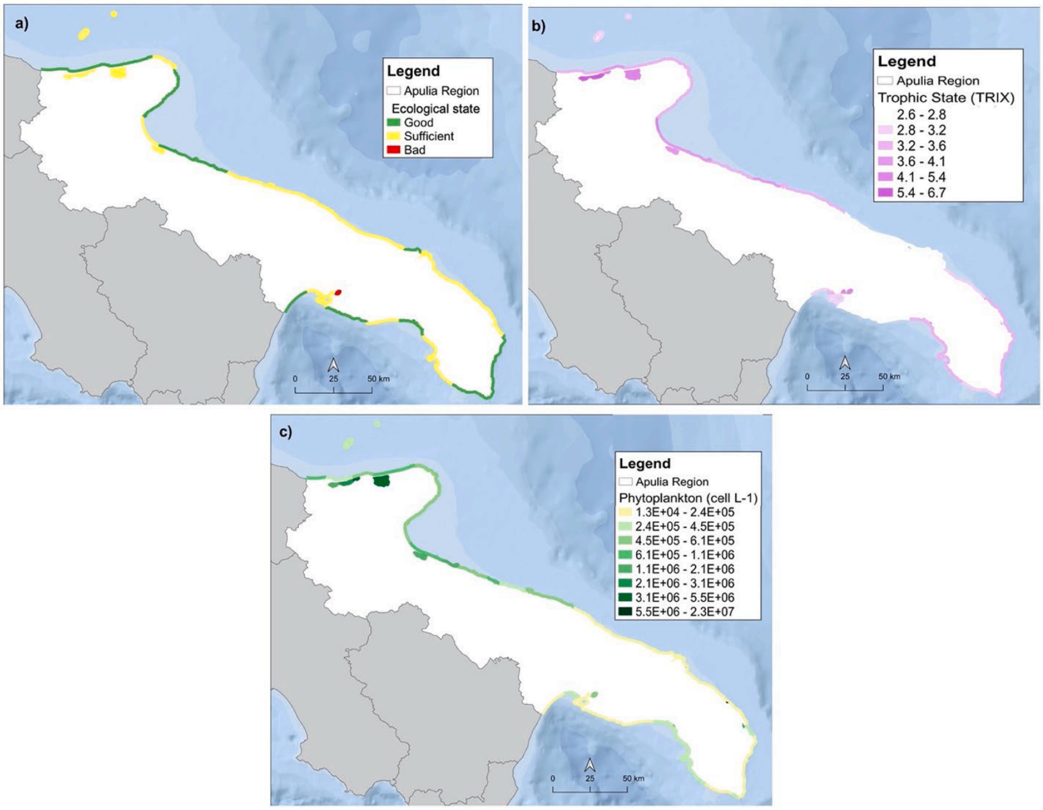

Fig. 4. Map of (a) ecological state, (b) trophic state (average value over three-years period 2016–2018), and (c) phytoplankton density (average value over three years period 2016–2018) for m-SWBs (marine surface water bodies) and t-SWBs (transitional surface water bodies) of Apulia Region coasts.

3.2.2. Hydrodynamic characterization of the study area

The average annual velocity field (of the year 2019) as shown in Fig. 5a confirms the typical hydrodynamic characteristics already reported in the literature (e.g. Poulain 2001; Gačić et al., 2011). In fact, a stable cyclonic gyre in the Southern Adriatic basin and a coastal current flowing along the Western boundary, directed towards the Otranto Strait, are evident. In addition, we also note the Levantine Surface and Intermediate Waters entering through the Strait and moving along the Balkan coast. In the Northern Ionian area it is possible to observe the cyclonic circulation established in the Gulf of Taranto, induced by waters coming from the Southern Adriatic and entering in the Northern Ionian Sea. Finally, the merged representation of currents on the three investigated layers highlights a substantial homogeneous circulation, in terms of direction, along the vertical.

As an example, Fig. 5b shows the average winter and summer circulations in the horizontal plane, at the sea surface (L1), intermediate layer (L50) and deep layer (L500) respectively.

The seasonal averages confirm the structures already observed in the annual map but allow us to better detect their changes in pattern and intensity. Generally increased current intensities are noted in summer and autumn, especially in the western branch of the South gyre. The cyclonic circulation already observed in the Gulf of Taranto is preserved, while a rotation of the current at varying depths at the extreme eastern side of the Ionian Gulf is noted, inducing a swirling structure in the summer months.

In Fig. 5c the horizontal distribution maps of averaged winter and summer temperature in the superficial layer is plotted, as an example. The global analysis has highlighted that the Gulf of Manfredonia is the coastal area characterized by the greatest temperature excursion during the year, while the Gulf of Taranto is characterized, in all seasons, by temperatures on average higher than those observed along the Southern Adriatic coast. It is worth noting that both current and thermohaline values detected by such maps are within the limits reported by Marino et al. (2020). However, to have a more thorough description of their distribution in the target areas, closer to the coast, other detailed and local investigations are needed, based on a higher resolution both in time and space.

Successively, a possible release of tracers has been added to our examined conditions. The numerical Lagrangian model (Pini et al., 2018; 2022) has been used to investigate the spreading and diffusion of the plume. For brevity, here only a selection of our tested scenarios is illustrated, specifically the case of SST (total suspended solids) continuously issued with a flowrate of 0.0042 kg/s by the outfall of a wastewater plant, at coordinates 15.408030° E and 41.990816° N, i.e. at 5 km from the coastline, at the bathymetric line of 30 m.

Fig. 6 shows the concentration maps of the depth-averaged SST respectively fifteen and forty-six days after the initial release. It is evident the contribution of the western coastal current, whose intensity increases with time, to SST transport and spreading towards the South. The approaching of the spring season contributes to the confinement of SST concentration along the Southern Adratic italian coast. It should be remarked that even when such plumes seem to possibly impact the areas of existing (or future) aquaculture sites, the values of these concentrations are very low (having order of magnitude of 10^{-5} g/m^3). Furthermore, based on the quite coarse spatial resolution of the input data by CMEMS, the obtained results should be considered as indicative of possible trends. On the contrary, for a more thorough study, as already previously written, simulations on a local scale basis, characterized by a finer spatial and temporal resolution, should be performed.

3.2.3. Natural characterization of the study area

The maps of the sea grass *Posidonia oceanica* and coralligenous bed are shown in Fig. 7. Both are relevant biocenoses representing a benthic formation endemic for the Mediterranean Sea.

Posidonia oceanica is considered a priority habitat according to the Habitat Directive (43/92/EEC with the code 1120*). Priority natural

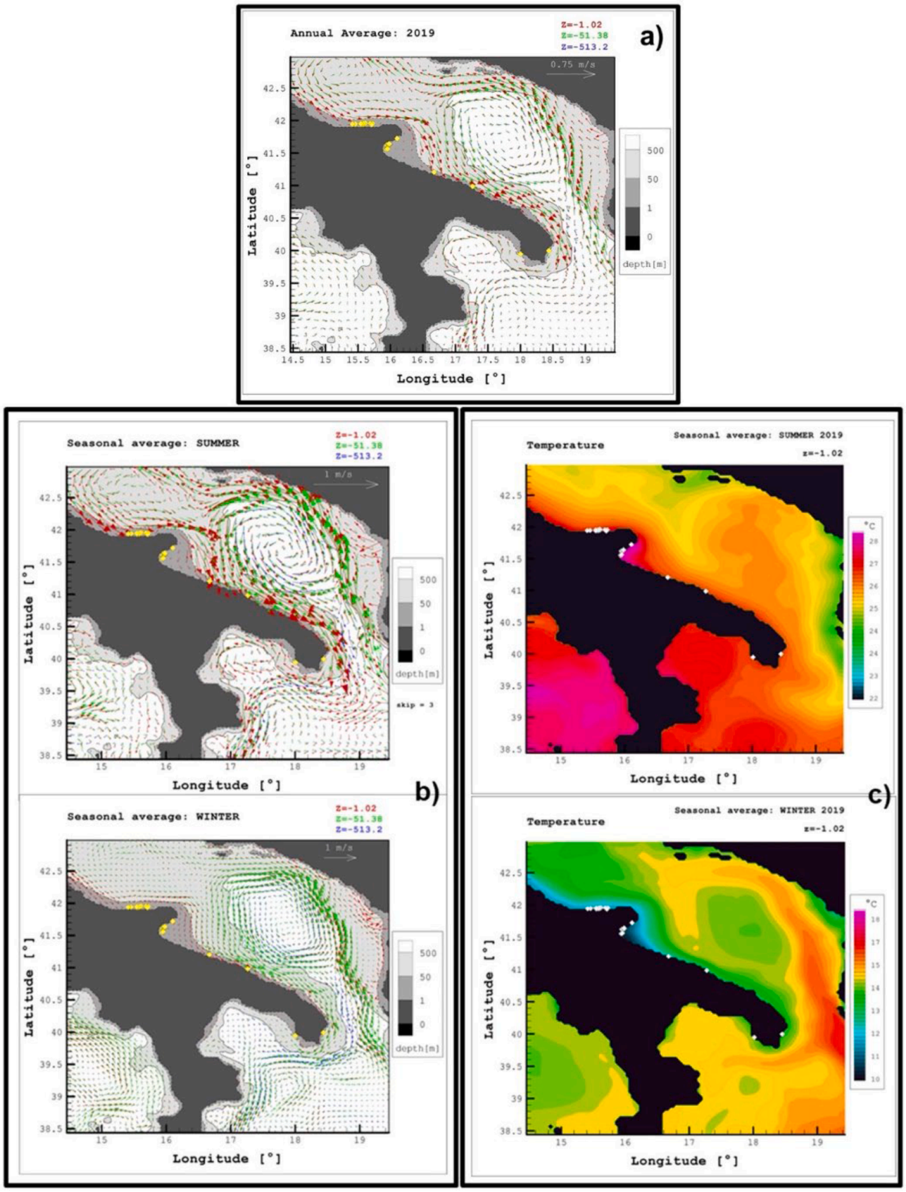

Fig. 5. A) annual and b) seasonal horizontal circulation maps at the three different investigated depths (year 2019); c) horizontal maps of average seasonal temperature at the surface. yellow points stand for existing aquaculture sites. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

habitats marked with an asterisk are habitats that occupy less than 5% of the European territory. For their small spatial extent, they risk disappearing, therefore they are considered at high risk of alteration, due to their intrinsic fragility and their exposure to human impact alteration.

The coralligenous bed are Mediterranean marine bioconstructions classified as Habitat code 1170 “Reefs” under the EU Habitat Directive 92/43/EEC (Savini et al., 2014).

Posidonia oceanica is the most effective coastal plant systems for fixing CO_2 as organic matter (Pergent et al., 2014), removing it from the atmosphere; it can reduce the hydrodynamics and resuspension of sediments (Boudouresque et al., 2006), protecting the coastline from coastal erosion and maintaining high transparency of the water (Evans and Arvela, 2011). Posidonia together with the coralligenous bed contribute to the marine biodiversity providing habitats for several species.

The main stresses to these habitats are the decrease in water transparency and alteration of the sediment regime but also anchoring of vessels, illegal trawling, pollution, competition from invasive algal species, as well as coastal constructions that directly impact or alter the water and suspended sediments circulation regime. This is the reason why these marine habitats must be considered when new human activities have to be installed along the coast, since they can as sink of sediments and organic pollution coming from the fish and shellfish farms.

3.2.4. Identification of the socio-economic, ecological, and legal-military constraints

Fig. 8 represents the map of already existing socio-economic, ecological, cultural, and legal military constrains, in particular:

- National defense and security (military and legal constraints), including all the military areas unsuitable for all human activities;
- Marine biodiversity conservation (ecological constraints), integrating priority habitats (*Posidonia oceanica* and Coralligenous bed) with the presence of coastal dunes, of sites of community importance, and natural parks);

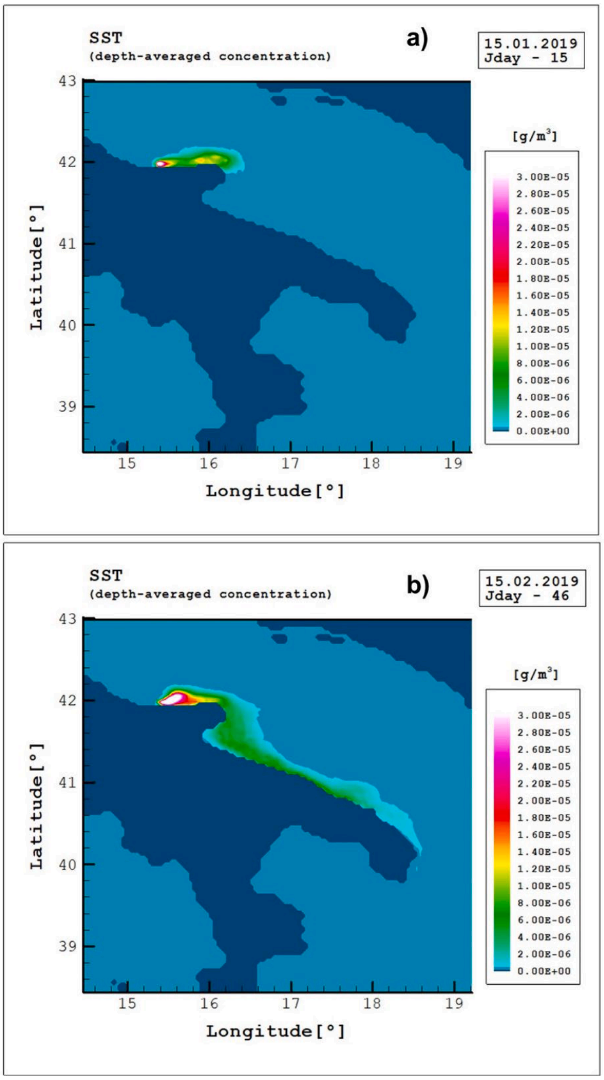

Fig. 6. Scenario showing the concentration maps of depth-averaged SST, continuously issued from a coastal outfall, after 15 days (a) and 46 days (b) from the initial release.

- Marine archeological heritage conservation (cultural constraints), including all the marine areas recognized for their cultural heritage;
- Anthropic uses of the coastal system (socio-economic constraints), based on the integration of different economic activities already present along the coast like tourist facilities, submarine pipelines, industrial and tourist ports.

The map in Fig. 8 shows in red the areas unsuitable for new shellfish and fish farms.

3.2.5. *Identification of suitable areas for fish and shellfish farms.*

Once the areas free from restrictions have been identified along the coast, only in these areas the suitability index has been calculated according to the variables reported in Table 2 for fish farms and in Table 3 for shellfish farms. In particular, the “highly suitable areas” for new fish farms are mainly those along the Gargano coast and the Gulf of Manfredonia, and along the Ionian coast at an average of 5 nm from the coast (Fig. 9).

The “highly suitable areas” for the shellfish farms are those along the coast of Gargano and Gulf of Manfredonia. The “suitable areas” along the Northern Ionian Sea are very fragmented for the presence of several constraints that limit the presence of new shellfish farms (Fig. 10).

4. Discussion

Marine aquaculture is one of the most crucial sectors for economic growth and food security at global scale (FAO, 2015). Aquaculture today is an important component of the Europe’s Blue Growth and Green Transition policies towards an equitable, healthy, and environmentally sound food system. The “Farm to Fork” strategy reaffirms this within the European Green Deal. According to the FAO, aquaculture will play a strategic role for food security and sustainability in the coming years, but it interacts with other activities in the marine-coastal zone. Along the coastal area of Apulia region there is a very complex system because of the presence of numerous activities, but also for the presence of very large areas of valuable naturalness, characterized by important biodiversity hotspots. Therefore, planning for new aquaculture farms requires the integration of data and information on multiple and often incompatible sectors (Longdill et al., 2008).

The research has intended to provide policy makers with a tool to support them in the process of identifying suitable areas for aquaculture, by integrating biodiversity conservation and human uses of the coast (Venier et al., 2021). The geo-spatial integration of different data has resulted completely in line with the maritime spatial planning framework, in order to minimize human impacts on marine environment and conflicts among different sectors acting along the coast (Golden et al., 2017).

In the analysis carried out in this research, a systematic planning approach has been tested translated into areas of priorities in the aquaculture spatial zoning process. Understanding and quantifying the spatial distribution of different typologies of constraints and multiple stressors should help to improve and rationalize the spatial management of human activities, considering both the Water Framework Directive (Commission, 2000) and the Marine Strategy Framework Directive (Commission, 2008).

The site selection model used in this study combined satellite data and other site-specific data through GIS technology, demonstrating the

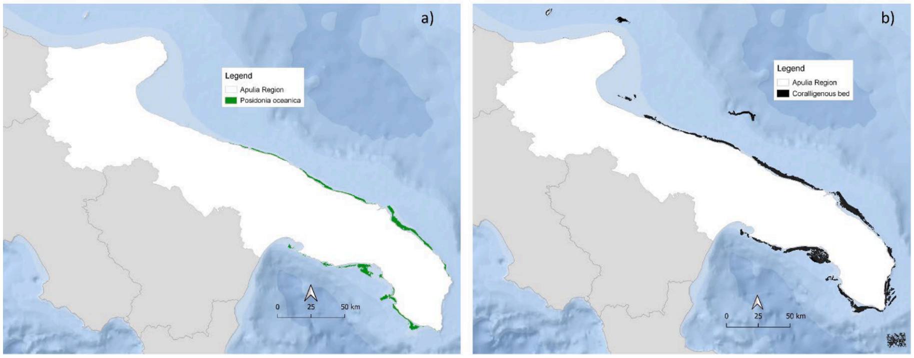

Fig. 7. (a) Map of *Posidonia oceanica*, (b) Map of Coralligenous bed.

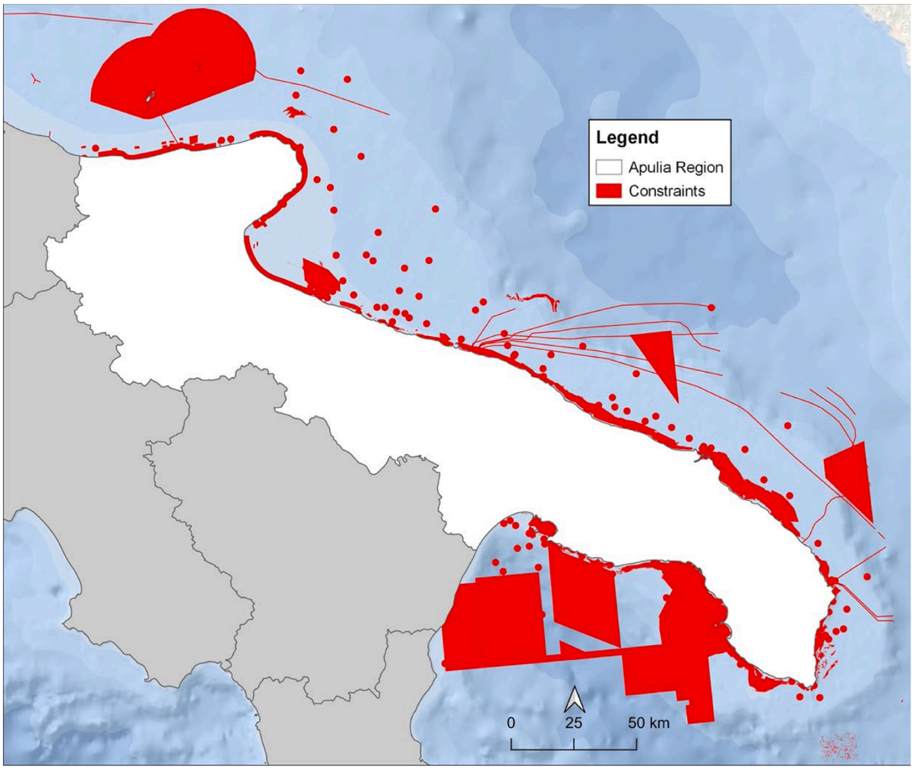

Fig. 8. Map of the socio-economic, ecological, cultural, and legal-military constraints.

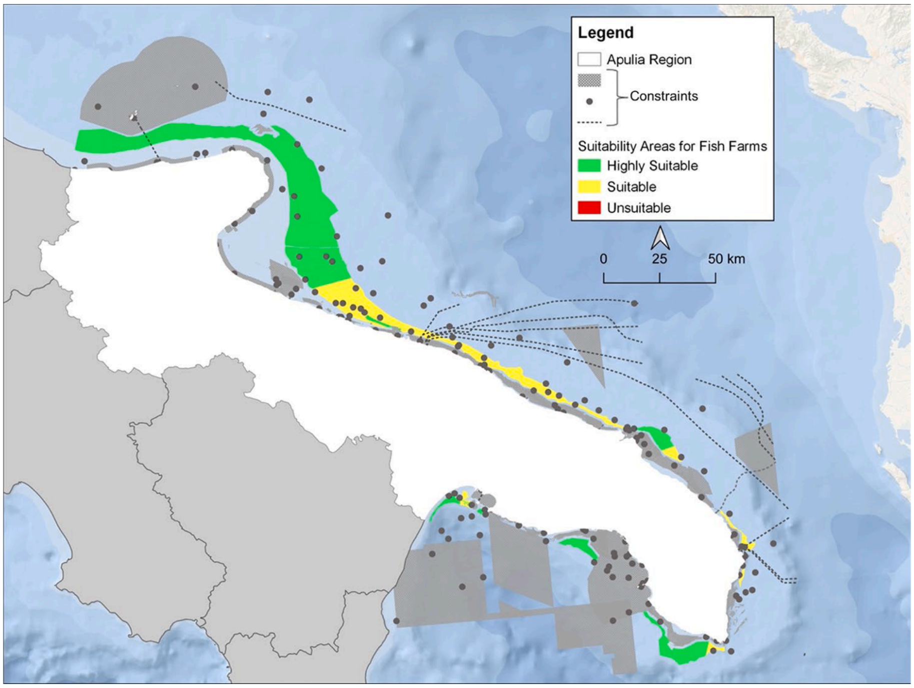

Fig. 9. Suitability areas that can be potentially used for new fish farms. The highly suitable areas are in green, while in grey are all the possible constraints. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

remarkable potential of spatial tools to identify suitable areas by linking important factors (infrastructure, land, water), with unique capabilities to automate, manage and analyze a variety of spatial data. The GIS platform offers the ability to zone aquaculture potential by combining multiple data and information into a multidimensional model (Jayanthi et al., 2022).

The selection of environmental variables, the range of values associated with the suitability index, and the weighting factor (Table 2 and Table 3) are critical aspects to determine where fish or shellfish farms can be realized with low socio-economic-environmental impacts. These values have been integrated to determine the most suitable areas for both farms (Fig. 7 and Fig. 8), however specific suitability studies should

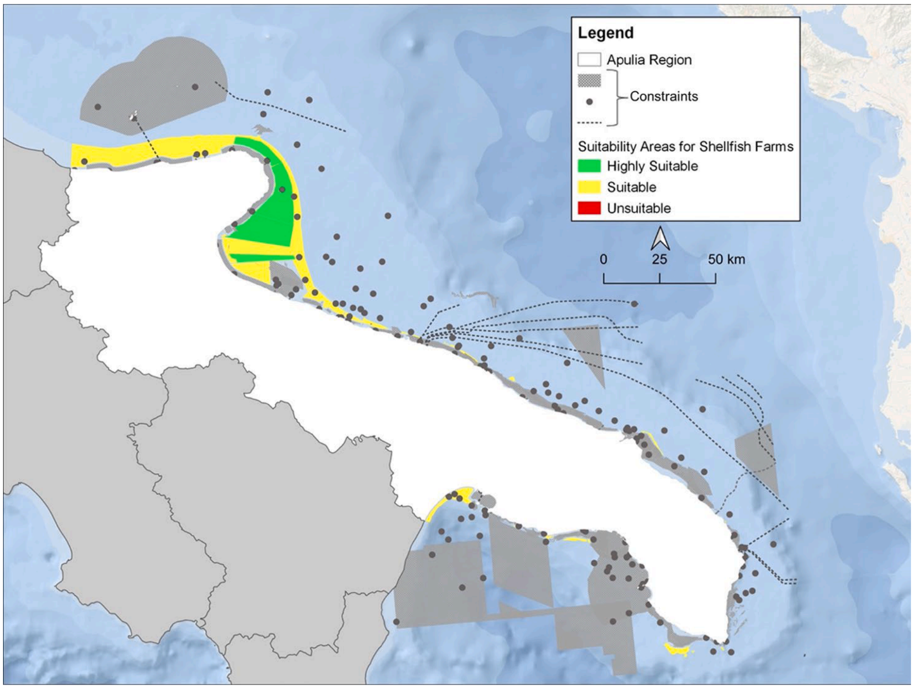

Fig. 10. Suitability areas that can be potentially used for new shellfish farms. The highly suitable areas are in green, while in grey are all the possible constraints. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

carry out to take into account species specific environmental conditions.

The integration of the existing farms' map with the suitability map highlighted that while the existing fish farms are located in suitable areas, this seems not true for shellfish farms. A high number of shellfish farms are currently in areas unsuitable for the presence of environmental constraints or for the presence of hot-spots of biodiversity (norther part of Apulia region) or for the presence of highly impacting heavy industrial activities, as in the case of Gulf of Taranto. In the latter case, mussel farms have traditionally been present in Taranto's seas for centuries, well before the implementation of industrial activities and, therefore, beforehand the Marine Spatial Planning Directive recommendations.

The spatial planning of marine areas affects and is affected by terrestrial economic activities as in the case of constraints do not allow the settlements of new farms in specific areas. On the other side, some anthropic activities like tourism can be threatened by the presence of new fish/shellfish farms. Sea aquaculture could affect local biodiversity bus, economically, can be the sink of a predatory pressure by avifauna. This is the case of cormorants (*Phalacrocorax carbo sinensis*) that are protected under Birds Directive 2009/147/EC (Commission, 2009b). Cormorant colonies move from northern Europe to the coastal wetlands of Apulia for the winter and then migrate again in late spring before the breeding season. The most recent data available for Apulia region on the wintering population are from censuses conducted during the period 2007–2019, as part of Wetlands International's IWC project, and are reported in Fig. 11, showing that their numbers increased from 2018 to 2019. The presence of cormorants represents a well-known management problem for the aquaculture sector in Apulia region. All farms manage the problem with anti-predator nets and acoustic deterrents (gas cannons or other blank firing systems) used in case of emergency. Their increasing numbers can represent a potential pressure in specific periods that a company interested in investing in aquaculture has to take into account.

5. Conclusions

It is crucial to consider aquaculture as a not stand-alone sector, but rather strongly interconnected with both purely environmental and socio-economic dynamics and aspects (Puszkarski and Sniadach, 2022). The ability to integrate the many and diverse aspects concerning marine-coastal socio-ecological system must be considered a fundamental aspect in any sustainable planning process that can ensure the success of integrated Maritime Spatial Planning policies. Ensuring strong

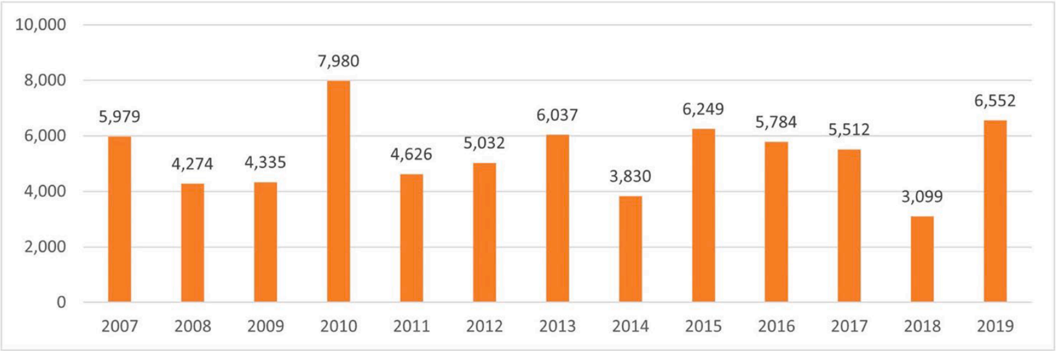

Fig. 11. Wintering population census of cormorants 2007–2019 (Zenatello et al., 2020).

integrative capacity in management framework is a fundamental requirement for effective marine-coastal environmental protection.

The collection of so different data derived from different sources, can represent a very complex and long proved process, necessary to ensure a high quality of the data set (Vaitis et al., 2022). The discrepancies and heterogeneity of data that characterize coastal and marine system have been effectively integrated through GIS technologies. The GIS platform, as a spatial tool, can find suitable areas by relating crucial factors in marine-coastal planning. This spatial tool can be easily applied by decision-makers and allows the development of aquaculture while maintaining the integrity of ecosystem resources in coastal regions (Froehlich et al., 2018; Jayanthi et al., 2022). The regional scale has resulted the rightest spatial scale to plan for marine system, despite the difficulty of acquiring all the needed data at comparable spatial and temporal scale. The results of this research are useful for decision-makers that can plan in a more aware way, by taking into consideration not only the economic development but also the conservation of biodiversity and the sustainability of aquaculture sector. The results of the research are useful also for people or company interested in investing in aquaculture sector, because can select in a more appropriate way areas more suitable for the development of sector without impacting the environment.

The Apulia region, in the perspective of reaching the SDG 14 of the 2030 Agenda for sustainable development, is a step forward in comparison with other regions towards the right balance between the conservation of marine habitat and resources and the sustainable use of the sea. This research can represent an useful tool for other Mediterranean regions that consider aquaculture an economic sector that can develop in a sustainable way.

CRediT authorship contribution statement

Irene Petrosillo: Writing – original draft, Conceptualization, Methodology, Supervision, Writing – review & editing, Validation, Visualization. **Angela Maria Scardia Scardia:** Methodology, Writing – review & editing. **Nicola Ungaro:** Conceptualization, Methodology, Writing – review & editing. **Antonietta Specchiulli:** Conceptualization, Methodology, Writing – review & editing. **Giovanni Fanelli:** Conceptualization, Methodology, Writing – review & editing. **Gerardo Centoducati:** Conceptualization, Methodology, Writing – review & editing. **Francesca De Serio:** Writing – original draft, Conceptualization, Methodology, Writing – review & editing. **Roberto Carlucci:** Conceptualization, Methodology, Writing – review & editing. **Donatella Valente:** Conceptualization, Methodology. **Enrico Barbone:** Data curation, Formal analysis, Methodology. **Agnese Pini:** Methodology, Data curation, Visualization. **Cosimo Gaspare Giannuzzi:** Methodology, Data curation, Visualization, Investigation. **Tommaso Scirocco:** Data curation, Visualization, Investigation. **Erica Maria Lovello:** Methodology, Data curation, Visualization. **Michele Deflorio:** Data curation, Visualization, Investigation. **Antonio Oscar Lillo:** Methodology, Data curation, Visualization. **Diana De Padova:** Data curation, Visualization, Investigation. **Loredana Papa:** Data curation, Visualization, Investigation. **Elisa Goffredo:** Data curation. **Maria Emanuela Mancini:** Data curation. **Michele Mossa:** Conceptualization, Methodology, Supervision, 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.

Data availability

Data will be made available on request.

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