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***DEVELOPMENT OF A SPATIAL DECISION SUPPORT SYSTEMS (SDSS)
FOR SUSTAINABLE DEVELOPMENT: SPATIALLY EXPLICIT
ANALYSIS OF ECOSYSTEM SERVICES PROVIDED BY THE LIGURIAN
COASTAL AREA***

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ABSTRACT

Coastal zones are dynamic and complex ecosystems, where interactions between terrestrial, pelagic, benthic, and intertidal systems support biodiversity and essential ecosystem services. These areas play a critical role in climate regulation, food supply, and recreation, yet they are increasingly vulnerable to anthropogenic pressures such as urbanization, resource exploitation, and habitat degradation. Effective management of coastal zones is essential to maintain their ecological integrity and ensure the sustainable provision of ecosystem services. However, this requires tools that integrate environmental, social, and economic dimensions to address the challenges posed by competing demands on these ecosystems.

This dissertation, presented as a collection of journal articles, focuses on the development of a Spatial Decision Support System (SDSS) tailored for coastal and marine ecosystems. The SDSS integrates advanced modeling techniques, spatial data analysis, and stakeholder engagement to provide strategies for sustainable coastal management. Using Geographic Information Systems (GIS), cartographic, satellite, remote sensing, and field data, the research delivers a framework for assessing the impacts of human activities, identifying areas for conservation and restoration, and balancing ecosystem health with sustainable development goals.

The first two studies investigate the biological and monetary valuation of natural capital in the Ligurian Sea, a Mediterranean biodiversity hotspot. Using emergy analysis, the natural capital of the Ligurian coastal and marine area was valued at €2.11 billion in emergy terms, with annual environmental flows worth €1.43 billion. Protected areas were shown to have significantly higher values, highlighting the effectiveness of conservation efforts. Furthermore, anthropogenic factors, such as coastal development and pollution, were found to have a stronger influence on natural capital distribution than natural variables, reinforcing the need for robust management interventions. The results demonstrate the effectiveness of conservation measures and provide a baseline for monitoring and managing natural capital.

Subsequent studies focus on habitat suitability models (HSMs) for two keystone species: *Posidonia oceanica* and *Ericaria amentacea*. These models identify potential areas for habitat expansion and restoration, providing insights into the environmental and human factors that influence species distributions. By combining predictive modeling with spatial analysis, these studies contribute to the design of targeted conservation efforts that align with regional and international policies, such as the EU Biodiversity Strategy and the Nature Restoration Law.

A spatial risk assessment framework further contributes to the SDSS by assessing the balance between ecosystem service supply and human-induced pressures. Applied to the Ligurian

coastal and marine area, this dynamic analysis highlights the trade-offs between human activities and ecosystem health. Regional differences in risk levels also identified critical areas for targeted interventions and the need for improved data collection in less studied regions. The flexibility of the framework is demonstrated through scenario analyses that highlight the dynamic interactions between human activities and ecosystem resilience, drawing attention to the need for adaptive strategies to mitigate risks and fill data gaps.

The integration of these studies culminates in a WebGIS platform that serves as the operational interface of the SDSS. This user-friendly tool allows stakeholders, researchers, and policy makers to visualize, explore, and download geographic and alphanumeric data. The platform includes base maps and thematic maps derived from the dissertation's research to facilitate transparent and informed decision-making processes. By addressing the spatial dimensions of environmental, economic, and social challenges, the SDSS supports the development of sustainable strategies that balance human activities with the conservation of coastal ecosystems. This dissertation contributes to advancing the theoretical and practical understanding of sustainable coastal management by demonstrating the value of integrative approaches and innovative tools.

LIST OF ORIGINAL ARTICLES AND RESEARCH

This dissertation consists of the following articles and research:

PAPER I:

Bordoni, R., Rigo, I., Dapuzeto, G., Povero, P., Vassallo, P., Paoli, C. (2023). Assessment of natural capital and environmental flows distribution: A Mediterranean case study. *Journal of Cleaner Production*, 409, 137228.

PAPER II:

Rigo, I., Bordoni, R., Betti, F., Dapuzeto, G., Massa, F., Paoli, C., Ruggeri, F., Vassallo, P. (2024). Which natural or anthropogenic variables influence natural capital? An Italian case study. *Ecological Indicators*, 166, 112387.

PAPER III:

Bordoni R., Paoli C., Montefalcone M., Oprandi A., Rigo I., Ruggeri F., Vassallo P. Habitat suitability modeling for *Posidonia oceanica* distribution along a Mediterranean region (NW Italy). *Environmental and Sustainability Indicators*. In press.

RESEARCH I:

Bordoni R., Paoli C., Asnaghi, V., Chiantore, M., Farina L., Gaino, F., Rigo, I., Ruggeri, F., Vassallo, P. Habitat Suitability Models as a prioritization tool for enhancing the restoration success of *Ericaria amentacea*. In preparation.

RESEARCH II:

Bordoni R., Paoli C., Rigo I., Vassallo P. Spatial risk evaluation of coastal and marine ecosystem services exploitation in an Italian coastal area. In preparation.

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1. INTRODUCTION

1.1 Background

The coastal zone represents a very complex, sensitive, and fragile environmental system characterized by strong variability in chemical, physical, and biological processes. Its structure and functioning are the result of the interactions among several physical drivers—geomorphology, hydrodynamics, terrestrial inputs, and climate—on this intricate web of interactions between terrestrial, pelagic, benthic, and intertidal systems. This natural complexity is further compounded by anthropogenic activities, rendering coastal zones especially dynamic and vulnerable. Coastal areas play a critical role in ocean-land interactions and provide important ecosystem services such as tourism and leisure, food supply, climate regulation, and biodiversity conservation (Costanza et al., 1997; Daily, 1997; Yanes et al., 2018). However, these ecosystems are under unprecedented anthropogenic pressure (Halpern et al., 2008). Global population growth, urbanization, and increasing demands for resources, transportation, and energy have intensified these pressures, especially along densely populated coastal regions (Neumann et al., 2015; Merkens et al., 2016; Agardy et al., 2005). The world's population is projected to reach 8.5 billion by 2030 under UN projections, with an increase in resource demand by up to 50% (Hester and Harrison, 2010). This trend will increase competition for limited resources, thus stressing coastal ecosystems and threatening their ability to sustainably provide ecosystem services.

More than 60% of global ecosystem services are being degraded with significant consequences for human activities, according to the Millennium Ecosystem Assessment (2005). This is only going to get worse for biodiversity (Sala et al., 2000), given direct and indirect impacts of change in ecosystems on human welfare due to the complexity and non-linear causal pathways that describe the interactions (Crossland et al., 2005; Sekovski et al., 2012; Pinto et al., 2014). Poor planning, incoherent governance, and fragmented land-sea management, further complicated by a lack of regulation and enforcement, exacerbate these challenges (Duxbury and Dickinson, 2007; Visbeck et al., 2014).

To respond to such threats, impacts due to human activities on coastal ecosystems have to be assessed with precision in order to come up with areas for conservation and restoration. This approach is critical in maintaining ecosystem services and preventing loss of biodiversity to achieve sustainable management (Oliver et al., 2015). Effective management must be based on

informed decision-making processes, supported by innovative tools and policies that are aligned with national, regional, and international frameworks. For such threats to be managed, there are comprehensive framework instruments designed for both European and global actions. The EU Marine Spatial Planning Directive (2014/89/EU) aims at promoting the sustainable use of marine resources by integrating environmental, social, and economic considerations into planning processes. Complementing this, the Marine Strategy Framework Directive (2008/56/EC) strives towards achieving "good environmental status" for EU marine waters by taking an ecosystem approach that targets biodiversity conservation, pollution reduction, and climate adaptation measures. These directives are important instruments to ensure coherence in the use of marine and coastal resources.

At the global level, the 2030 Agenda for Sustainable Development underscores the importance of sustainable practices, with specific goals addressing the health of coastal and marine ecosystems. In particular, Sustainable Development Goals 14 (*Life Below Water*) promotes the protection and restoration of marine ecosystems as a means of improving human well-being. In the European context, the EU Biodiversity Strategy for 2030, part of the European Green Deal, sets ambitious targets for halting biodiversity loss and restoring ecosystems: it aims to protect at least 30% of land and marine areas and restore degraded habitats.

Building on these efforts, the Nature Restoration Law, recently adopted by the EU, establishes targets for restoring degraded ecosystems across Europe, including coastal and marine habitats. Spatial Decision Support Systems (SDSS) are particularly valuable in addressing these challenges. Designed to improve decision making for complex spatial problems, SDSS improve the quality and consistency of management decisions by assessing the environmental impacts of different human activities (Malczewski, 1997; Rizzoli and Young, 1997; Cortés et al., 2000; Poch et al., 2003; Dapueto et al., 2015, Dapueto et al., 2020). Because of their adaptability, these systems can accommodate different management needs, allowing for tailored strategies for multiple activities.

The conservation of coastal ecosystems requires a collective and urgent effort. By integrating advanced tools such as the SDSS with robust policy frameworks, it is possible to balance human activities with ecosystem health. Collaboration at local, national and international levels is essential to implement effective strategies, restore degraded environments and ensure the sustainable provision of ecosystem services. Coastal zones are vital not only for biodiversity, but also for the well-being of present and future generations, making their protection an urgent shared responsibility.

1.2 Aim of the thesis and research questions

This dissertation is a collection of journal articles written over the course of the PhD.

The main objective is to develop a SDSS capable of integrating economic, social and environmental criteria to propose sustainable development strategies for coastal areas.

The second chapter, Theoretical and Conceptual Framework, provides a general introduction of the key concepts underlying the thesis, natural capital and ecosystem services, habitat suitability models and SDSS.

The third chapter provides summaries of each paper and research project included in the thesis.

The fourth chapter, Results and Discussion, summarizes two published articles, one currently in press, and two others in preparation.

FIGURE 1 **Error! Reference source not found.** illustrates the overarching research connections shared by these papers. Specifically, all projects aim to explore different aspects of the study area in order to develop an SDSS that addresses different aspects of coastal and marine areas. The first two studies focus on the biological and monetary valuation of natural capital, analyzing its dependence on environmental and anthropogenic variables. These variables also play an important role in the next two studies, which focus on the development of habitat suitability models. The final research project assesses and maps the ecosystem services of the study area, making spatially explicit the trade-offs between supply and demand for these services.

Each paper then deals with specific research questions that have been addressed separately. The projects share a common approach based on the integration of cartographic, satellite, remote sensing, and field data in a GIS (Geographic Information System) environment, which allowed, as a first step, to display the spatial distribution of the assessed evaluations and, secondly, to provide the basis for the creation of the final SDSS.

Finally, the final chapter presents the concluding remarks.

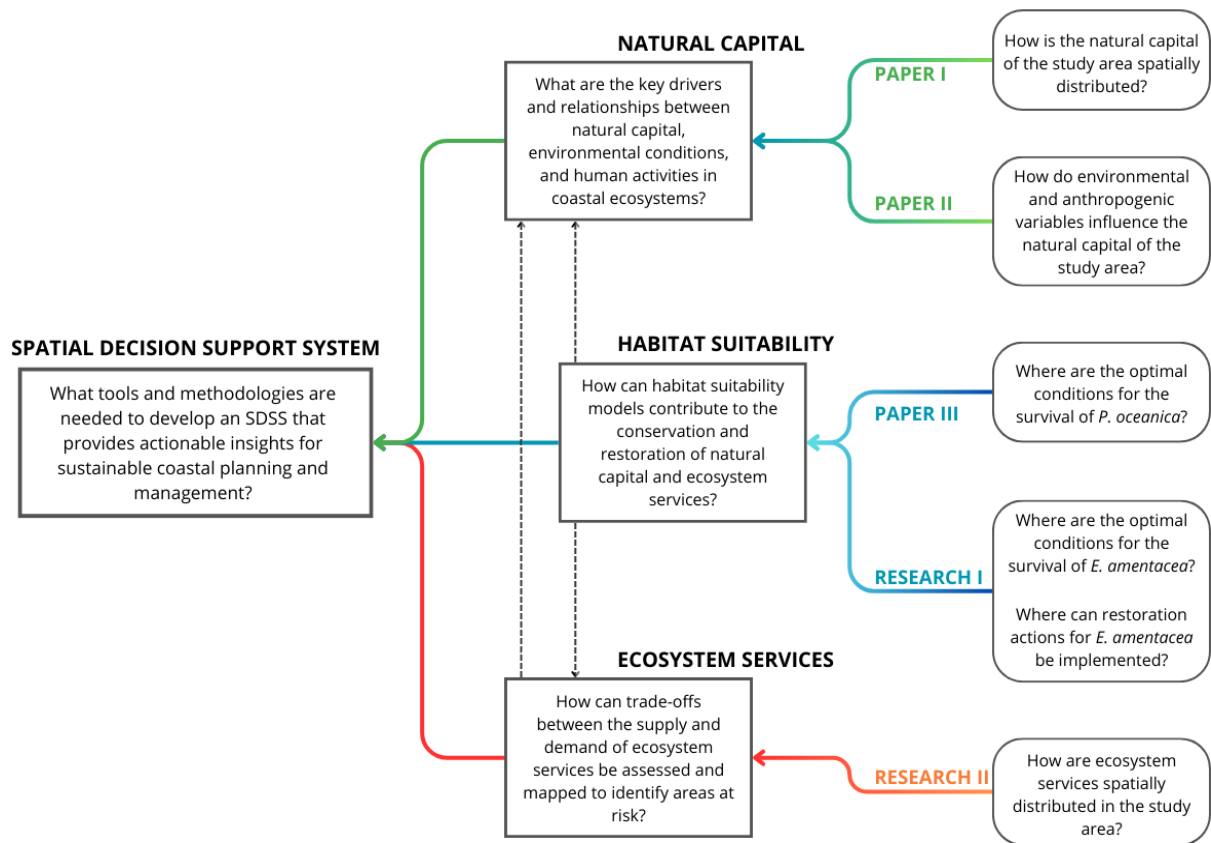


FIGURE 1. Research questions and connections.

2. THEORETICAL AND CONCEPTUAL FRAMEWORK

2.1 Natural capital and ecosystem services

Three main types of capital are commonly recognized: natural, human, and manufactured capital. National accounts primarily report on the marketable flows of value derived from these capital stocks, such as roads, buildings, machinery, knowledge, and skills, using measures such as gross domestic product (GDP). However, they do not account for the capital stocks themselves. In economic terms, natural capital can be seen as a source of productive inputs that, when combined with human and manufactured inputs, produce goods and services that benefit society (Edens & Hein, 2013).

Natural capital differs from other forms of capital because it is freely available and often self-regulating and self-renewing without human intervention (Mace et al., 2015).

The term natural capital is defined as “the elements of nature that directly and indirectly provide value or benefits to people, including ecosystems, species, freshwater, land, minerals, air, oceans, as well as natural processes and functions” (Natural Capital Committee, 2014).

Natural capital supports essential services such as food and water provision, storm protection, and climate regulation, that are essential to human health and well-being (Costanza et al., 2014; Duarte et al., 2013).

In simple terms, it is the set of biotic and abiotic resources within ecosystems that sustain natural processes. The biotic components of natural capital include all levels of biodiversity within terrestrial and marine ecosystems, particularly flora and fauna. The abiotic components consist of soil, subsoil resources (e.g., minerals, metals, fossil fuels), water, and the atmosphere. Abiotic components can be further categorized as either non-renewable resources (e.g., minerals, fossil fuels) or renewable resources (e.g., water, solar energy) (CCN, 2017).

Natural capital is often closely associated with ecosystem services (e.g., Kareiva., 2011), ecosystems (Dasgupta, 2010), and biodiversity (TEEB, 2010). At its core, natural capital consists of the essential environmental stock, including the structures and processes that underpin ecosystem functioning. Ecosystem processes are the dynamic physical, chemical, and biological activities within ecosystems, such as nutrient cycling, energy flow, and decomposition of organic matter. These processes control the ability of ecosystems to support life and provide services. Ecosystem structure refers to the physical and biological framework of ecosystems, including components such as soil composition, vegetation layers, and habitat configurations.

From this baseline, ecosystem functions emerge, which encompass the full range of flows produced by natural processes. These functions represent the capacity of ecosystems to provide goods and services that support human well-being and benefit other species (De Groot, 1992). Ecosystem goods (e.g., fish and seafood) and ecosystem services (e.g., fishing supported by marine ecosystems) are those aspects of natural capital that are directly used by humans. These benefits, accessed either directly or indirectly, are derived from ecosystem functions (Costanza et al., 1997; MA, 2005). The flows of ecosystem services provide essential benefits that sustain human life and enhance societal well-being, serving as the end products of ecosystem processes. In essence, the components of natural capital work together to provide ecosystem services that are important to human well-being. These services are often complemented by additional contributions from social, human, financial, or manufactured capital (Biggs et al., 2015; Palomo et al., 2016; Reyers et al., 2013).

Ecosystem functions operate independently of human use, whereas ecosystem services are defined by the benefits that humans derive from these functions. The relationship between ecosystem functions and services is not always straightforward: a single service may depend on multiple functions, while a single function may generate multiple services. Ecosystem services therefore represent those components of natural capital and ecosystem functions that humans perceive and use, either directly or indirectly. This perception is inherently instrumental, shaped by human use rather than the intrinsic value of the ecosystem itself. The importance attached to different ecosystem services varies across social and economic contexts, influenced by factors such as wealth distribution, technological progress, future expectations, aesthetic preferences, and education levels (Pascual et al., 2010).

Ecosystem services can be further analyzed in terms of supply and demand. Supply refers to the capacity of a particular area or habitat to produce goods and services over a given period of time, driven by its natural capital and ecological characteristics. In contrast, demand reflects the ecosystem services that humans recognize, use, or require within a given time frame, as well as the resources extracted from that area.

In human-dominated systems, value is often attributed primarily to the final benefits derived from ecosystem services, as these are the most tangible and directly experienced aspects. However, the sustainability of these benefits depends on maintaining the underlying stock of natural capital in both quality and quantity. Without this foundation, the continued flow of ecosystem services, and their associated economic and non-economic benefits, cannot be sustained at levels required for current and future generations (de Groot et al., 2012).

2.2.1. Ecosystem services classification

Ecosystem functions and services have been widely catalogued, and many classification systems have been developed, particularly for ecosystem services. A key step in understanding their relationships is to resolve the complexity of ecological structures and processes into a more concise framework of ecosystem functions. The classification of Costanza et al. (1997), later refined by De Groot et al. (2002), organizes ecosystem services into four primary categories:

1. Regulation functions: these include the capacity of natural or semi-natural systems to maintain essential ecological processes and life-support systems through biogeochemical cycles and other biospheric activities. Regulation functions maintain ecosystems and provide services such as air, water, and soil purification, as well as biological pest control.
2. Habitat functions: ecosystems provide suitable environments for plant and animal species by providing shelter and breeding sites. These habitats play a key role in maintaining genetic and biological diversity and supporting evolutionary processes.
3. Production functions: autotrophic organisms in ecosystems produce carbohydrate structures, that are used by secondary producers to create various forms of living biomass. This biomass provides humans with essential goods, including food, raw materials, fuels, and genetic resources.
4. Information functions: ecosystems contribute to human well-being by offering spaces for spiritual enrichment, cognitive development, recreation, and the aesthetic appreciation of landscapes.

In the early 2000s, ecosystem services came to public attention through the Millennium Ecosystem Assessment (MA) project, sponsored by the United Nations Environment Programme (UNEP). The goal of the MA was to provide a comprehensive overview of the state of the world's ecosystems, describing their services both quantitatively and qualitatively, in light of the global changes that threaten ecosystems and affect human health and well-being (MA, 2005). Additionally, the MA introduced one of the first classifications of ecosystem services, identifying four key categories:

- Provisioning services: goods, resources, and raw materials essential for human survival, such as food, water, timber, fuel, and genetic material.

- Cultural services: non-material psychological, aesthetic, and recreational benefits, contributing to human well-being through spiritual growth, cognitive development, and more.
- Regulating services: ecosystem processes and functions that regulate environmental components and maintain ecological conditions.
- Supporting services: ecological functions and processes that indirectly support and maintain the overall structure and functioning of ecosystems.

Subsequent research on ecosystem services (Boyd and Banzhaf, 2007; Fisher et al., 2009; Haines-Young and Potschin, 2012; Landers and Nahlik, 2013; Staub et al., 2011; Wallace, 2007) have contributed to the development of different frameworks for assessing changes in ecosystems, understanding their impacts on human well-being, and identifying actions for their sustainable management (Albert et al., 2016). However, the proliferation of different conceptualizations and classification systems for ecosystem services has led to differences in terminology and interpretation, especially in their practical application (Boerema et al., 2016). These differences often arise in the definitions of key concepts such as biophysical structure, ecological functions, intermediate services, and final services (e.g., Landers and Nahlik, 2013; Mononen et al., 2016; Spangenberg et al., 2014; TEEB, 2010). As a result, many ecosystem service classification systems struggle to clearly link services to their benefits and tend to blur the line between intermediate and final services. Among these, the Common International Classification for Ecosystem Services (CICES), developed by the European Environment Agency (EEA) and the United Nations Statistical Division (UNSD) working group, has become an important reference framework for ecosystem services research (Maes et al., 2013).

CICES and much of the ecosystem services literature is based on and informed by the cascade framework introduced by Haines-Young and Potschin in 2010 (Haines-Young and Potschin, 2010; Potschin and Haines-Young, 2016). The cascade framework illustrates the pathway of ecosystem services, from ecological structures and processes to human well-being. CICES aims to unify existing classification systems, facilitating comparisons between different approaches. It organizes ecosystem services into three main categories, each of which is further subdivided into types and subtypes, creating a hierarchical structure for identifying and categorizing ecosystem services (FIGURE 2Error! Reference source not found.). The three main groups are:

1. Provisioning services: the tangible, marketable goods and energy produced by ecosystems that are directly consumed by humans. This category includes three

subgroups: food, biotic and abiotic materials used in the production of goods, and renewable energy sources from both biological and non-biological origin.

2. Regulation and maintenance services: services that encompass the processes by which ecosystems regulate and modify the abiotic and biotic environments to maintain conditions that support human life. Although not directly consumed, these services affect individuals, communities, and populations. This category includes four subgroups: waste remediation, flow regulation, regulation of the physical environment, and regulation of the biotic environment.
3. Cultural and social services: non-material benefits that have symbolic, cultural, or intellectual value. This category is divided into two subgroups: symbolic services and intellectual or experiential benefits.

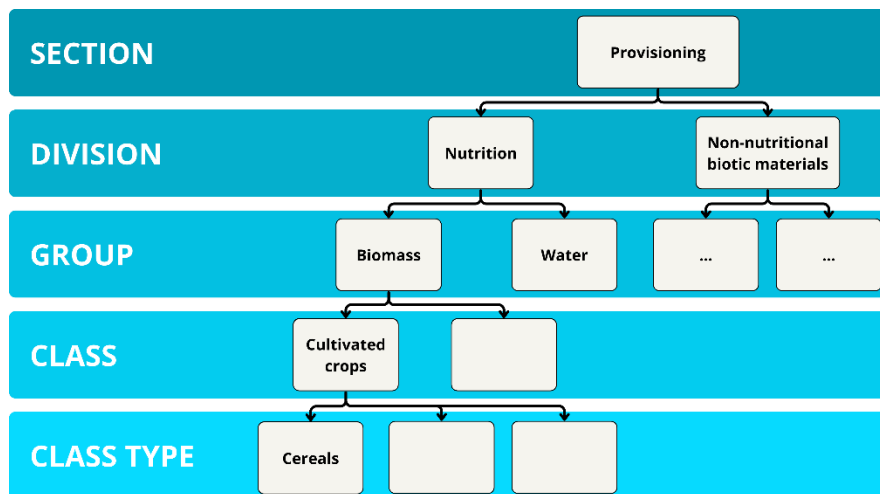


FIGURE 2. Diagram showing the hierarchical structure of the CICES classification (edit from CICES, 2018)

2.2.2. Ecosystem services cascade

Policy and business decision-makers are increasingly recognizing the importance of managing natural capital sustainably. However, they often lack appropriate tools and robust evidence to assess the impacts of different management decisions (Guerry et al., 2015; Maseyk et al., 2017). One gap is in understanding how the biotic and abiotic attributes of natural capital influence the capacity of ecosystems to provide different services (Maseyk et al., 2017).

The terms ecosystem services, ecosystem functions, and benefits are often used interchangeably, leading to confusion in conceptual definitions and challenges in quantification and evaluation efforts. To address this, the ecosystem service cascade framework proposed by Haines-Young and Potschin (2010) provides an approach to clarify these relationships. This

framework outlines a five-step sequence in the production of ecosystem services, as shown in FIGURE 3. It begins with an ecological entity or process that contributes to an ecosystem function with potential benefits to humans. This function then generates an ecosystem service, which provides benefits to humans. These benefits are often associated with an economic value, that can be identified through actual or hypothetical markets.

For example, seagrass beds (i.e., ecosystem component) stabilize sediment and improve water clarity (i.e., function), offering coastal protection and supporting fish populations (i.e., service). These contributions, in turn, increase biodiversity and fishery yields (i.e., benefits), leading to more sustainable fisheries for humans (i.e., non-market benefits). These benefits can be indirectly quantified in terms of increased income from fishing or improved food security.

Building on this framework, Braat & De Groot (2012) and Spangenberg et al. (2014) introduced the concept of potential ecosystem services, which are services that exist without active human involvement or use, such as sunlight as a public good. In contrast, functions that provide unrecognized benefits are not classified as ecosystem services.

The ecosystem service cascade is a valuable tool for identifying the key components involved in delivering a service and supporting its sustainable management. It also promote the development of hypotheses about the linkages between human well-being and ecosystems at each level of the cascade.

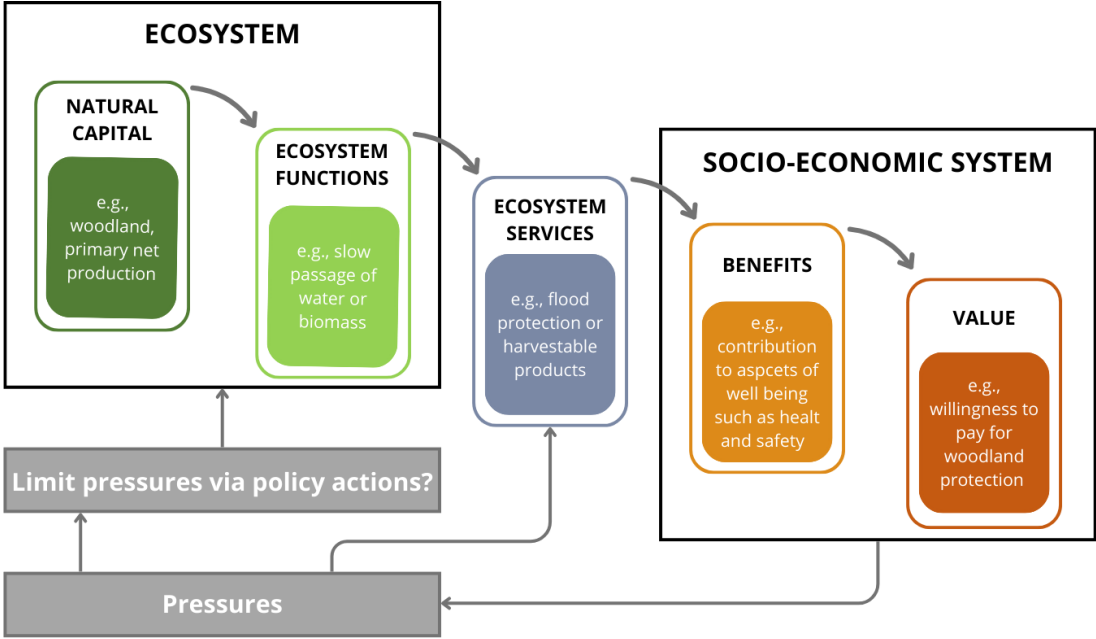


FIGURE 3. Example of ecosystem service cascade (edit from Spangenberg et al., 2014).

The ecosystem service cascade highlights the relationships and dependencies between human well-being and ecosystems at different levels. At each level, units may depend on multiple

components from the level below them, while at the same time influencing outcomes at higher levels. This connectivity can lead to conflicts or trade-offs, where the use of one ecosystem service reduces the availability or quality of others, thereby reducing their overall benefits.

Trade-offs have an important role in environmental decision-making and management. Rooted in economic theory, trade-offs recognize that limited resources require compromises. For example, prioritizing a forest for timber production may limit recreational opportunities and degrade water quality in nearby areas. Similarly, overfishing can deplete fish stocks and reduce future harvests. These trade-offs can occur within the same location or across different regions, driven by changes in the supply or demand for ecosystem services. Addressing these trade-offs will ensure the sustainable and equitable use of ecosystem services, balancing short-term needs with long-term ecological integrity.

The sustainability of ecosystem services relies on maintaining the capacity of ecosystems to provide these services at current levels over the long term, without exceeding ecological limits. For example, the sustainable provision of fish requires that only surplus stocks are harvested so that the resource base is not depleted. In a broader context, sustainability aligns with the principles of sustainable development outlined by Herman Daly (1990). These principles emphasize that renewable resources should be used at rates that do not exceed their natural regenerative capacity, that emissions should remain within the environment's capacity to absorb and regenerate, and that the consumption of non-renewable resources should be balanced by the production of renewable alternatives.

Exceeding these thresholds results in the depletion of natural capital. By applying these sustainability principles, human pressures and management actions can be integrated into the ecosystem service cascade, helping to ensure that ecosystems continue to provide essential services over time. This approach promotes the long-term sustainability of ecosystem services and achieves a balance between maintaining ecological integrity and promoting human well-being.

2.2 Habitat Suitability Models

2.2.1. Habitat and biodiversity conservation

Biodiversity conservation is a global priority as habitat loss and degradation continue to cause alarming declines in species populations. This ongoing crisis, often referred to as the "sixth mass extinction" (Barnosky et al., 2011), has led to urgent calls for effective conservation strategies. The UK Biodiversity Steering Group (1995) defines habitat as "an assemblage of plants and animals found together and the geographical area and features on which they exist," highlighting the intrinsic interdependence between species and their environments.

Efforts to conserve biodiversity are supported by a number of international and regional frameworks. The Convention on Biological Diversity (CBD, 2010) requires member countries to develop national strategies to conserve biodiversity and restore degraded ecosystems. In Europe, the EU Habitats Directive (92/43/EEC) calls for the protection of species and habitats through the Natura 2000 network of protected sites. These frameworks underscore the need to effectively identify and manage key habitats, ensuring that they continue to provide ecosystem services critical to human well-being.

In line with these challenges, the EU Biodiversity Strategy to 2020 (European Commission, 2011) reflects the EU's commitments under the CBD. The strategy aims to halt further biodiversity loss by promoting better implementation of the Habitats Directive. It also emphasizes the importance of assessing and mapping all ecosystems and their services across the EU (Maes et al., 2013).

Effective conservation and habitat management depend on robust data on species distributions and ecological dynamics (Loiselle et al., 2003). Despite significant advances, global biodiversity knowledge remains incomplete (Wilson, 2001; Balmford et al., 2005). Habitat Suitability Models (HSMs) have emerged as useful tools to fill these gaps. The HSM offers important insights for environmental policy, spatial planning, and conservation action through the integration of patchy and unbalanced occurrence data with landscape-level projections of habitat suitability and associated environmental variables (Guisan et al., 2014). These models allow researchers to make informed decisions about species management and habitat restoration (Franklin, 1995; Guisan and Zimmermann, 2000).

2.2.2. Applications and methodologies of HSMs

HSMs are particularly valuable when data on the presence and absence of species are available. These models use statistical correlations between occurrence data and environmental variables to generate spatial predictions of species distributions. This approach allows the estimation of potential species distributions over a geographic area (Guisan and Zimmermann, 2000; Elith and Leathwick, 2009b; Franklin, 2009). HSMs can help identify new potential habitats and assess changes in habitat suitability over time (Franklin, 1995; Guisan and Zimmermann, 2000; Hirzel and Le Lay, 2008).

By combining information on species locations with associated environmental conditions, HSMs generate statistical functions that can be applied to areas with known environmental data but unsampled species presence. This provides predictions of where suitable habitat is likely to exist (Brotons et al., 2004).

HSM methods can be broadly divided into two categories: those that rely solely on presence data and those that use both presence and absence data.

Presence-only methods include conceptual models based on expert judgment, such as habitat suitability indices (e.g., Yamada et al., 2003; Uhmann et al., 2001) and Bayesian network models (e.g., Marcot, 2006; Smith et al., 2007; Newton, 2009a). These approaches also include environmental or climatic envelope models, such as ecological niche factor analysis (e.g., Hirzel et al., 2002; Pearson and Dawson, 2003; Huntley et al., 2004). Additionally, machine learning techniques capable of using presence-only data or interpreting background data as non-presence include artificial neural networks (Lek et al., 1996), genetic algorithms for rule-set prediction (Stockwell and Peters, 1999), and maximum entropy models (Phillips et al., 2006). Presence-absence methods primarily include regression-based approaches, such as logistic regression, generalized linear models, and generalized additive models (e.g., Pearce and Ferrier, 2000b). Tree-based methods, including classification and regression trees (e.g., Moisen and Frescino, 2002), are also widely used in this category.

The success of HSMs depends on the selection of appropriate environmental predictors. Species distributions are shaped by their needs for essential resources, which may vary over their life cycle. This variability complicates habitat modeling efforts (Mackey and Lindenmayer, 2001). Environmental predictors influence species in two main ways: directly, by affecting growth and survival, or indirectly, without physiological effects. These influences can be categorized into three groups: limiting factors (e.g., temperature, soil composition, water) that regulate eco-

physiological processes; disturbances, which include natural or human-induced disturbances; and resources, such as water and energy, that are essential for survival (Austin and Meyers, 1996; Guisan and Zimmermann, 2000; Huston, 2002; Guisan and Thuiller, 2005).

Incorporating all relevant variables into habitat models is challenging, particularly due to the lack of spatial data for certain factors, such as intraspecific interactions (Wilson, 2003). In addition, distinguishing causal predictors from correlated variables is difficult because environmental factors are often interdependent (Huston, 2002). While correlation does not imply causation, especially given the complexity of ecological systems, careful interpretation can provide valuable insights (Johnson and Gillingham, 2005).

Overfitting, resulting from too many variables, and underfitting, caused by too few variables, can both compromise model reliability. While model performance typically improves with the inclusion of more data, it may eventually plateau, where additional information contributes little to the accuracy (Stockwell, 1997; Peterson and Cohoon, 1999; Stockwell and Peterson, 2002b). In some cases, including too many variables can actually reduce model accuracy, as overly specific models may have difficulty generalizing to new data, a phenomenon known as overfitting or prediction bias (Stockwell & Peterson, 2002b). Conversely, using too few variables can exclude key factors that limit species distributions, leading to overly broad predictions of geographic ranges (Peterson et al., 2002).

Marine ecosystems have historically been underrepresented in HSM studies. However, their critical role in biodiversity conservation is increasingly recognized. This shift is largely driven by the growing availability of datasets and international commitments, such as the UN Sustainable Development Goal 14 (Life Below Water), which aim to map and sustainably manage marine resources. These efforts have led to an increased interest in applying HSMs to marine environments, with the aim of protecting, restoring, and reversing habitat degradation and biodiversity loss.

In the Mediterranean marine environment, HSMs have proven to be valuable in a number of applications. For example, these models have been used to assess the distribution and conservation status of various marine species and habitats (e.g., Falace et al., 2015; Carlucci et al., 2016; Vassallo et al., 2018; Fabbri et al., 2020; Holon et al., 2018; Bakirman et al., 2020). These studies have used HSMs to better understand habitat distribution and predict how environmental changes may affect marine biodiversity and ecosystem services.

2.3 Spatial Decision Support System

The increasing pressure on natural resources and environmental systems, such as water, land, and air, is considered as unsustainable, especially in light of the ongoing global population growth. The fundamental goal of sustainable development is to enable people around the world to meet their basic needs and improve their quality of life without compromising the ability of future generations to do the same.

As global awareness of environmental challenges increases, policymakers, practitioners, and businesses are becoming more aware of the need to manage natural capital sustainably. However, they often face challenges in accessing appropriate tools and evidence to assess the impacts of management decisions (Guerry et al., 2015; Maseyk et al., 2017). Moreover, there is an ongoing debate about the compatibility of the ecosystem services framework with biodiversity conservation goals. While the ecosystem services approach presents opportunities to build broader support for conservation efforts, influence decision-making, and add value to protected areas (Haslett et al., 2010; Ingram et al., 2012; Reyers et al., 2012), it also offers a way to promote sustainable management of ecosystems beyond protected areas (García-Llorente et al., 2016).

As resource and environmental issues are central to the challenges of sustainable development, efforts must focus on the rational use of natural resources, effective ecosystem management, and environmental protection. Access to reliable and up-to-date data on resources, ecosystems, and the environment is essential for informed decision-making in sustainable development.

To ensure the effectiveness of land and ecosystem management, policies must be based on well-informed decision-making processes. This requires ready access to data and information that are accurate, relevant, and regularly updated (Pérez et al., 2005). In addition, due to the biophysical and socio-economic differences between regions, much of this data has a spatial dimension that needs to be carefully considered in the decision-making process.

Building on the previous discussion, the development and implementation of innovative systems to facilitate decision-making is becoming more important, particularly in coastal and marine environments. This is crucial for integrated and sustainable coastal zone management, such as outlined in the ICZM Protocol and the Maritime Spatial Planning Directive 2014/89/EU.

Decision-making is a cognitive process that leads to the selection of a course of action among various alternatives. Any decision-making process results in a final choice, which may be an action or an opinion. It begins when individuals or groups recognize a need but are uncertain

about the best way to address it. Consequently, decision-making is both a rational and sometimes irrational reasoning process, often based on explicit or implicit assumptions. As such, decision-making is integral to each stage of the planning process.

Decision Support Systems (DSS) are specifically designed to assist and improve the decision-making process for complex problems. These systems are information tools that assist decision-makers in selecting among alternative actions by applying domain knowledge to generate recommendations for different options. DSS incorporate explicit decision-making procedures based on a set of theoretical principles to ensure the "rationality" of the decision. This requires an awareness of the problem that must be informed by data, experiences and an understanding of the process at hand (Poch et al., 2003).

In the context of urban and regional planning, where the complexity of decision problems is evident (Witlox et al., 2009), DSS are used to support governments and communities by assisting urban planners in organizing, analyzing, modifying, and re-evaluating spatial information for land-use planning activities (Tsamboulas et al., 2006).

DSS are constructed by integrating various artificial intelligence methods, GIS components, mathematical-statistical techniques, and environmental ontologies (Poch et al., 2003). The relevance and use of these components vary depending on the specific case study and its unique requirements.

Building on the previous discussion, planning is inherently a multi-stage process involving multiple actors, whose decisions are shaped by the specific conditions of the areas and their economic development. These decisions are influenced by the information available at each stage (Hall, 1996). In its broadest sense, planning is an activity that heavily relies on spatial information to support many core activities, including land use planning (Boddy, 1995).

When the problem is spatially distributed, Geographic Information Systems (GIS) must be integrated, leading to the creation of SDSS. GIS allows planners to quickly and efficiently generate and evaluate alternative development scenarios and assess their likely environmental impacts, such as land use patterns, population trends, and employment projections. This enables public officials to make informed decisions about land use planning and development.

SDSS links policy (which is non-spatial) to spatial plans by using various techniques to formulate and evaluate spatial planning models. Furthermore, GIS supports a wide range of spatial analysis functions, that use planning data stored in the GIS database to generate new information layers. These layers can be visualized through maps, reports, or charts, offering valuable insights to decision-makers.

As highlighted by Maniezzo et al. (1998), the integration of spatially referenced information into DSS is crucial for improving the performance of decision-makers. Spatially integrated DSS play a key role in bridging the gap between policy makers and complex computational models, ensuring that the spatial dimension of planning is effectively addressed.

2.3.1. Software for SDSS

Geographic Information System (GIS)

The Geographic Information System (GIS), including hardware and software components, allows the acquisition, storage, manipulation, analysis, management, and presentation of spatial or geographic data. In other words, GIS allows you to create interactive queries, modify data within maps, analyze spatial information (Clarke, 1986).

The system uses spatial location to integrate different types of data layers in raster and vector formats, including images, features, and base maps (Arifa and Suker, 2018).

At the heart of GIS data management is digital cartography, where spatial data is represented not only visually, but also in a way that allows for detailed and accurate spatial analysis. Unlike traditional cartography, where the map itself contains implicit coordinate data, digital cartography stores geographic information directly through coordinates. These coordinates can be expressed in two or three dimensions and serve as the basis for further spatial analysis and decision making.

GIS data can be divided into two main types: geographic data and descriptive data. Geospatial data represents the spatial configuration of physical features on the Earth's surface, while descriptive data provides additional context, such as measurements, characteristics, or other non-spatial attributes.

Geographic data can be represented in two formats: raster and vector. The choice of format depends on the type of analysis being performed.

- Raster format: geographic features are represented by a grid of cells (pixels), each containing a value that corresponds to a particular attribute or measurement. Raster data is effective for continuous spatial phenomena, such as climate patterns or satellite imagery, where the data is inherently continuous across space.
- Vector format: geometric primitives such as points, lines, and polygons are used to represent geographic features. Points can represent locations, lines can represent linear features, and polygons can represent areas. Vector data is typically used for discrete features where

precise boundaries and relationships between entities are important. Each geometric feature is defined by coordinates and can be associated with attribute data that provides additional information about that feature.

These two formats are complementary and are often used together in GIS applications. For example, a GIS might combine vector data for administrative boundaries with raster data for satellite imagery to provide a more comprehensive analysis of an area (FIGURE 4).

Metadata plays a critical role in ensuring the accuracy, usability, and interpretation of GIS data. Metadata provides essential information about the data, including how it was collected, the date and method of collection, the accuracy of the data, and its intended use. This information is essential for assessing the quality and limitations of the data and ensuring that it is used correctly in analyses. Metadata also includes descriptions of the data's attributes and explains the meaning behind them, ensuring that the data is understandable and actionable for decision makers.

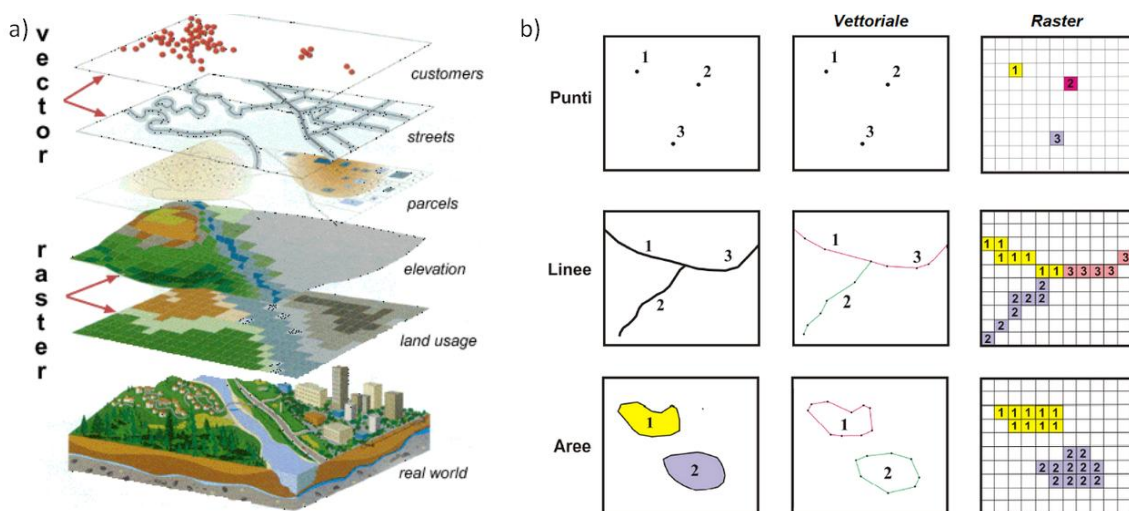


FIGURE 4. a) Informative GIS layers; b) Vector and raster representation of points, lines and polygons (Clerici, 2012).

GISs can be divided into two categories: static and mobile. The first category includes the so-called "desktop GIS", i.e. traditional GIS where a user sits at a workstation to perform spatial analysis (Egenhofer and Kuhn, 1998). This group includes the GIS archives (geodatabases), which represent a collection of information on the territorial distribution of one or more features. The geospatial data can be distributed on internet and intranet networks, using the analysis derived from GIS software and publishing geographic information on the World Wide Web through the classic web-based application features, in which case they are referred to as WebGIS (Agrawal and Gupta, 2017). The development of web applications has led to the

development of mobile GISs, that can be used on phones or tablets enabling navigation applications such as Google Maps (Fu and Sun, 2011).

Today, GIS plays a critical role as a DSS in a variety of fields, including environmental science, urban planning, agriculture, disaster management, and more. It helps decision makers assess complex spatial phenomena, visualize the impact of different scenarios, and develop strategies for managing natural resources and ecosystems. The integration of GIS into SDSS is particularly important in contexts such as coastal ecosystem management, where human pressures and environmental changes overlap spatially.

Understanding the relationships between human activities and ecosystem health is essential for effective spatial planning. GIS provides the tools to visualize these relationships through detailed cartographic outputs that help identify management alternatives and communicate the results of different strategies. For example, coastal ecosystems are subject to various pressures such as urbanization, pollution, and climate change, and understanding how these factors spatially interact with the ecosystem is essential for developing sustainable management plans (Parravicini et al., 2012).

In particular, in recent years there has been a notable increase in the use of tools provided by GIS to analyze, understand and manage coastal and marine environments. Therefore, the term Coastal and Marine Geographic Information System has been introduced, precisely to indicate the purpose of using GIS to integrate heterogeneous data belonging to coastal, marine and oceanic environments (Alcaras et al., 2019). The applications cover several aspects, such as analysis and management of the coastal environment (Kitsiou et al., 2002), coastal monitoring (Alcaras et al., 2022), bathymetric modelling (Figliomeni and Parente, 2023).

Quantum GIS

Quantum GIS (QGIS) is a free and open source GIS software released under the GNU General Public License. Available on multiple platforms, including Linux, Unix, Windows, and MacOS, QGIS provides a highly accessible solution for users of all levels, thanks to an intuitive graphical user interface (GUI) that makes it both appealing and easy to use. Its versatility is enhanced by support for a wide range of data formats and databases, as well as the ability to connect to various geodatabases, making it an excellent choice for both novice and advanced GIS users.

QGIS offers many core GIS features, such as data visualization, geodata creation, editing, management, export, spatial analysis, data exploration, and map assembly. It also makes it easy

to publish maps on the web and to extend the capabilities of the software through a wide range of plug-ins.

By default, QGIS uses ESRI Shapefile for vector data, which is widely supported through the OGR library. For raster data, it relies on formats supported by the GDAL library, ensuring compatibility with a wide range of raster file types.

One of the key features of QGIS is its project-based structure: data layers in QGIS are not stored within the software itself. Instead, the software keeps a reference to their location on the computer or other platforms. This means that QGIS works directly with the original data files, dynamically retrieving them from their specified paths whenever the project is opened.

Once a QGIS project is set up, it's important to make the data accessible to non-GIS professionals. To this end, QGIS includes a printing tool that allows users to create maps and layouts that can be easily shared. These printed maps can include essential map elements such as gridlines, legends, scale bars, and images, and can explicitly show the relationships between different elements on the map. QGIS provides options to export these printed maps in a variety of formats, including PDF, SVG, PNG, JPEG, TIFF, and others, at custom resolutions. This makes it an ideal tool not only for GIS specialists, but also for a broader audience that needs to interpret spatial data.

PostgreSQL/PostGIS and DBEaver

PostgreSQL is an open-source, object-relational database management system (DBMS) known for its advanced features, scalability, and reliability. It conforms to the ANSI-SQL: 2008 standard, which ensures compatibility with other systems that follow the same specifications. PostgreSQL offers comprehensive support for a variety of data types and can efficiently handle large datasets while maintaining high performance, even in complex use cases.

In computer science, a database is an organized collection of data that facilitates efficient data management and supports complex queries. Databases are designed to eliminate data redundancy, maintain consistency, ensure platform independence, and secure transactions. Additionally, they allow for effective management of multimedia data and can be easily integrated with various applications, making them central to modern computing environments. PostgreSQL uses SQL (Structured Query Language), the standard language for managing relational databases. However, it goes beyond basic relational database management by supporting both structured and unstructured data. PostgreSQL's extensibility allows users to

add custom functions, data types, and other features, making it a powerful solution for a range of applications, from Web development to geospatial data management.

A relational database organizes data into tables, each containing records and fields (attributes) that represent specific pieces of information. These tables can be cross-referenced and queried in many ways, enabling complex data analysis and updates. Data in the table is structured into rows (records), which identify specific pieces of information, and columns (fields), which define the attributes of each record. Tables are grouped into schemas, and each schema can contain one or more related tables.

A relational database structure is typically represented in a diagram that shows how tables are related to one another and how data is organized (FIGURE 5).

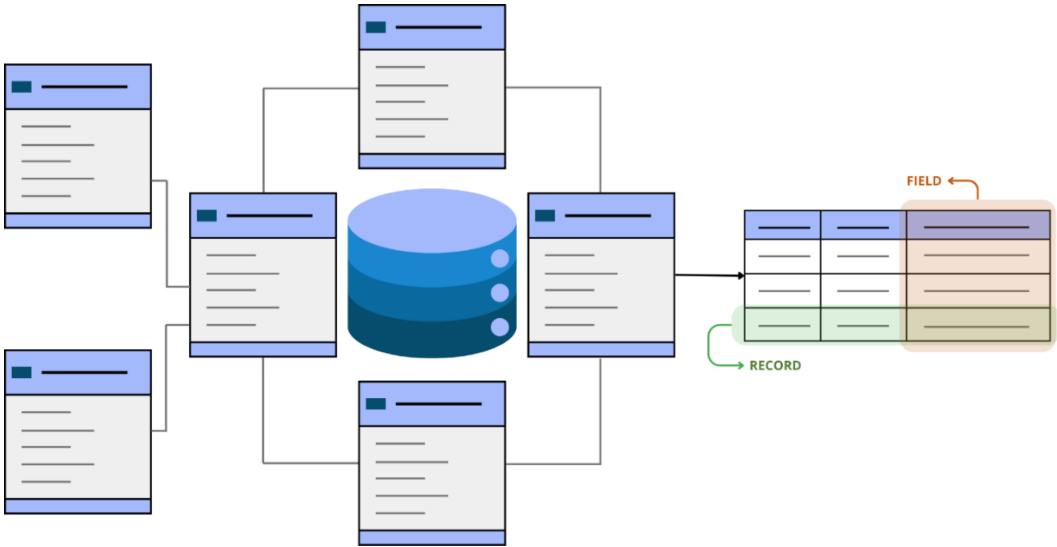


FIGURE 5. Example of a relational database structure.

Users can perform various queries using SQL or through a GUI to extract, reorganize, and reclassify data. Views can be created to store query results, becoming part of the database. However, views are always linked to their source tables, meaning that any changes made to the underlying table are reflected in the view. While views cannot be directly modified, they remain updated with the source table. Both tables and views are organized separately in the database. It is also possible to create new tables that are derived from existing tables or views. These tables are "autonomous" and are not linked to the original data sources. The definition of a primary key is critical to ensure the distinct nature of records within a table and to minimize redundancy. The primary key can be a single field or a combination of fields, and it is essential for creating relationships between multiple tables.

A foreign key relationship is used to link tables. This involves using a code or identifier from one table that also appears in another, allowing data to be referenced between the tables without redundancy.

A geodatabase is a specialized type of database designed to manage spatial information. It extends the relational database model to include geometric data (such as points, lines, and polygons) and topological relationships (such as adjacency or containment). A geodatabase also stores descriptive data about these geographic elements.

PostGIS is a spatial extension for PostgreSQL that adds support for geographic objects, enabling PostgreSQL to function as a powerful backend database for GIS applications. With PostGIS, users can manage spatial data types, perform spatial analysis (such as distance measurements, area calculations, and intersections), and use spatial indexing for better performance with large datasets. PostGIS adheres to the Simple Features Specification for SQL by the Open Geospatial Consortium (OGC) and supports standard data types and operations used in the geospatial community.

A DBMS is used to manage a database. A DBMS controls the organization, storage, retrieval, and security of data within the database. It also ensures data integrity and allows for the creation and management of databases, including data loading, backup, and transaction control.

DBeaver is a graphical user interface for managing PostgreSQL databases. It allows users to interact with PostgreSQL through an intuitive interface rather than relying solely on command-line tools. DBeaver provides features such as schema management, query execution, and data visualization, making it a tool for both database administrators and developers.

Both PostgreSQL and PostGIS are open source and free to use. These systems are continually improved and updated by a global community of developers, ensuring that they meet the needs of modern applications.

G3W-Suite

G3W-Suite is an open source, modular client-server application designed to manage and publish QGIS-based web mapping projects. It provides an intuitive, fast, and flexible way to handle complex GIS projects, making it suitable for various use cases. The suite consists of two main components: G3W-Admin and G3W-Client.

G3W-Admin is the web administration interface, built on Django and Python, which allows users to manage spatial data and configure QGIS projects. It allows efficient administration of

user profiles, access permissions, and system settings. Through G3W-Admin, users can configure and manage map projects, connect to spatial databases, and define access policies.

G3W-Client is the front-end map viewer, based on OpenLayers and Vue.js, providing a web interface for interacting with cartographic data. It supports interactive map visualization, layer management, and querying of spatial data. The G3W-Client allows users to view and analyze geospatial information using tools for navigation, zooming, measuring distances and areas, and performing advanced spatial queries. The results of these queries can be displayed in a table or list format, with options for exporting data in multiple formats.

G3W-Suite is fully compatible with QGIS and its tools, allowing seamless spatial data integration and advanced GIS processing capabilities. The system supports data from various sources, including local databases, external DBs, and web services compliant with OGC standards (such as WMS and WFS). Its flexible architecture makes it easy to create of web-based GIS solutions that include dynamic data visualization, editing tools, and spatial analysis features.

One of the key advantages of G3W-Suite is its integration with QGIS, making it a powerful tool for managing and publishing GIS data through a web interface. It offers features such as time series management, layer symbology control, and the ability to manage multiple data sources across different servers. Furthermore, the suite supports extensive user profiling and role-based access, making it suitable for multi-user environments.

G3W-Suite is ideal for projects requiring a customizable and scalable WebGIS solution, offering the flexibility to manage spatial data efficiently and provide a user-friendly interface for data interaction.

3. PAPERS AND RESEARCHES

The dissertation is composed of three papers and two research studies that collectively showcase features to be integrated into the final SDSS. Paper I provides a comprehensive biological and monetary assessment of the natural capital in the Ligurian marine and coastal area, utilizing emergy analysis to quantify its value. Building on these findings, Paper II investigates the relationship between the natural capital of the study area and various environmental and anthropogenic variables, which act as forcing factors influencing its current state. This analysis employs the random forest algorithm to model and evaluate these complex interactions.

Paper III and Research I study shift focus toward the development of habitat suitability models. The third paper presents a detailed habitat suitability model for *P. oceanica* habitats on both soft and rocky bottoms within the Ligurian study area, analyzing their distribution in relation to environmental and anthropogenic variables. The random forest method is applied here as well, classifying the presence or absence of these habitats based on the spatial distribution of influencing factors. Similarly, the first research study uses a comparable modeling approach to determine habitat suitability for *E. amentacea*. Beyond habitat prediction, this study incorporates criteria such as habitat quality and logistical considerations to identify priority areas for restoration, focusing on sectors that are not only predicted to be suitable but are also strategically favorable for restoration initiatives.

Research II study delves into the assessment of ecosystem services within the Ligurian study area, emphasizing the trade-offs between the supply of these services and the pressures exerted on them by human activities. By mapping the spatial distribution of ecosystem service supply, associated pressures, and resulting risks, the study provides a detailed picture of the current state of the ecosystem. It also explores how altering specific factors in the analysis can lead to different risk scenarios, offering valuable insights for sustainable management.

All the models and analyses developed throughout the research are ultimately integrated into a Web-GIS platform. This platform serves as a user-friendly tool designed to support decision-making processes, which is discussed in detail in the final chapter titled *SDSS*.

3.1 PAPER I

Paper I assessed the distribution and current state of natural capital and environmental flows in the Ligurian Sea, a Mediterranean biodiversity hotspot, by dividing the area into 43 functional spatial sections, or "biomarine units". Using data on benthic and fish biomass, emergy

analysis—a thermodynamics-based method—was employed to quantify natural capital and ecosystem services in both biophysical terms (solar energy joules, sej) and monetary terms (energy euro, em€), facilitating their integration into socioeconomic and policy discussions. The total natural capital of the Ligurian coastal and marine area was valued at 2.11 billion em€, with environmental flows valued at 1.43 billion em€ annually. Protected areas exhibited higher values, underscoring the effectiveness of conservation measures. These findings provide a baseline for maintaining natural capital and ensuring the continued provision of ecosystem services. The methodology developed offers a practical tool for stakeholders and policymakers to monitor and manage the region's natural resources effectively.

3.2 PAPER II

Paper II examines how natural and anthropogenic variables along the Ligurian coast influence the distribution of natural capital (NC) and environmental flows (ENFL) in marine coastal habitats. Using the Random Forest technique, combined with expert interviews, the analysis revealed that anthropogenic variables have a stronger impact on NC and ENFL values than natural factors. Protective measures, such as anchoring bans and Special Zones of Conservation, were shown to have a positive effect, increasing these values and highlighting their importance for conservation and management efforts.

By identifying the key variables affecting NC and ENFL, this study provides actionable insights for better monitoring, sustainable development, and management of the coastal marine area.

3.3 PAPER III

Paper III develops HSMs to predict the distribution of *Posidonia oceanica* (L.) Delile in the Ligurian Sea (NW Italy), addressing the urgent need for effective management and conservation of this seagrass species. By incorporating both natural and anthropogenic factors, the study aims to provide an understanding of the environmental conditions that support *P. oceanica* habitats.

The models, created using the Random Forest algorithm, assess potential seabed areas for *P. oceanica* on soft and rocky bottoms up to 50 meters deep. Explanatory variables include seawater salinity, temperature, and human activities along the coastal strip. The results showed high accuracy, with prediction rates of 82% for soft-bottom habitats and 99% for rocky-bottom habitats. The models predict a potential increase in *P. oceanica* meadows on soft bottoms (from

2448 ha to 11623 ha) and a smaller increase on rocky bottoms (from 159 ha to 200 ha), with the western Ligurian coast hosting more extensive meadows than the eastern coast.

The results provide valuable tools for sustainable management and conservation of *P. oceanica* meadows, a keystone habitat of Mediterranean coastal ecosystems, against increasing environmental pressures..

3.4 RESEARCH I

Research I develops a HSM for *Ericaria amentacea* along the Ligurian coast (NW Mediterranean) to support ecological restoration efforts and address global environmental challenges such as biodiversity loss and ecosystem degradation. As an "ecosystem engineer", *E. amentacea* forms vital coastal forests, but its populations have declined significantly due to human pressures. Restoration of these habitats is critical, particularly in the context of initiatives like the EU Nature Restoration Law and the European Biodiversity Strategy.

Using presence data from the CARLIT index, along with environmental and anthropogenic variables, the study employed the Random Forest algorithm to predict 920 new sectors suitable for *E. amentacea* beyond the 313 locations where it has already been observed. To prioritize these sectors for restoration, the Habitat Quality model (INVEST Workbench) and an assessment of proximity to harbors and marinas were applied, identifying areas with the highest potential for successful restoration based on accessibility and habitat quality.

The results provide a practical framework for enhancing biodiversity conservation and restoration efforts in Mediterranean coastal ecosystems. This study offers insights and tools for stakeholders, researchers, and policymakers aiming to restore degraded habitats and promote ecosystem resilience.

3.5 RESEARCH II

Research II presents a spatial risk assessment framework to evaluate the balance between ecosystem service supply and human-induced pressures in coastal and marine ecosystems, which are increasingly threatened by unsustainable activities. By calculating relative risk based on the relationship between ecosystem service capacity (supply) and theoretical human demand (pressure), the model identifies areas where demand may exceed supply, highlighting potential risks to ecosystem health.

The framework was applied to the Ligurian coastal and marine area as a case study, demonstrating its flexibility through scenarios that adjusted the number of berths in ports. The impacts on three key ecosystem services—recreational fishing, professional fishing, and boating—were analyzed. Results showed that increasing berths shifted more areas into high-risk zones, while decreasing berths expanded low-risk zones. Spatial analysis revealed higher risk levels in the western region, whereas unexplored risk zones in the eastern region highlighted data gaps or less-defined dynamics.

This framework serves as a practical tool for ecosystem management, providing insights into how local changes can affect risk distribution. By incorporating additional ecosystem variables, the approach could be further refined to support adaptive management strategies in the face of evolving environmental pressures.

3.6 SDSS

A dedicated website for the SDSS has been developed as part of a WebGIS project, providing a user-friendly platform for visualizing, exploring, and downloading geographic and alphanumeric data. The platform offers multiple data layers, including base maps and thematic maps related to Papers and Research finding.

4. RESULTS AND DISCUSSION

4.1 PAPER I

I

ASSESSMENT OF NATURAL CAPITAL AND ENVIRONMENTAL FLOWS DISTRIBUTION: A MEDITERRANEAN CASE STUDY

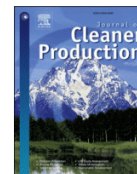
by

Bordoni R., Rigo I., Dapuzeto G., Povero P., Vassallo P., Paoli



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Assessment of natural capital and environmental flows distribution: A Mediterranean case study

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ABSTRACT

The coastal marine area hosts among the most productive ecosystems in the world, in terms of biomass and species richness. These ecosystems' natural capital stocks provide essential flows of resources for the environment and human life. The distribution of natural capital (NC) and environmental flows (ENFL) characterizing the coastal marine habitats of Ligurian Sea, a biodiversity hotspot in the Mediterranean region, were assessed to define their current state. The study area was divided into 43 functional spatial sections, defined as "biomarine units". In each biomarine unit natural capital and environmental flows were estimated using data on benthic and fish biomass. Emergy analysis, a thermodynamics-based methodology that expresses the costs in terms of resources incurred by nature to maintain the ecological processes of the marine coastal habitats, was then applied to assess the natural capital and the environmental flows in biophysical terms (solar emergy joules, sej), and using appropriate conversion factors, in monetary terms (emergy euro, em€). The monetary equivalents facilitate understanding for stakeholders and pave the way for the inclusion of marine resources value in socioeconomic and political contexts. The total value of natural capital for the Ligurian coastal and marine area is 2.11 billion em€, while for environmental flows, it is 1.43 billion em€ a⁻¹. Greater values belong to units included within the boundaries of protected areas, proving the efficiency of the protection measures taken. These values represent a reference point and shall be kept constant to preserve natural capital and to ensure services provisioning at least at the current level. This work identifies a method useful to monitor the status of natural capital value and environmental flows along Ligurian coast, which can be helpful to stakeholders and policymakers for better monitoring and management of the area.

1. Introduction

The marine coastal ecosystems can maintain a continuous exchange of materials and energy, providing high environmental diversity, both physical-morphological and biological, and also representing complex and sensitive systems (Reiners and Driese, 2001). These ecosystems generate a wide range of ecosystem services (MEA, 2005), fundamental to human health and well-being. However, to provide human benefits from ecosystems, natural capital stocks must be protected through effective conservation actions (Guidetti et al., 2008; Hoffmann et al., 2018). In recent decades, the need to preserve biodiversity as an

essential component of natural capital has become increasingly interesting for European Union environmental policies and biodiversity conservation strategies, which explicitly refer to natural capital (Comitato per il Capitale Naturale, 2021). In 2007, an international initiative called TEEB (The Economics of Ecosystem and Biodiversity) was launched by the Ministers for Environment joining the G8+5 meeting in Potsdam, with the support of the European Commission, to investigate, on global scale, the economic benefits and costs derived from biodiversity loss and environmental heritage management and protection. To achieve the objectives proposed by TEEB, a biophysical and monetary assessment of natural capital and environmental flows characterizing

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the system is needed. Natural capital (NC) can be defined as the stock of natural resources able to provide fluxes, goods, and ecological services to sustain life and generate wealth (Comitato per il Capitale Naturale, 2017). Environmental flows (ENFL) are instead those fluxes essential to the annual maintenance of natural capital itself (Paoli et al., 2018).

Given the complexity of marine ecosystems it is harder to model them compared to terrestrial ones (Carr et al., 2003); nonetheless, in Italy, two research projects were developed in 2014 and 2020 to perform a biophysical and monetary assessment for NC stocks and ENFL (Franzese et al., 2015; Vassallo et al., 2017; Paoli et al., 2018, 2022) to build an environmental accounting system for Italian marine protected areas (MPAs): the national project Environmental accounting in Italian Marine Protected Areas (EAMPA) and the European INTERREG MARITIME project Integrated management of ecological networks through parks and marine areas (GIREPAM). However, the literature published after these projects only concerns the natural capital and ecosystem services assessment of habitats (e.g., De La Fuente et al., 2019; Rigo et al., 2021) or MPAs (e.g., Buonocore et al., 2021; Franzese et al., 2008; Paoli et al., 2018; Picone et al., 2017).

This study, based on the premises laid out by those projects, proposes an implementation of the biophysical and trophodynamic environmental accounting model, expanding the field of application out of the MPAs boundaries and covering a region-wide area applied to the entire Ligurian Sea coastal zone. Specifically, the quantification and assessment of the spatial distribution of NC and ENFL values characterizing the marine coastal habitats were carried out through the application of energy analysis, which allowed the identification of resources along coastal area and a view of the system functioning. This work outlines the current state of the Ligurian coast in terms of NC and ENFL and offers a point of reflection for the development of environmental management tools and practices, considering compromises between the environmental, social and economic spheres. Quantifying NC can potentially increase social efficiency in decision-making processes in coastal areas, supporting policymakers in evaluating the trade-offs and synergies of ecosystem-based management (Torres and Hanley, 2017). According to Hecht (2000), there are three ways in which NC accounting can help decision-making processes: 1) providing tools to link economic and environmental aspects so that they can be jointly analyzed; 2) due to its wide coverage, it can be used for macroeconomic policy-making and sectoral analysis; 3) the availability of time series data enables analysis of trends over time.

2. Materials and methods

2.1. Study area

The study area encompasses the marine coastal zone of Liguria (Fig. 1), a region in northwestern Italy that borders France to the west and faces south on the Ligurian Sea (Western Mediterranean). Regions are the first level in which the Italian territory is divided, they are public institutions with administrative and political autonomy granted by the

Constitution of the Italian Republic. Liguria is one of the 21 administrative regions in which the Italian territory is divided, with a 330 km long coastline (Burgos et al., 2017) and covering a surface area of 5422 km², representing approximately 1.8% of the national territory. The Ligurian coastal marine environment is an incredibly diverse and distinctive reality in the Mediterranean seascape, hosting vulnerable environments to be safeguarded, and a valuable biodiversity (Regione Liguria, 2020). Several animal and plant species that colonize the seabed are particularly important in creating complex structures that can host, in turn, a rich biological community (Bollito, 2017). Due to the narrow continental platform, Ligurian Sea is characterized by a steep slope of the seabed, reaching high depths, only a few kilometers from the coast. The typical Ligurian sea vegetation, consisting of algal meadows and marine phanerogams, such as *Posidonia oceanica* (L.) Delile and *Cymodocea nodosa* (Ucria) Ascherson, can be found up to 20 m depth. Below 35 m, where light energy becomes insufficient for underwater plants' survival, gorgonians, bryozoans, and sponges (which constitute a specific and high-value habitat named coralligenous) still endure (Bianchi and Peirano, 1995).

In Italy, national law identifies two kinds of marine spaces subjected to natural resources safeguard from over-exploitation and human activities management. These are: 1) Marine Protected Areas (MPAs), established by a national law (Law for defense of the sea n.979-1982 and Legge Quadro sulle Aree Protette - L. n. 394 of 6/12/1991) and divided into three types of zones with different regimes of protection (zone A - integral reserve, the most severe; zone B - general reserve; zone C - partial reserve, almost all activities allowed) and 2) Marine Conservation Areas (MCAs), established by administrative regions and often embedded in natural parks, and without different types of protection regimes. Along the Ligurian coast, there are three MPAs, located in Portofino, Cinque Terre and Bergeggi Island, while the MCAs are Capo Mortola, Portovenere and Gallinara Island (in the process of being established).

2.2. Spatial analysis

Maps play a crucial role in analyzing and managing natural environments, facilitating the creation of spatial plans, which allow the cartographic visualization of the results of different management alternatives and the status of ecosystems (Parravicini et al., 2012; Dapuzo et al., 2020, 2022).

Geographic Information Systems (GIS) are currently an important decision support tool in the spatial domain, with a wide range of applications. A GIS is an organized collection of hardware, software, data, procedures, and people that enables the acquisition, recording, analysis visualization and retrieval of information from georeferenced data. In this study, QGIS (version 3.10.9) was utilized for data extraction, processing, and representation of the results. The ETRS89-ETRF89 reference system with UTM32 cartographic representation was used as a single reference system for all data, in accordance with the recommendations of the Military Geographic Institute at European level (IGM, 2016).

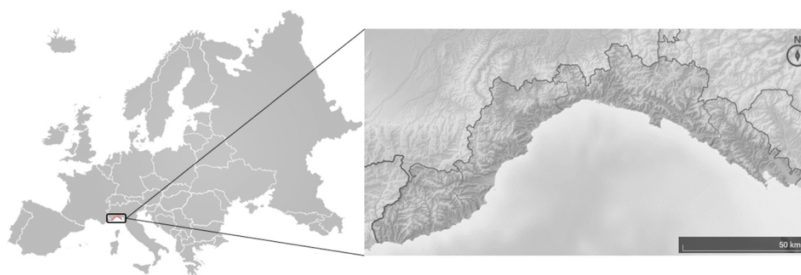


Fig. 1. Study area: the administrative Liguria region.

2.2.1. Identification of spatial functional units

The first step in data processing was identifying the functional spatial sectors of the Ligurian coastal zone, which were defined as "biomarine units". To accomplish this, the following cartographic data were obtained from the Geoportal of Liguria Region (<https://geoportal.regione.liguria.it>):

- 1) the marine coastal zone was divided into 26 "water bodies", which extend 3 km from the coast and had a maximum depth of 50 m. These were used by the Regional Agency for the Protection of the Ligurian Environment (ARPAL) and commissioned by Liguria Region for monitoring projects defined by the Water Directive 2000/60/EC, implemented in Italy by Legislative Decree 152/06 (Fig. 2, a.);
- 2) the boundaries of the protected areas of Capo Mortola, Bergoggi, Portofino, Cinque Terre and Portovenere were identified, as well as their eventually subdivision into protection zones (zone A, B and C) (Fig. 2, b.);
- 3) the benthic map reported in the Atlas of Marine Habitats of Liguria (Diviaco et al., 2020) was used (Fig. 2, c.). The Atlas provides fundamental knowledge of the Ligurian seabed and its primary habitats (Table 1).

The final map of biomarine units, along with the habitat surfaces within each biomarine unit, was obtained through the QGIS's spatial operations of union and intersection of the aforementioned maps.

2.3. Biophysical and monetary assessment of natural capital and environmental flows

The research carried out in this work was developed using emergy analysis to assess the values of NC and ENFL characterizing Ligurian marine coastal habitats.

2.3.1. Emergy analysis

Emergy analysis is a thermodynamics-based methodology developed by H.T. Odum (Odum, 1983, 1996). It enables the determination of the energy quality and the detailed list of all the incoming resources that maintain, directly or indirectly, a process or a product and converge through a chain of energy and matter transformations, both in time and space (Ulgiati and Brown, 2009). The analysis relies on a donor-side approach, which considers the environmental costs required to generate NC stock and to maintain the ENFL of a system. According to H. T. Odum definition, emergy is defined as the total equivalent solar energy used, both directly and indirectly, to produce goods and services (Odum, 1996). The more energy stored for the generation of natural resources and ecosystem services, the higher is their value (Odum, 1988, 1996) since the cost incurred by nature to maintain them is greater. Its unit of measure is solar energy Joule (sej) (Odum, 1996), as it shows the solar energy used to generate and maintain the biomass of all the organisms living the habitats (Paoli et al., 2018).

The first step is to draw a system diagram, according to the standardized energy system language proposed by Odum (1994, 1996) in order to organize relationship between the system's components. The system diagram guides the emergy charts development.

Conversion factors, defined as Unit Emergy Values (UEVs), were used to convert inputs and outputs feeding and characterizing a system into solar energy, the main driver of all the processes that take place in the biosphere. These define the equivalent solar energy necessary to obtain a single unit of a product. The more transformations required to obtain a product, the higher the UEV is (Brown and Ulgiati, 1997).

Then, the results can be converted in monetary equivalent values (according to the currency of the study system), using conversion factors given by the combination between emergy and economic values.

Emergy analysis methodology implemented in this work follows the procedure appropriately set up for NC assessment described by Vassallo et al. (2017) and already applied in Liguria by De La Fuente et al., 2019,

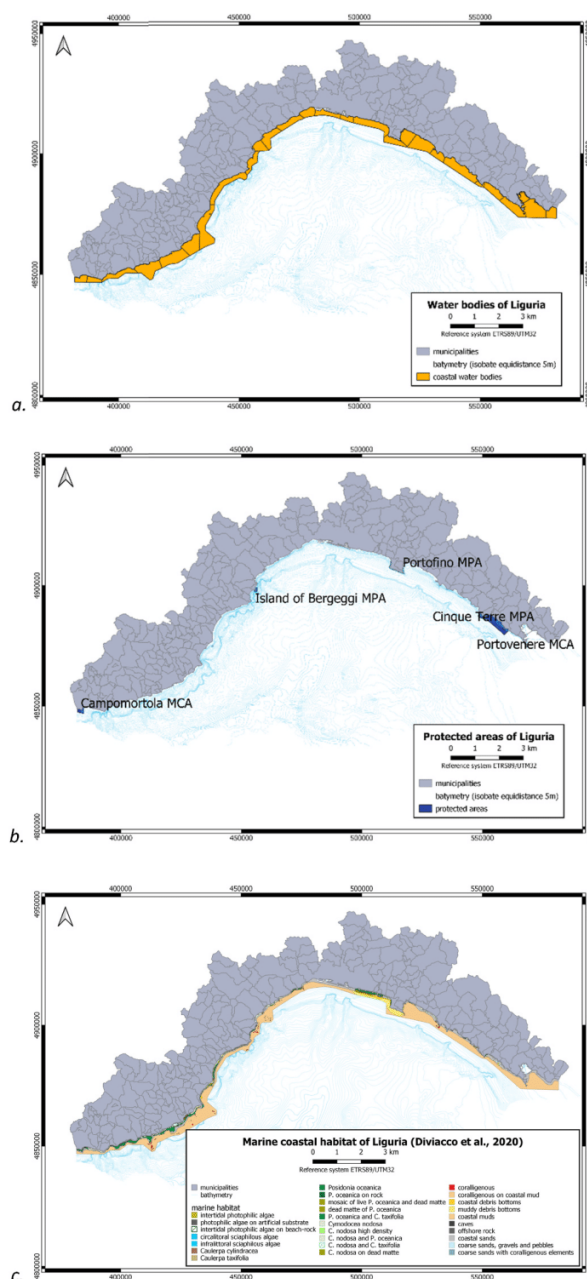


Fig. 2. Cartographic data considered to obtain biomarine units along Liguria region: a) water bodies used by regional management for monitoring water quality status; b) boundaries of marine protected areas; c) marine coastal habitats (realized with QGIS version 3.10.9).

Paoli et al. (2018) and Rigo et al. (2021). This methodology includes: trophodynamics analysis, biophysical accounting, and monetary conversion.

2.3.1.1. Trophodynamics analysis. The first phase of the study involves modeling the trophic network that characterizes the marine coastal habitats in the Liguria seascape, in order to estimate the primary productivity required to sustain the NC stocks of the study area. The main

Table 1
Ligurian marine coastal habitats (Diviacco et al., 2020).

Class	Nomenclature of this study
PA	Infralittoral photophilous algae on hard seabed Infralittoral photophilous algae on artificial seabed Infralittoral photophilous algae on beach-rock seabed
SA	Infralittoral sciaphilous algae Circal-littoral sciaphilous algae
C	Coralligenous Coralligenous on mud Coarse sands and coralligenous
CAU	<i>Caulerpa taxifolia</i> <i>Caulerpa cylindracea</i>
CYM	<i>Cymodocea nodosa</i> Dense <i>Cymodocea nodosa</i> <i>Cymodocea nodosa</i> with <i>Posidonia oceanica</i> <i>Cymodocea nodosa</i> and <i>Caulerpa taxifolia</i> <i>Cymodocea nodosa</i> on dead Matte
POS	<i>Posidonia oceanica</i> <i>Posidonia oceanica</i> between and on rock Mosaic of <i>Posidonia oceanica</i> Dead Matte <i>Posidonia oceanica</i> and <i>Caulerpa taxifolia</i>
CA	Caves
R	Rock
DMS	Detrital beds Muddy detrital beds Muds Sand Coarse sediments

taxonomic groups (e.g., phytoplankton, seagrass, microphytobenthos, bryozoan, porifera, cnidaria, echinodermata, crustacea) that make up the habitats were assessed. The biomass of both benthic and fish species were estimated in grams of carbon (gC). The benthic data were obtained from previous studies (Paoli et al., 2018 and references within), while fish biomass was sampled through a visual census technique commonly used to study coastal fish community, particularly in protected areas (Azzurro et al., 2007; Guidetti et al., 2002; Harmelin-Vivien et al., 1985). This technique is usually used to assess the increase in density and size of fishes as response of the effectiveness of protection in MPAs (Guidetti et al., 2008). Visual census campaigns are performed yearly in Italian MPAs using the same protocol, but Cinque Terre and Portofino MPAs are implementing annual visual census campaigns to monitor the fish fauna also outside the MPAs' borders. In Portofino and Cinque Terre MPAs, the values used in this study belonged to sampling inside borders and they were divided into the protection zones (A, B and C). The sampling provided length and abundance values, which were used to obtain fish biomass through length-weight relationships (Froese, 1998; Froese and Pauly, 2022, <https://www.fishbase.com>).

The biomass stocks of autotrophic and heterotrophic organisms were converted into the primary biomass (Bp) needed for its generation using the following equation formulated by Pauly and Christensen (1995):

$$B_p = \sum B_i \cdot 7^{(T_i-1)} \quad i = 1, 2, 3, \dots, n$$

$$\max(\text{carbon, nitrogen, phosphorous}) + \max(\text{solar radiation, rain, wind, kinetic current}) + \text{runoff} + \text{tides} + \text{geothermal heat}$$

where B_i is the biomass and T_i stands for the trophic level of the i -th group.

The trophic level of each species considered was computed with a simulation of the trophic net (Paoli et al., 2016) or, in the case of fishes, through data found in literature (Froese and Pauly, 2022, <https://www.fishbase.com>).

Subsequently, the time required to create the resources used to generate and store the biomass within the system (time for stock formation) was calculated. For the autotrophic group, the time was estimated as the reciprocal of the P/B ratio, and for the heterotrophic group, through the ratio between the sum of the primary production which sustained the heterotrophic stocks and an average productivity rate typical for marine benthic environment, i.e., the sum of the average productivity of macrophytes and phanerogams with the phytoplanktonic ones (Allen, 1971; Charpy-Roubaud and Sournia, 1990).

The ENFL assessment is also based on the biomass matrix of the taxonomic groups. To determine the annual primary production (Pa), the biomass of each autotrophic group was converted using appropriate P/B ratios, while the annual consumption made by the heterotrophic group (Pe) was calculated through appropriate Q/B ratios (Paoli et al., 2018 and references within).

Finally, the surfaces needed to maintain and support the calculated primary production (supporting area) were calculated. The supporting area is based on a balance between the annual primary production (Pa) and the consumption (Pe) in each habitat, which allows to define if the system is self-sustaining (Vassallo et al., 2017). There are two different scenarios:

- If $Pa \geq Pe$, the system can sustain its internal consumption and export the primary production surplus towards external habitats. The supporting area of the system is therefore smaller than or equal to its physical surface.
- If $Pa < Pe$, the system is not able to sustain its internal consumption and requires additional primary production to maintain itself, imported from outside the system. In this case, the supporting area of the system is considered larger than its physical area.

2.3.1.2. Biophysical accounting and monetary conversion. In the second phase, emery analysis returns the biophysical values of NC and ENFL that are essential to the maintenance of the processes within the habitats, both in extensive (sej) and intensive (sej m^{-2}) terms. The necessary data include natural resources such as:

- organic matter nutrients (i.e., carbon, nitrogen and phosphorous) content: carbon is obtained from the total primary biomass (Bp) expressed in carbon grams, while nitrogen and phosphorus are assessed by applying the Redfield et al. (1963) ratio to carbon content (Table 2);
- assessment of natural flows that support biomass production (i.e., solar radiation, rain, wind, currents, geothermal heat, tides, runoff) expressed in energy terms (Joule) using formulas reported in Table 2.

Natural flows data refers to 2019 (Appendix) and were collected at different location scattered throughout the study area. These data were averaged for each biomarine unit. Once the resources needed to maintain the system were obtained, they were converted into emery units (sej) by using specific UEVs (Table 3).

NC and ENFL values were obtained from the following sum:

The formula considers the higher value between carbon, nitrogen and phosphorus and solar radiation, rain, and wind (Odum, 1996) because they are co-products resulting from the same processes that occur at the biosphere level. The obtained values, referred to each

Table 2
Formulas for the calculation of nutrients and natural flows in the second phase of energy analysis.

Elements	Formulas	Unit	Reference
Carbon	Bp	g	This work
Nitrogen	Bp · 7/41	g	This work
Phosphorous	Bp/41	g	This work
Solar radiation	annual solar radiation per unit area · (1-albedo) · area · time for stocks formation (or supporting area)	J	Odum (1996)
Rain (chemical energy)	annual rainfall · Gibbs free energy · water density · area · time for stocks formation (or supporting area)	J	Odum (1996)
Wind	air density · drag coeff. · (geostrophic wind velocity) ³ · area · seconds per year · time for stocks formation (or supporting area)	J	Campbell et al. (2005)
Currents	½ · water mass · velocity ² · time for stocks formation (or supporting area)	J	Odum et al. (2000)
Geothermal heat	area · geothermal flux · time for stocks formation (or supporting area)	J	Brown and Bardi (2001)
Tides	½ · number of tides per year · (height) ² · density · gravity · area · time for stocks formation (or supporting area)	J	Odum (1996)
Runoff	(annual rainfall · evaporation · aquifer infiltration) · water density · Gibbs free energy · catchment area	J	Brown and Bardi (2001)

biomarine unit's the entire surface (sej), were also calculated for surface unit (sej m⁻¹).

The NC and ENFL biophysical values were converted into a monetary equivalent (em€) value, expressed as energy euro (em€), using an index defined as the “energy-to-money-ratio” (EMR), which represents the ratio between the energy flow of a nation and its GDP. Its conversion is given by sej coin⁻¹ (sej €⁻¹ in this study). The EMR used in this study is 9.60E+11 sej €⁻¹ (Pereira et al., 2013), as it was obtained for Italy and it has already been used in other Italian research works (e.g., Buonocore et al., 2021; Franzese et al., 2008; Picone et al., 2017; Paoli et al., 2016; Paoli et al., 2018; Rigo et al., 2020; Rigo et al., 2021; Vassallo et al., 2021). The conversion provides an estimate of how much a single solar energy joule (sej€⁻¹) is worth in monetary terms and allows for a better understanding of the correspondence between natural resources and a monetary unit. This step is crucial for communicating the importance of NC in political and socio-economic contexts (Vassallo et al., 2017).

Even in this phase of NC and ENFL assessment, the values obtained are in extensive terms (depending on the system size, i.e., the area surface) and intensive terms (not depending on the system size, i.e., values per meter square) for each habitat and each biomarine unit.

3. Results

3.1. Spatial analysis

3.1.1. Identification of spatial functional units

The identified biomarine units identified (Fig. 3) along the Ligurian

Table 3
Values of the UEVs used in this work and calculated on Brown and Ulgiati (2010) baseline.

Input	UEV (sej/unit)	Reference
Carbon	1.02E+08	Campbell and Tilley (2014)
Nitrogen	7.40E+09	Odum (1996)
Phosphorous	2.86E+10	Odum (1996)
Sun	1.00E+00	Odum (1996)
Rain	2.93E+04	Odum (1996)
Wind	2.41E+03	Odum (1996)
Currents	1.77E+07	Brown e Bardi (2001)
Geothermal heat	5.53E+04	Odum (1996)
Tides	2.71E+04	Odum (1996)
Run off	6.61E+04	Odum (1996)

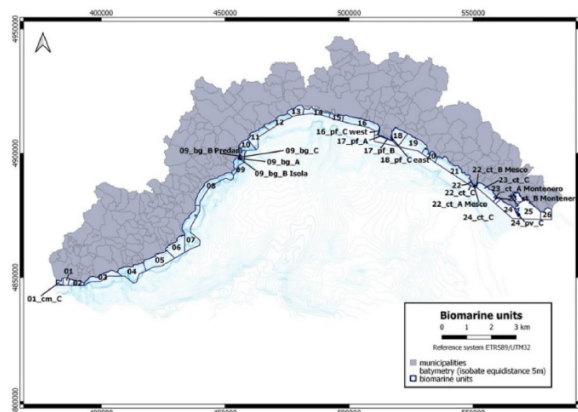


Fig. 3. Map of biomarine units (realized with QGIS version 3.10.9).

Table 4
Correspondence between protected areas, with relative zonations, and biomarine units and biomarine units surfaces (m²).
° MCAs, *MPAs.

Protected areas and zonations	Biomarine units	Surface (m2)
Outside MPAs and MCAs	01	8,19E+06
Capo Mortola	01_cm_C°	4,46E+06
Outside MPAs and MCAs	02	1,18E+07
Outside MPAs and MCAs	03	2,76E+07
Outside MPAs and MCAs	04	4,95E+07
Outside MPAs and MCAs	05	5,01E+07
Outside MPAs and MCAs	06	4,23E+07
Outside MPAs and MCAs	07	6,60E+07
Outside MPAs and MCAs	08	4,42E+07
Outside MPAs and MCAs	09	2,03E+07
Bergeggi A	09_bg_A*	3,43E+04
Bergeggi B	09_bg_B Isola*	1,75E+05
Bergeggi B	09_bg_B Predani*	2,42E+05
Bergeggi C	09_bg_C*	1,70E+06
Outside MPAs and MCAs	10	1,99E+07
Outside MPAs and MCAs	11	3,03E+07
Outside MPAs and MCAs	12	2,54E+07
Outside MPAs and MCAs	13	1,98E+07
Outside MPAs and MCAs	14	1,99E+07
Outside MPAs and MCAs	15	1,10E+07
Outside MPAs and MCAs	16	4,32E+07
Portofino C	16_pf_C west*	9,79E+05
Outside MPAs and MCAs	17	1,90E+07
Portofino A	17_pf_A	1,62E+05
Portofino B	17_pf_B	1,63E+06
Portofino C	18_pf_C east*	8,57E+05
Outside MPAs and MCAs	18	2,82E+07
Outside MPAs and MCAs	19	4,65E+07
Outside MPAs and MCAs	20	1,66E+07
Outside MPAs and MCAs	21	5,24E+07
Outside MPAs and MCAs	22	7,25E+05
Cinque Terre A	22_ct_A Mesco*	7,20E+05
Cinque Terre B	22_ct_B Mesco*	1,12E+06
Cinque Terre C	22_ct_C*	5,71E+06
Cinque Terre A	23_ct_A Montenero*	1,34E+05
Cinque Terre B	23_ct_B Montenero*	9,17E+05
Cinque Terre C	23_ct_C*	3,55E+07
Cinque Terre C	24_ct_C*	5,71E+06
Outside MPAs and MCAs	24	3,16E+07
Portovenere	24_pv_C°	1,28E+06
Portovenere	25_pv_C°	4,79E+04
Outside MPAs and MCAs	25	5,59E+07
Outside MPAs and MCAs	26	1,76E+07

coast consists of 43 sectors, from the French border (biomarine unit 01) to the Tuscany border (biomarine unit 26). Biomarine units 01, 09, 16, 17, 18, 22, 23, 24 and 25 are internally divided according to the

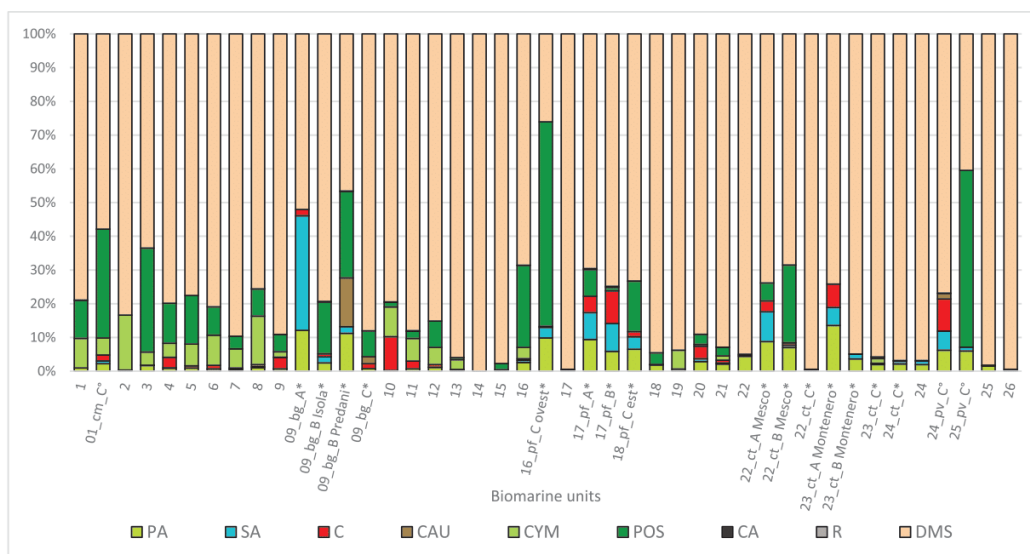


Fig. 4. Percentual composition of habitats in each biomarine unit. ° MCAs, *MPAs.

zonation of MPAs and the borders of MCAs (Table 4).

Table 4 also displays the surfaces of each biomarine unit. The total surface area occupied by biomarine units is $8.18E+08 \text{ m}^2$. The surface area of each biomarine unit varies between a minimum of $3.43E+04 \text{ m}^2$ (unit 09_bg_A) and maximum of $6.60E+07 \text{ m}^2$ (unit 07).

Fig. 4 illustrates the composition of each biomarine unit in terms of the percentage of surface area occupied by each habitat. The habitats within the DMS class cover more than 50% of the surface in every biomarine unit, except for 09_bg_B Predani (47%), 16_pf_C Ovest (26%) and 25_pv_C (40%). The DMS habitats completely cover biomarine unit 14. As for the POS class, surface areas greater than 50% are only found in two biomarine units: 16_pf_C_ovest (61%) and 25_pv_C (52%). POS is dominant for more than one-third of the surface area in biomarine units 01_cm_C (32%) and 03 (31%). Habitats with coralligenous (class C) occur with percentages around 5–10% inside Portofino and Cinque Terre MPAs units (17_pf_A, 17_pf_B, 23_ct_A Montenero), Portovenere (biomarine unit 24_pv_C) and biomarine unit 10.

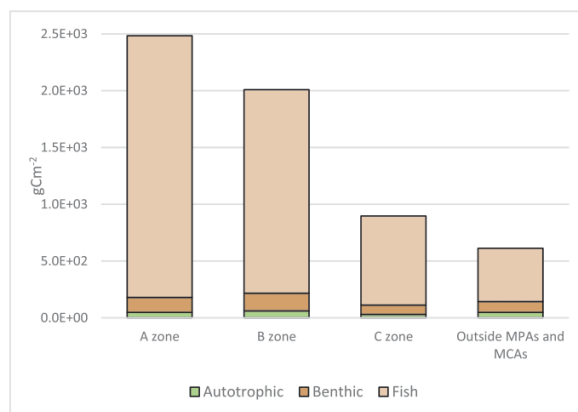


Fig. 6. Average primary production needed for the generation of the biomass (gCm^{-2}), for A, B and C zones of protected areas and for biomarine units outside their borders.

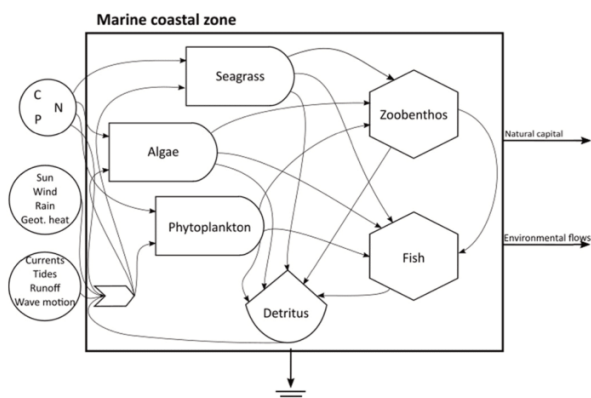


Fig. 5. System diagram of Ligurian marine coastal zone.

3.2. Biophysical and monetary assessment of natural capital and environmental flows

3.2.1. Emery analysis

Fig. 5 shows the system diagram of the study area, highlighting the inflows of natural resources from outside the system, the producers, the consumers, the storages and the interactions between them, which together support the generation of NC stocks.

3.2.1.1. Trophodynamic analysis. Fig. 6 shows the average primary production required (B_p) per unit area (gCm^{-2}) for the autotrophic and heterotrophic components of biomarine units located inside and outside of protected areas. The biomarine units that require the most B_p to generate their biomass are mainly those in protected areas, particularly A and B zones, which require the highest values (more than $2.00E+03 \text{ gCm}^{-2}$) of primary production.

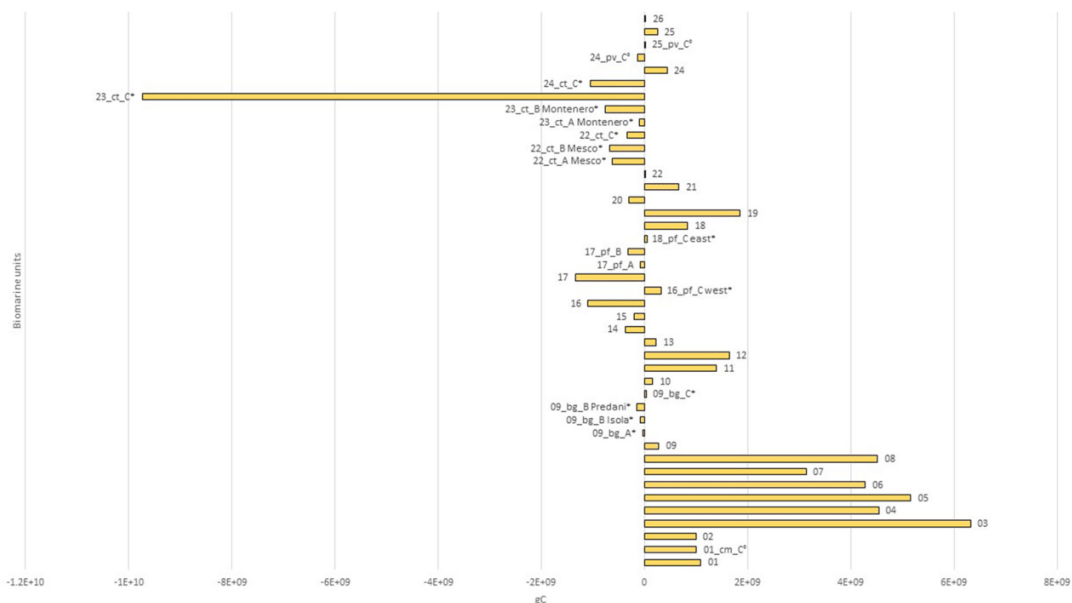


Fig. 7. Balance between the generated and required productivity (gC) inside each biomarine unit.
° MCAs, *MPAs.

Generally, more production is required for the generation of heterotrophic biomass compared to autotrophic biomass: in every biomarine unit, the primary production required for the heterotrophic groups is always higher than 90% of the total needed. The heterotrophic group is composed of benthic and fish components, and the fish component contributes more than 75% to the total value of primary production.

Moreover, Fig. 7 shows the balance between annual primary production and consumption in each biomarine unit, as explained in paragraph 2.3.1.2, is shown in. The biomarine unit with the greatest surplus 03 ($6.33E+09$ gC), while the one with the lowest deficit is biomarine unit 23_ct_C ($-9.73E+09$ gC).

3.2.1.2. Biophysical accounting and monetary conversion. The results for the conversion of natural resources to solar equivalent (sej) can be found in the Appendix. When considering the average values of natural resources in each biomarine unit, tides have the lowest impact on the system, at around 0.1% ($2.19E+18$ sej for NC and $2.02E+18$ a⁻¹ sej for ENFL) to create NC and exploit functions flows annually. The contribution of runoff represents around 54% for NC and 67% for ENFL, equivalent to $1.09E+21$ sej and $9.18E+20$ sej a⁻¹, respectively.

The extensive biophysical (sej) and monetary equivalent (em€) values obtained are listed in Table 5. For the entire study area, NC values resulted in $2.03E+21$ sej and $2.11E+09$ em€, while ENFL values resulted in $1.37E+21$ sej a⁻¹ and $1.43E+09$ em€ a⁻¹.

For further details look at Table 8 and Tabella 9 in Appendix.

Fig. 8 shows intensive values (sej m⁻²) for NC and ENFL in every biomarine unit. Average values were found to be $2.48E+12$ sej m⁻² for NC and $1.68E+12$ sej m⁻²a⁻¹ for ENFL. The biomarine units with the highest NC values are 22_ct_B Mesco and 09_bg_A (both $1.26E+13$ sej m⁻²), while the one with the lowest value is biomarine unit 24 ($7.86E+11$ sej m⁻²). The biomarine unit with the highest ENFL value is 09_bg_A ($8.14E+12$ sej m⁻²a⁻¹), while those with the lowest values are 18, 24 and 02 (each about $1.35E+12$ sej m⁻²a⁻¹).

Fig. 9 represents the distribution maps of NC and ENFL as monetary equivalent values per unit area (em€ m⁻²) for any biomarine unit. The average intensive values are 2.58 em€ m⁻² and 1.75 em€ m⁻²a⁻¹. The

trend of the values along the coast reflects what has been described above for extensive and intensive values obtained in solar equivalents (sej and sej m⁻²). NC values lie between 13.13 em€ m⁻² (09_bg_A) and 0.82 em€ m⁻² (biomarine unit 24), while those for ENFL lie between 8.48 em€ m⁻²a⁻¹ (09_bg_A) and 1.41 em€ m⁻²a⁻¹ (biomarine unit 18).

Finally, Fig. 10 represents the average NC values for all the A, B and C zones of protected areas and the average NC value for the biomarine units with no protection. A, B and C zones of protected areas show greater values than those of biomarine units outside their borders, with a maximum value for A zone of MPAs (9.98 em€ m⁻²).

4. Discussion

The study reports on the varying spatial distribution of NC and ENFL values within the biomarine units of the Liguria Region. The application of the same methodology for the assessment of NC to marine areas under the same administrative level allows for a broader and standardized NC evaluation compared to previous studies carried out in local areas (Buonocore et al., 2020, 2021; Burgos et al., 2017; Dapuetto et al., 2022; De La Fuente et al., 2019; Franzese et al., 2015, 2017; Paoli et al., 2016, 2018; Picone et al., 2017; Rigo et al., 2020, 2021; Vassallo et al., 2009). This could be a helpful tool for developing management and protection plans for the entire marine and coastal area of the Region. Moreover, the breakdown of biomarine units enables the implementation of specific strategies for each situation. This method could also be applied to other Italian coastal Regions to obtain a framework of natural capital assessment at the national level. However, standardization of data collection and availability is strongly suggested, which has already been partially initiated with the Water Framework Directive (WFD; 2000/60/EG) and the Marine Strategy Framework Directive (MSFD; 2008/56/CE).

The average intensive NC and ENFL values obtained within the protected areas are greater, respectively 3.94 em€ m⁻² and 3.24 em€ m⁻²a⁻¹, compared with those obtained for biomarine units outside protected areas: 2.47 em€ m⁻² for NC and 1.63 em€ m⁻² a⁻¹ for ENFL. The significant role of protected areas is highlighted at the international level through the Convention on Biological Diversity, the Ramsar Convention and the Agenda 2030 for Sustainable Development

Table 5
NC and ENFL values expressed in extensive terms (sej and em€).
° MCAs, *MPAs.

Biomarine units	NC		ENFL	
	sej	em€	sej a ⁻¹	em€ a ⁻¹
1	1.12E+19	2.60E+07	1.12E+19	1.17E+07
01_cm_C°	7.95E+18	2.54E+07	7.95E+18	8.28E+06
2	1.59E+19	2.25E+07	1.59E+19	1.66E+07
3	4.19E+19	1.67E+08	4.19E+19	4.37E+07
4	7.82E+19	1.75E+08	7.82E+19	8.15E+07
5	7.57E+19	2.00E+08	7.57E+19	7.88E+07
6	5.78E+19	1.17E+08	5.78E+19	6.02E+07
7	8.97E+19	1.13E+08	8.97E+19	9.35E+07
8	6.55E+19	1.43E+08	6.55E+19	6.82E+07
9	3.12E+19	4.19E+07	3.12E+19	3.25E+07
09_bg_A*	2.80E+17	4.50E+05	2.80E+17	2.91E+05
09_bg_B Isola*	8.27E+17	1.35E+06	8.27E+17	8.61E+05
09_bg_B Predani*	1.39E+18	3.03E+06	1.39E+18	1.45E+06
09_bg_C*	2.67E+18	3.74E+06	2.67E+18	2.78E+06
10	3.42E+19	5.49E+07	3.42E+19	3.56E+07
11	4.35E+19	5.07E+07	4.35E+19	4.53E+07
12	3.82E+19	6.02E+07	3.82E+19	3.98E+07
13	3.05E+19	2.31E+07	3.05E+19	3.17E+07
14	3.33E+19	2.16E+07	3.33E+19	3.47E+07
15	1.94E+19	1.74E+07	1.94E+19	2.02E+07
16	1.17E+20	3.09E+08	1.17E+20	1.22E+08
16_pf_C ovest*	1.81E+18	6.88E+06	1.81E+18	1.88E+06
17	3.80E+19	3.62E+07	3.80E+19	3.96E+07
17_pf_A*	7.93E+17	1.24E+06	7.93E+17	8.27E+05
17_pf_B*	4.88E+18	6.64E+06	4.88E+18	5.08E+06
18_pf_C est*	1.40E+18	2.05E+06	1.40E+18	1.45E+06
18	3.81E+19	3.33E+07	3.81E+19	3.97E+07
19	6.31E+19	4.97E+07	6.31E+19	6.57E+07
20	2.81E+19	3.72E+07	2.81E+19	2.93E+07
21	7.89E+19	8.44E+07	7.89E+19	8.21E+07
22	1.04E+18	8.55E+05	1.04E+18	1.08E+06
22_ct_A Mesco*	4.93E+18	7.30E+06	4.93E+18	5.14E+06
22_ct_B Mesco*	6.28E+18	1.48E+07	6.28E+18	6.54E+06
22_ct_C*	9.52E+18	6.12E+06	9.52E+18	9.91E+06
23_ct_A Montenero*	8.49E+17	1.39E+06	8.49E+17	8.84E+05
23_ct_B Montenero*	6.02E+18	6.94E+06	6.02E+18	6.27E+06
23_ct_C*	1.18E+20	1.30E+08	1.18E+20	1.23E+08
24_ct_C*	1.60E+19	1.50E+07	1.60E+19	1.66E+07
24	4.28E+19	2.59E+07	4.28E+19	4.45E+07
24_pv_C°	2.85E+18	4.07E+06	2.85E+18	2.97E+06
25_pv_C°	9.75E+16	3.46E+05	9.75E+16	1.02E+05
25	8.42E+19	5.06E+07	8.42E+19	8.77E+07
26	2.73E+19	1.48E+07	2.73E+19	2.85E+07
Total	2.03E+21	2.11E+09	1.37E+21	1.43E+09

(Buonocore et al., 2021; UNEP-WCMC, 2018; Terraube et al., 2017; UNEP-WCMC, 2018). The results of this study confirm the effectiveness in identifying those areas which most need significant management and conservation of the marine ecosystem, having as final purpose biodiversity conservation and the maintenance or enhancement of resources (Campbell and Hewitt, 2006; NRC, 2001; Pita et al., 2011).

This study also shows the effectiveness of zonation with different protection regimes in MPAs (Bergeggi, Portofino and Cinque Terre). As showed in Fig. 10A and B zones show greater average values for NC (9.88 em€ m⁻² and 8.01 em€ m⁻²) and ENFL (6.80 em€ m⁻²a⁻¹ and 4.94 em€ m⁻²a⁻¹) compared to C zones (3.53 em€ m⁻² for NC and 3.04 em€ m⁻²a⁻¹ for ENFL), which have lower protection level. NC and ENFL values for A zone suggest that the decision to establish strict protection measures was correct (only rescue, surveillance, and research activities are allowed), in contrast with what happens in C zone, where the allowance to perform activities as bathing, navigation, diving and anchoring does not ensure the same conservation level of coastal habitats and associated NC. Portovenere and Capo Mortola are MCAs with no kind of restriction for bathing, navigation, anchoring and fishing activities. Furthermore, Capo Mortola was approved by the Regional Council on 28 September 2018 (L.R. 31/2000), while Portovenere on 11 October 2007 (L.R. 30/2001). The recent establishment and the fewer

activities restrictions at the time of this may have created unfavorable conditions for the maintenance of NC and ENFL. This confirms previous research (Claudet et al., 2008; Edgar et al., 2014; Giakoumi et al., 2017; Guidetti et al., 2008), which identify the age and level of enforcement as key features for the improvement of protected areas, especially in terms of fish density and biomass. Moreover, the values shown in Figs. 6 and 10 could confirm the effectiveness of marine reserve establishment, as the fish component values are higher in areas with more restrictions on fishing. Specifically, for A and B zone with fishing bans, the values of NC are more than 6 em€ m⁻², whereas in areas with fewer or no restrictions, the NC value does not exceed 2.98 em€ m⁻².

The results also reveal that the extensive values of NC and ENFL for biomarine units outside protected areas are higher along the Ligurian western coast (from the biomarine unit 14 corresponding to the Genoa area), which reports overall NC and ENFL values of 1.22E+09 em€ and 6.74E+08 em€ a⁻¹, respectively, compared to 6.59E+08 em€ and 5.60E+08 em€ a⁻¹ in the eastern regions. This difference was confirmed by further spatial analysis. Analyzing the surfaces of each habitat, it was found that the western coast has greater extension of *Posidonia oceanica* (about 84% compared to all the eastern biomarine units) and coralligenous habitats (about 77% compared to all the eastern biomarine units). The morphology of Ligurian coast reveals differences between the west coast, which is characterized by wide valleys bound to alpine mountains in proximity to the coast, where *P. oceanica* meadows can develop, and the east coast, which is defined by narrow valleys related to the Apennine mountains that typically generate pocket beaches where less extended meadows are associated (Bianchi and Peirano, 1995; Oprandi et al., 2021). *P. oceanica* is acknowledged as a high-value ecosystem, appearing as a stable and specialized system with great production and qualitative and structural complexity (Paoli et al., 2016, 2018). The coralligenous is also a high-value ecosystem, being constructed by high heterotrophic biomass, which characterizes the highest levels of the trophic net hierarchy. The prevalence of consumers in the coralligenous habitat makes it a non-self-sustaining habitat, as confirmed by previous studies (Buonocore et al., 2019; Paoli et al., 2018), because it requires flows of resources that must be channeled from elsewhere with a considerable effort by nature to sustain its functional and structural complexity (Paoli et al., 2016). Therefore, larger *P. oceanica* meadows in the western coast could support the provision of resources needed by adjacent coralligenous habitats. The western biomarine units (units 1–14), excluding the protected areas, are indeed in surplus, while those belonging to the Ligurian east coast (units 15–26) do not have enough primary production that grant their self-sustaining.

The structural complexity of *P. oceanica* and coralligenous habitats (Paoli et al., 2016) allows protected areas to have highest NC and ENFL values. For instance, high values in the A zone of Bergeggi MPA are due to the coralligenous habitat, which supports about the 20% of fish biomass present throughout the biomarine unit. However, excluding Capo Mortola and Portovenere and zones C of Bergeggi, protected areas show a deficit situation (Fig. 7). These areas concentrate large amount of biomass, making them not self-sustaining and requiring external resources to preserve their NC, as shown in previous studies carried out in Ligurian MPAs (Paoli et al., 2018). The consequence of deficit condition is the dependence on external systems not subjected to protection, which increase the risk of degradation. This implies the need to establish in advance the size and location of MPAs by incorporating habitats that are able to maintenance themselves, meaning those with a positive or neutral balance between the annual primary production and the consumption. Moreover, as stated by Roughgarden et al. (1987), the species composition of a marine community depends largely on the arrival of recruits from outside, not only on the breeding of adults already there. The consequences is often a shift of biodiversity into nearby areas that must be preserved by the same protection measures. For this reason, the best combination of habitats has to be considered at the design stage.

The procedure used in this study could be implemented by

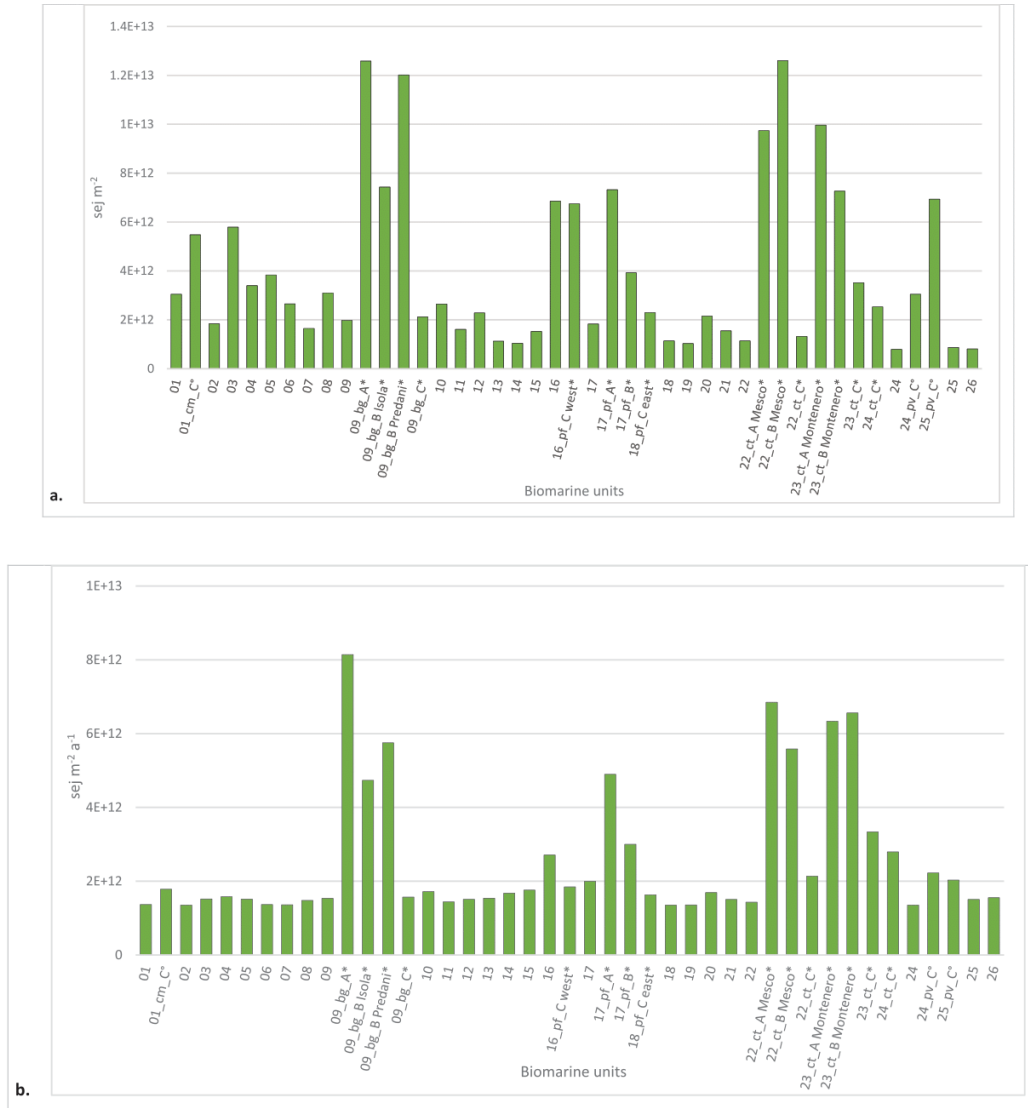


Fig. 8. Intensive values of a.) NC (sej m⁻²) and b.) ENFL (sej m⁻² a⁻¹) for each biomarine unit.
 ° MCAs, *MPAs.

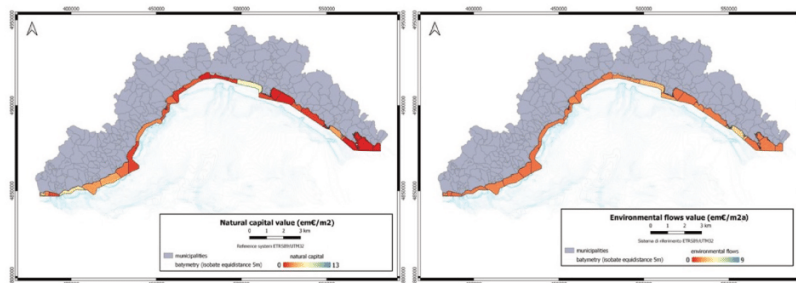


Fig. 9. a.) NC value (em€ m⁻²) for each biomarine unit. b.) ENFL value (em€ m⁻²a⁻¹) for each biomarine unit (realized with QGIS version 3.10.9).

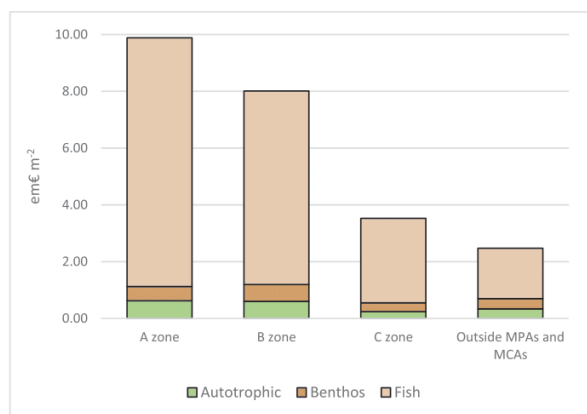


Fig. 10. Average natural capital (em€m⁻²) for A, B and C zones of protected areas and for biomarine units outside their borders.

integrating the methodology used for data gathering with other techniques. For instance, visual census technique could be complemented with the assessment of the presence of cryptic species, species with escape behaviors in the presence of operators or even pelagic species. Since the real composition of species of all the biomarine units is therefore not considered, more sampling in several sites along the marine coastal area, both outside and inside protected areas, using the same protocol approved at the national level, would be necessary to better understand the entire fish communities of the studied area (Tessier et al., 2005) and carry out assessments on them.

5. Conclusion

This study provides an initial analysis and serves as a starting point for evaluating the spatial distribution of NC and ENFL values along the Ligurian coast. The results obtained, both biophysical and monetary terms, enable the integration of the analysis into management plans,

emphasizing their importance and enabling efficient monitoring (Vassallo et al., 2009). Converting the results into monetary equivalents does not alter the biophysical characteristic of the model, but it simplifies the inclusion of the environmental cost for generating and maintaining NC in political and socio-economic contexts (Franzese et al., 2008). This approach, in conjunction with environmental factors, can aid in defining environmental management and preservation strategies (Paoli et al., 2018). Spatial analysis is also useful in achieving these objectives: since NC and ENFL have a spatial distribution, their analysis must also be spatially explicit. The mapping of their spatial distribution is an effective communication tool, allowing both experts and stakeholders to easily locate and characterize areas based on their ecological value. Moreover, cartographic representation helps monitor changes in NC and ENFL over time.

CRedit authorship contribution statement

Rachele Bordoni: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Ilaria Rigo:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing. **Giulia Daputo:** Methodology, Data curation, Writing – review & editing. **Paolo Povero:** Supervision. **Paolo Vassallo:** Conceptualization, Methodology, Supervision, Writing – review & editing, Visualization. **Chiara Paoli:** Conceptualization, Methodology, Supervision, Writing – review & editing, Visualization.

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.

Appendix

Table 6 Natural resources and their references.

Element	References
Solar radiation (J m ⁻² a ⁻¹)	ENEA (http://www.solaritaly.enea.it/) Pannelli solari (http://www.infopannellisolari.com/)
Wind (m s ⁻¹)	ilMeteo (https://www.ilmeteo.it/http://www.ilmeteo.it/)
Rain (mm a ⁻¹)	AMBIENTE IN LIGURIA: METEO (http://www.cartografiarL.regione.liguria.it https://geoportal.regione.liguria.it/)
Geothermal heat (MW m ⁻²)	Geothopica – Banca Dati Nazionale Geotermica – CNR (http://palici.igg.cnr.it/wm_geothopica/map.php?wsize=large&language=it&config=http://www.palici.igg.cnr.it/)
Tides (cm)	Il Cybernauta (https://www.paolociraci.it/)
Waves (m)	BOA CAPO MELE (http://servizi-meteoliguria.arpal.gov.it/boacapomele.html)
Currents (m s ⁻¹)	BOA CAPO MELE (http://servizi-meteoliguria.arpal.gov.it/boacapomele.html)

Natural capital

Table 7 Nutrients and natural flows in emery terms (sej).

Biomarine units	Carbon (sej)	Nitrogen (sej)	Phosphorous (sej)	Sun (sej)	Rain (sej)	Wind (sej)	Currents (sej)	Geothermal heat (sej)	Tides (sej)	Run off (sej)	NC (sej)
1	6.83E+17	8.45E+18	4.67E+18	5.44E+16	1.45E+18	5.76E+17	5.66E+16	1.27E+18	2.42E+16	1.38E+19	2.49E+19
01_cm_C	6.49E+17	8.02E+18	4.44E+18	5.41E+16	1.44E+18	5.72E+17	5.62E+16	1.26E+18	2.40E+16	1.37E+19	2.44E+19
2	6.02E+17	7.44E+18	4.11E+18	4.65E+16	1.30E+18	4.93E+17	4.84E+16	1.08E+18	2.07E+16	1.18E+19	2.16E+19
3	4.33E+18	5.35E+19	2.96E+19	3.50E+17	9.59E+18	3.71E+18	3.64E+17	8.16E+18	1.56E+17	8.85E+19	1.60E+20

(continued on next page)

Table 7 (continued)

Biomarine units	Carbon (sej)	Nitrogen (sej)	Phosphorous (sej)	Sun (sej)	Rain (sej)	Wind (sej)	Currents (sej)	Geothermal heat (sej)	Tides (sej)	Run off (sej)	NC (sej)
4	4.34E+18	5.37E+19	2.97E+19	3.50E+17	1.71E+19	3.88E+18	3.65E+17	8.19E+18	1.56E+17	8.88E+19	1.68E+20
5	5.21E+18	6.44E+19	3.56E+19	4.22E+17	1.01E+19	4.73E+18	4.42E+17	9.91E+18	1.89E+17	1.07E+20	1.92E+20
6	2.97E+18	3.67E+19	2.03E+19	2.42E+17	8.09E+18	2.71E+18	2.53E+17	5.68E+18	1.09E+17	6.16E+19	1.12E+20
7	2.85E+18	3.52E+19	1.95E+19	2.34E+17	8.23E+18	2.33E+18	2.45E+17	5.48E+18	1.06E+17	5.95E+19	1.09E+20
8	3.61E+18	4.46E+19	2.47E+19	2.92E+17	1.11E+19	2.30E+18	3.06E+17	6.85E+18	1.32E+17	7.43E+19	1.37E+20
9	1.06E+18	1.31E+19	7.23E+18	8.64E+16	3.09E+18	6.74E+17	9.04E+16	2.03E+18	3.90E+16	2.20E+19	4.02E+19
09_bg_A	1.15E+16	1.43E+17	7.89E+16	9.23E+14	3.30E+16	7.19E+15	9.65E+14	2.16E+16	4.17E+14	2.35E+17	4.32E+17
09_bg_B Isola	3.55E+16	4.38E+17	2.42E+17	2.74E+15	9.80E+16	2.13E+16	2.86E+15	6.42E+16	1.24E+15	6.96E+17	1.30E+18
09_bg_B Predani	7.70E+16	9.51E+17	5.26E+17	6.23E+15	2.23E+17	4.86E+16	6.52E+15	1.46E+17	2.81E+15	1.58E+18	2.91E+18
09_bg_C	9.34E+16	1.15E+18	6.38E+17	7.77E+15	2.78E+17	6.06E+16	8.13E+15	1.82E+17	3.51E+15	1.98E+18	3.59E+18
10	1.33E+18	1.64E+19	9.06E+18	1.10E+17	5.46E+18	8.66E+17	1.16E+17	2.60E+18	5.01E+16	2.82E+19	5.27E+19
11	1.24E+18	1.53E+19	8.45E+18	9.93E+16	5.49E+18	8.64E+17	1.05E+17	2.36E+18	4.54E+16	2.55E+19	4.87E+19
12	1.43E+18	1.77E+19	9.79E+18	1.16E+17	7.59E+18	1.03E+18	1.22E+17	2.74E+18	5.31E+16	2.97E+19	5.78E+19
13	5.86E+17	7.24E+18	4.00E+18	4.42E+16	2.51E+18	3.95E+17	4.69E+16	1.05E+18	2.04E+16	1.14E+19	2.22E+19
14	5.60E+17	6.92E+18	3.83E+18	4.03E+16	2.31E+18	3.63E+17	4.31E+16	9.66E+17	1.88E+16	1.05E+19	2.07E+19
15	4.45E+17	5.50E+18	3.04E+18	3.29E+16	1.88E+18	2.96E+17	3.52E+16	7.88E+17	1.53E+16	8.55E+18	1.67E+19
16	7.81E+18	9.65E+19	5.33E+19	6.06E+17	2.75E+19	5.46E+18	6.48E+17	1.45E+19	2.82E+17	1.57E+20	2.96E+20
16_pf_C ovest	1.55E+17	1.92E+18	1.06E+18	1.40E+16	7.07E+17	1.26E+17	1.49E+16	3.35E+17	6.52E+15	3.63E+18	6.60E+18
17	9.52E+17	1.18E+19	6.51E+18	6.87E+16	3.47E+18	6.19E+17	7.34E+16	1.65E+18	3.20E+16	1.79E+19	3.48E+19
17_pf_A	3.08E+16	3.80E+17	2.10E+17	2.41E+15	1.22E+17	2.17E+16	2.58E+15	5.78E+16	1.12E+15	6.26E+17	1.19E+18
17_pf_B	1.58E+17	1.95E+18	1.08E+18	1.32E+16	6.69E+17	1.19E+17	1.41E+16	3.17E+17	6.17E+15	3.44E+18	6.38E+18
18_pf_C est	4.53E+16	5.59E+17	3.09E+17	4.24E+15	2.03E+17	3.82E+16	4.53E+15	1.02E+17	1.98E+15	1.10E+18	1.97E+18
18	8.26E+17	1.02E+19	5.64E+18	6.61E+16	2.94E+18	5.95E+17	7.06E+16	1.58E+18	3.08E+16	1.72E+19	3.19E+19
19	1.29E+18	1.59E+19	8.80E+18	9.73E+16	4.28E+18	8.73E+17	1.04E+17	2.32E+18	4.52E+16	2.52E+19	4.77E+19
20	9.28E+17	1.15E+19	6.34E+18	7.50E+16	3.07E+18	6.71E+17	7.96E+16	1.79E+18	3.47E+16	1.94E+19	3.57E+19
21	2.14E+18	2.65E+19	1.46E+19	1.69E+17	6.35E+18	5.70E+17	1.79E+17	4.43E+18	1.20E+17	4.36E+19	8.10E+19
22	2.13E+16	2.63E+17	1.46E+17	1.71E+15	6.62E+16	4.55E+15	1.82E+15	4.71E+16	1.46E+15	4.42E+17	8.20E+17
22_ct_A Mesco	1.89E+17	2.33E+18	1.29E+18	1.44E+16	5.56E+17	3.82E+16	1.53E+16	3.95E+17	1.23E+16	3.71E+18	7.01E+18
22_ct_B Mesco	3.85E+17	4.76E+18	2.63E+18	2.89E+16	1.12E+18	7.68E+16	3.07E+16	7.95E+17	2.47E+16	7.47E+18	1.42E+19
22_ct_C	1.63E+17	2.01E+18	1.11E+18	1.19E+16	4.59E+17	3.16E+16	1.26E+16	3.27E+17	1.01E+16	3.07E+18	5.88E+18
23_ct_A	3.57E+16	4.42E+17	2.44E+17	2.73E+15	1.10E+17	9.21E+15	2.90E+15	7.50E+16	2.33E+15	7.05E+17	1.33E+18
Montenero											
23_ct_B	1.84E+17	2.28E+18	1.26E+18	1.34E+16	5.43E+17	4.53E+16	1.43E+16	3.69E+17	1.15E+16	3.46E+18	6.66E+18
Montenero											
23_ct_C	3.44E+18	4.25E+19	2.35E+19	2.53E+17	1.02E+19	5.33E+17	2.68E+17	6.94E+18	2.16E+17	6.52E+19	1.25E+20
24_ct_C	3.93E+17	4.86E+18	2.69E+18	2.91E+16	1.23E+18	9.83E+16	3.09E+16	8.01E+17	2.49E+16	7.52E+18	1.44E+19
24	6.41E+17	7.93E+18	4.38E+18	5.14E+16	2.17E+18	1.08E+17	5.46E+16	1.41E+18	4.39E+16	1.33E+19	2.48E+19
24_pv_C	9.50E+16	1.17E+18	6.49E+17	8.35E+15	3.40E+17	2.22E+16	8.87E+15	2.29E+17	7.13E+15	2.16E+18	3.91E+18
25_pv_C	1.02E+16	1.27E+17	7.00E+16	6.30E+14	2.57E+16	1.67E+15	6.68E+14	1.73E+16	5.37E+14	1.63E+17	3.33E+17
25	1.25E+18	1.55E+19	8.57E+18	9.59E+16	5.56E+18	2.55E+17	1.02E+17	2.63E+18	8.19E+16	2.48E+19	4.85E+19
26	3.69E+17	4.56E+18	2.52E+18	2.73E+16	1.80E+18	4.42E+16	2.90E+16	7.50E+17	2.33E+16	7.05E+18	1.42E+19

° MCAs, *MPAs.

Environmental flows

Tabella 8

Nutrients and natural flows in emergy terms (sej).

Biomarine units	Carbon (sej)	Nitrogen (sej)	Phosphorous (sej)	Sun (sej)	Rain (sej)	Wind (sej)	Currents (sej)	Geothermal heat (sej)	Tides (sej)	Run off (sej)	ENFL (sej)
1	1.63E+17	2.02E+18	1.12E+18	3.03E+16	8.05E+17	3.21E+17	3.15E+16	7.06E+17	1.35E+16	7.66E+18	1.120E+19
01_cm_C	1.51E+17	1.87E+18	1.03E+18	2.01E+16	5.33E+17	2.12E+17	2.09E+16	4.68E+17	8.92E+15	5.07E+18	7.949E+18
2	1.72E+17	2.13E+18	1.18E+18	4.53E+16	1.26E+18	4.8E+17	4.71E+16	1.06E+18	2.01E+16	1.15E+19	1.592E+19
3	8.77E+17	1.08E+19	5.99E+18	1.02E+17	2.8E+18	1.08E+18	1.06E+17	2.39E+18	4.55E+16	2.59E+19	4.193E+19
4	1.08E+18	1.34E+19	7.4E+18	1.99E+17	9.68E+18	2.2E+18	2.07E+17	4.65E+18	8.87E+16	5.04E+19	7.822E+19
5	1.21E+18	1.5E+19	8.28E+18	2.01E+17	4.81E+18	2.25E+18	2.1E+17	4.71E+18	8.98E+16	5.11E+19	7.567E+19
6	7.67E+17	9.48E+18	5.24E+18	1.55E+17	5.18E+18	1.74E+18	1.62E+17	3.64E+18	6.97E+16	3.95E+19	5.783E+19
7	9.52E+17	1.18E+19	6.5E+18	2.49E+17	8.76E+18	2.48E+18	2.6E+17	5.84E+18	1.12E+17	6.33E+19	8.975E+19
8	9.08E+17	1.12E+19	6.2E+18	1.72E+17	6.54E+18	1.35E+18	1.79E+17	4.02E+18	7.74E+16	4.36E+19	6.545E+19
9	3.39E+17	4.19E+18	2.32E+18	8.61E+16	3.08E+18	6.72E+17	9E+16	2.02E+18	3.89E+16	2.19E+19	3.122E+19
09_bg_A	4.57E+15	5.65E+16	3.12E+16	7.11E+14	2.54E+16	5.55E+15	7.43E+14	1.67E+16	3.21E+14	1.81E+17	2.797E+17
09_bg_B Isola	1.35E+16	1.67E+17	9.24E+16	2.1E+15	7.52E+16	1.64E+16	2.2E+15	4.93E+16	9.49E+14	5.34E+17	8.267E+17
09_bg_B Predani	2.56E+16	3.17E+17	1.75E+17	3.42E+15	1.22E+17	2.67E+16	3.58E+15	8.02E+16	1.54E+15	8.7E+17	1.391E+18
09_bg_C	3E+16	3.71E+17	2.05E+17	7.32E+15	2.62E+17	5.71E+16	7.65E+15	1.72E+17	3.31E+15	1.86E+18	2.669E+18
10	3.82E+17	4.72E+18	2.61E+18	8.89E+16	4.43E+18	7.03E+17	9.42E+16	2.11E+18	4.07E+16	2.29E+19	3.421E+19
11	4.12E+17	5.1E+18	2.82E+18	1.14E+17	6.31E+18	9.93E+17	1.21E+17	2.71E+18	5.21E+16	2.93E+19	4.350E+19
12	4.09E+17	5.05E+18	2.79E+18	9.62E+16	6.28E+18	8.52E+17	1.01E+17	2.27E+18	4.4E+16	2.46E+19	3.823E+19
13	2.48E+17	3.07E+18	1.7E+18	8.09E+16	4.59E+18	7.23E+17	8.58E+16	1.92E+18	3.74E+16	2.09E+19	3.048E+19
14	2.63E+17	3.25E+18	1.8E+18	8.81E+16	5.04E+18	7.93E+17	9.41E+16	2.11E+18	4.11E+16	2.29E+19	3.333E+19
15	1.72E+17	2.12E+18	1.17E+18	5.05E+16	2.89E+18	4.55E+17	5.4E+16	1.21E+18	2.35E+16	1.31E+19	1.937E+19
16	1.9E+18	2.34E+19	1.29E+19	2.84E+17	1.29E+19	2.56E+18	3.03E+17	6.8E+18	1.32E+17	7.38E+19	1.170E+20
16_pf_C ovest	4.34E+16	5.36E+17	2.96E+17	3.8E+15	1.92E+17	3.42E+16	4.06E+15	9.11E+16	1.77E+15	9.88E+17	1.809E+18
17	3.55E+17	4.39E+18	2.43E+18	1E+17	5.07E+18	9.04E+17	1.07E+17	2.41E+18	4.68E+16	2.61E+19	3.801E+19
17_pf_A	1.26E+16	1.56E+17	8.63E+16	1.9E+15	9.62E+16	1.71E+16	2.03E+15	4.56E+16	8.87E+14	4.95E+17	7.935E+17

(continued on next page)

Tabella 8 (continued)

Biomarine units	Carbon (sej)	Nitrogen (sej)	Phosphorous (sej)	Sun (sej)	Rain (sej)	Wind (sej)	Currents (sej)	Geothermal heat (sej)	Tides (sej)	Run off (sej)	ENFL (sej)
17_pf_B	6E+16	7.41E+17	4.1E+17	1.24E+16	6.24E+17	1.11E+17	1.32E+16	2.96E+17	5.76E+15	3.21E+18	4.877E+18
18_pf_C est	1.83E+16	2.26E+17	1.25E+17	3.52E+15	1.69E+17	3.17E+16	3.77E+15	8.44E+16	1.64E+15	9.15E+17	1.396E+18
18	3.37E+17	4.17E+18	2.3E+18	1.03E+17	4.58E+18	9.27E+17	1.1E+17	2.47E+18	4.8E+16	2.67E+19	3.800E+19
19	5.34E+17	6.6E+18	3.65E+18	1.73E+17	7.6E+18	1.55E+18	1.84E+17	4.12E+18	8.01E+16	4.47E+19	6.307E+19
20	2.97E+17	3.67E+18	2.03E+18	7.57E+16	3.1E+18	6.77E+17	8.03E+16	1.8E+18	3.5E+16	1.95E+19	2.814E+19
21	7.62E+17	9.41E+18	5.2E+18	2.15E+17	8.09E+18	7.26E+17	2.28E+17	5.65E+18	1.53E+17	5.55E+19	7.886E+19
22	8.74E+15	1.08E+17	5.97E+16	2.86E+15	1.1E+17	7.59E+15	3.04E+15	7.85E+16	2.44E+15	7.38E+17	1.038E+18
22_ct_A Mesco	7.95E+16	9.83E+17	5.43E+17	1.21E+16	4.69E+17	3.22E+16	1.29E+16	3.33E+17	1.04E+16	3.13E+18	4.930E+18
22_ct_B Mesco	1.18E+17	1.46E+18	8.09E+17	1.48E+16	5.72E+17	3.93E+16	1.57E+16	4.07E+17	1.26E+16	3.82E+18	6.275E+18
22_ct_C	8.64E+16	1.07E+18	5.9E+17	2.6E+16	1E+18	6.9E+16	2.76E+16	7.14E+17	2.22E+16	6.71E+18	9.518E+18
23_ct_A	1.28E+16	1.59E+17	8.77E+16	2.11E+15	8.54E+16	7.12E+15	2.24E+15	5.8E+16	1.8E+15	5.45E+17	8.485E+17
Montenero											
23_ct_B	8.92E+16	1.1E+18	6.09E+17	1.5E+16	6.08E+17	5.07E+16	1.6E+16	4.13E+17	1.28E+16	3.88E+18	6.017E+18
Montenero											
23_ct_C	1.47E+18	1.82E+19	1.01E+19	3.07E+17	1.24E+19	6.46E+17	3.25E+17	8.42E+18	2.62E+17	7.91E+19	1.184E+20
24_ct_C	1.76E+17	2.17E+18	1.2E+18	4.2E+16	1.77E+18	1.41E+17	4.45E+16	1.15E+18	3.58E+16	1.08E+19	1.596E+19
24	3.33E+17	4.12E+18	2.28E+18	1.18E+17	4.97E+18	2.48E+17	1.25E+17	3.23E+18	1E+17	3.03E+19	4.276E+19
24_pv_C	3.29E+16	4.07E+17	2.25E+17	7.47E+15	3.05E+17	1.98E+16	7.93E+15	2.05E+17	6.38E+15	1.93E+18	2.852E+18
25_pv_C	1.72E+15	2.12E+16	1.17E+16	2.33E+14	9.5E+15	6.19E+14	2.47E+14	6.4E+15	1.99E+14	6.02E+16	9.746E+16
25	6.31E+17	7.8E+18	4.31E+18	2.22E+17	1.29E+19	5.89E+17	2.35E+17	6.09E+18	1.89E+17	5.72E+19	8.417E+19
26	1.99E+17	2.45E+18	1.36E+18	7.06E+16	4.65E+18	1.14E+17	7.5E+16	1.94E+18	6.03E+16	1.82E+19	2.734E+19

° MCAs, *MPAs.

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4.1 PAPER II

II

WHICH NATURAL OR ANTHROPOGENIC VARIABLES INFLUENCE NATURAL CAPITAL? AN ITALIAN CASE STUDY

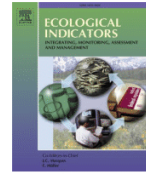
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Original Articles

Which natural or anthropogenic variables influence natural capital? An Italian case study

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ABSTRACT

Coastal marine ecosystems are among the most productive ecosystems worldwide, providing essential resources both for the environment itself and for human life. This is the case of the Ligurian Sea, rich in marine biodiversity that characterizes a valuable natural capital that has, however, been damaged by the development of human activities along the coast leading to a decline of this biodiversity and health status of coastal ecosystems.

This study analyzes the relationships between the distribution of natural capital and environmental flows values of Ligurian marine coastal habitats, and the natural and anthropogenic variables located along the coast. These variables may influence the capacity of the environment to generate and maintain the natural capital and affect, either directly or indirectly, positively or negatively, its spatial distribution together with that of the environmental flows. These relationships were analyzed using the Random Forest technique, subsequently compared with information from interviews administered to experts in the marine coastal field.

Both methods showed that the anthropogenic variables have a greater influence on values' distribution if compared with the natural ones, with a positive effect (namely the settlement of protection measures) showed as an increase in natural capital and environmental flows values, confirming how protection regimes (e.g., anchoring ban and establishment of Special Zones of Conservation) could be crucial for managing and conserving natural capital.

This study links the status of natural capital and environmental flows along the coast to the presence of a set of variables, in order to operate on them for a better monitoring and management of the area, as well as a sustainable development.

1. Introduction

The complex structure and functioning of the marine coastal ecosystems result from the convergence of chemical, physical and biological phenomena. Thanks to these mutual dependencies and their wide distribution, coastal marine ecosystems offer high environmental diversity (Martínez et al., 2007). This diversity represents the marine natural capital. The term capital refers to any stock (human or natural derived) that yields a flow of goods or services through time. Natural capital can be expressed as the stock of natural resources from which functions for

nature and ecosystem goods and services for humankind originate (Chiesura and De Groot, 2003). For instance, natural capital allows provision of food and water, storm protection and climate mitigation, that are fundamental to human health and well-being (Costanza et al., 2014; Duarte et al., 2013). Traditionally other types of capital have been identified: manufactured capital (that include factories, buildings, tools and all physical artifacts) and human capital (education, skills, culture, and knowledge preserved by human beings) (Ayres et al., 1996). The existence of manufactured and human capital is not assured in the absence of natural capital in good conditions as, for example, raw

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materials for industrial production or conditions for human survival may not be available. However, manufactured and human capital are necessary for humans to be able to enjoy ecosystem services because in the absence of machinery and expertise it is not possible to access resources. The value of services provided by coastal marine ecosystems reaches an estimated amount of \$74.5 trillion, equal to about 60 % of the total economic value of services provided by the biosphere (Costanza et al., 2014). Thus, natural and socio-economic processes are closely tied, especially in marine coastal zones (Coccosis, 2004; Daly and Farley, 2011; De Groot et al., 2002; Ietto, 2001, 2015; Judd and Lonsdale, 2021) also considering that areas where ecosystem services are flourishing become particularly suitable for the settlement of anthropogenic activities, endangering natural capital itself (Santana and Barroso, 2014) if not managed appropriately.

The over-exploitation and erosion of natural capital stocks over time lead to a serious decline in ecosystem services worldwide, with wide-ranging consequences in ecological, economic, and social spheres (De Groot et al., 2012). Human pressure has already altered 66 % of worldwide marine ecosystems and, at current rates of transformation, the biodiversity loss and the destruction of natural habitats could significantly deteriorate 90 % of ecosystems' status by 2050 (Natural Capital Committee, 2021). This deterioration, which may increase in the future (Nicholls et al., 2007), may result in the impaired ability of marine natural capital stocks to provide benefits to humans (Buonocore et al., 2021; Haines-Young and Potschin, 2010; Halpern et al., 2008; Pauna et al., 2019).

The EU Biodiversity Strategy 2030 (European Commission, 2020), following the guidelines of the EU Green Deal (COM/2019/640 final, Wolf et al., 2021), proposed stronger and more effective actions, at international and national levels, to compensate the loss of natural capital and to maintain its current value over time for future generations as part of sustainable resource management (Falcucci et al., 2007; Natural Capital Committee, 2021).

The area considered in this study is located in the Ligurian Sea (North-west of Italy), subjected to a wide range of natural and human pressures that may result in widespread regression for sensitive habitats (e.g. seagrass meadows, sponges and coral reefs) (Dapueto et al., 2020, 2022; Kühn et al., 2015; Montefalcone et al., 2007; Peirano et al., 2005; Richards and Beger, 2011; Rigo et al., 2021), water quality changes (Cancemi et al., 2003; Delgado et al., 1997, 1999; Dimech et al., 2000; Ruiz et al., 2001), mechanical erosion (Francour et al., 1999; García Charton et al., 1993; Martín et al., 1997; Milazzo et al., 2002, 2004; Sánchez Lizaso et al., 1990;) or seagrass burial (Fernández Torquemada and Sánchez Lizaso 2005; González Correa et al., 2008; Manzanera et al., 1998).

In the Liguria region, the biophysical assessment of natural capital stocks and environmental flows, together with the biophysical and economic valuations of ecosystem services, has already been carried out within two research programs: EAMPA (Environmental accounting in Italian Marine Protected Areas) project by the Italian Ministry of Ecological Transition from 2014 to 2019, and European Interreg Maritime GIREPAM (Integrated Management of Ecological Networks through Parks and Marine Areas) projects. Both projects lead to the development of an integrated environmental accounting framework in which natural capital and environmental flows are assessed through a biophysical approach (Vassallo et al., 2017). Natural capital is evaluated as all the resources required in space and time for its creation while environmental flows are intended as those fluxes of environmental resources required to maintain the natural capital itself on a yearly basis (Paoli et al., 2018). This approach has recently been applied to several MPAs (Buonocore et al., 2021; Franzese et al., 2017; Picone et al., 2017), including those located in Liguria (Paoli et al., 2018), to some coastal marine habitats exposed to natural and anthropogenic pressures (Dapueto et al., 2020, 2022; Rigo et al., 2020, 2021), and finally to the whole coastal zone of the region (Bordoni et al., 2023).

In this study, the values of natural capital and environmental flows of

Ligurian coast, calculated at regional level in Bordoni et al. (2023) were analyzed through a regression analysis (Random Forest), in order to identify both natural variables and human activities (here grouped under the label *forcing factors*) that influence and alter them. Thus, in this way it is possible to detect the system vulnerability in order to protect, recover, maintain, and manage the biological and ecological values belonging to the marine coastal zone. Additionally, the influence of *forcing factors* was also investigated by means of a subjective evaluation through questionnaires administration to experts in the coastal marine field of studies. This allowed the comparison between the results obtained through an objective evaluation (Random Forest) and a subjective one (questionnaires) in order to investigate how and if experts are able to assess the relevant drivers of natural capital in coastal areas.

2. Materials and methods

2.1. Study area

The study area is the marine coastal zone in front of the Ligurian region (North-west Mediterranean Sea, Italy) (Fig. 1). The Ligurian marine coastal habitats within 50 m depth consist mainly of algal and phanerogams meadows (such as *Posidonia oceanica* (L.) Delile, 1813 and *Cymodocea nodosa* (Ucria) Ascherson, 1980), within the first 20 m depth, and coralligenous cliffs below that isobath (Bianchi and Peirano, 1995). Due to the high species diversity, the Ligurian Sea represents a biodiversity hotspot, like most of the Mediterranean Sea, but it is also an anthropized area, with high population density and the interaction of productive activities, tourist attractions and urban centers (Cattaneo-Vietti et al., 2010) that may cause the decline of many habitats (Cancemi et al., 2003; Delgado et al., 1997, 1999; Dimech et al., 2000; Fernández Torquemada and Sánchez Lizaso 2005; Francour et al., 1999; García Charton et al., 1993; González Correa et al., 2008; Manzanera et al., 1998; Martín et al., 1997; Milazzo et al., 2002, 2004; Ruiz et al., 2001; Sánchez Lizaso et al., 1990). In particular, this is precisely what happened in the area of the Ligurian Sea, as reported by some studies (Betti et al., 2019, 2020; Bertolino et al., 2016; Longobardi et al., 2017). Since the early 1960s, most of the residential, industrial and tourist settlements, which represent the driving force for the Ligurian socio-economic activities, have been located in the coastal marine environment (Bianchi and Peirano, 1995), together with several other pressures such as shipping, fishing activities, and the input of marine litter derived from highly populated areas (Bo et al., 2014; Relini, 1972a, 1972b, 1989).

However, along the Ligurian coast (i.e., Portofino, Cinque Terre, Bergeggi Island, Capo Mortola and Portovenere) protected areas are present. This presence allows locally improvements in the ecological

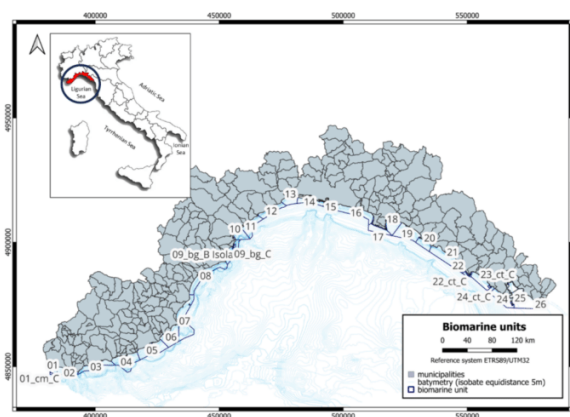


Fig. 1. Study area – Ligurian region, Italy.

status of habitats (Bordoni et al., 2023) due to protection as well as a management of environmental resources preventing over-exploitation thanks to restrictions of some anthropogenic activities (e.g., anchoring, fishing, diving and bathing) within these areas (Edgar et al., 2014; Kaplan, 2009; Mesnildrey et al., 2013) according to the national law 394/91 art. 19.

To achieve the research objectives, the study area was divided into 43 functional units (named here biomarine units) (Fig. 1) as previously proposed by Bordoni et al. (2023).

2.2. Previous data collection

All natural capital and environmental flow data used in this study to investigate their variations due to the presence of natural and anthropogenic forcing factors derives from literature (Bordoni et al., 2023) and reported in Appendix (Table A1).

Natural capital and environmental flow values were obtained through the energy analysis (Odum, 1983, 1996). This analysis is a thermodynamic methodology, introduced in the 1980s by H.T. Odum (Odum, 1983, 1996), that considers all energy resources and materials of different qualities that directly or indirectly support a process or product (Ulgiati and Brown, 2009). The natural capital and environmental flow values are expressed into solar energy joules (sej), because the method applied evaluates the solar energy used to generate or maintain the biomass of all organisms within the marine coastal habitats (Paoli et al., 2018). It identifies the value associated with the environmental cost required to generate natural capital stocks and maintain environmental flows within a system.

Thus, energy analysis is here applied to assess natural capital and environmental flows in each biomarine unit, to better define the differences found along the Ligurian coast, starting from data on benthic and fish biomass. Energy analysis was conducted, indeed, according to the procedure described by Vassallo et al. (2017) obtaining values of natural capital and environmental flow for each habitat and then grouped into each biomarine marine units. Results were considered in this study to evaluate natural capital and environmental flow variations due to the presence of natural and anthropogenic forcing factors.

2.3. Random Forest dependency analysis

Random Forest (RF) technique belongs to the so-called regression analyses: statistical tools for studying multifactorial data, whose aim is to find the optimal set of variables that best predicts a response (Breiman et al., 1984; Clark and Pregibon, 1992; Verbyla 1987). RF develops a model to predict the values of a dependent (or response) variable based on one or more independent (or explanatory) variables (Lewis-Beck, 1993) and then it evaluates the effectiveness of the model using statistical coefficients (Chatterjee and Hadi, 2006).

RF technique is a machine learning method that generates decision trees from a set of data (Hartshorn, 2016), producing accurate predictions without overestimating the data (Breiman, 2001; Hartshorn, 2016). It is based on the idea that systems can learn from data, identify patterns on their own and make decisions with minimal human intervention (Mitchell, 1997). The RF increases predictive performance by combining the outputs of a set of induced hypotheses into a single predictive model that aims to decrease variance, alter bias and improve predictions (Aria et al., 2021).

The RF approach combines several randomized decision trees, hence the name "forest", and aggregates their predictions by averaging them, showing excellent performance (Biau and Scornet, 2016). It also provides several metrics that help to interpret data. RF counts all votes from all decision trees that yield different results and takes the highest one as the solution or performs a weighting of all votes (Hartshorn, 2016). Furthermore, the decision about how many trees to get in the RF becomes a trade-off between the problem under analysis and the computational resources available, in that having more trees allows for

smoothing out anomalies in the data, but with each additional tree there are fewer benefits than the previous one (Hartshorn, 2016). For this reason, a sufficiently large number of trees of 1500 was chosen in this work. The analysis applied here used the R software (Liaw and Wiener, 2002). The natural capital and environmental flows in each biomarine unit obtained by Bordoni et al. (2023) (Appendix A) were considered as response variables and related to the intensity of a set of forcing factors (independent variables), in order to determine whether or not a mutual dependence may exist, which forcing factors are relevant and how the dependency is expressed.

2.3.1. Identification of forcing factors

The term forcing factor identifies a variable that can alter a natural system and, in turn, affect either positively or negatively the natural capital and the values of environmental flows. Information and data about the forcing factors (and their attributes) along the Ligurian coast, both on land and at sea, were collected as described in Table 1. A Geographic Information System was developed using QGIS software (version 3.10.9) for data extraction, processing and final representation of results using the geodetic reference system adopted at European level ETRS89 with UTM32 cartographic representation. The spatial data processing and the final maps were obtained by intersecting the forcing factors distribution with the biomarine units maps, in order to attribute an average intensity value for each factor to each biomarine unit.

2.3.2. Predictive scenarios of natural capital and environmental flow

Once the regression rules linking the natural capital and environmental flows to forcing factors have been identified, several scenarios were developed to simulate the effects of different combinations of forcing factors acting on the coastal zone (Table 2):

- Realistic situation: it considers natural and anthropogenic forcing factors that are present at this moment along the coast and for which data are available, in order to represent a situation that is as similar as possible to the real one;
- Zero anthropogenic impact: it considers only natural forcing factors, as to assume a situation where there is no human influence, in which further human impacts would still not affect the human impact in the same way as they have done so far;
- Negative anthropogenic impact: in addition to natural forcing factors, it includes the subset of human-generated factors supposed to have a negative impact on marine ecosystems basing on the expert opinion, such as tourism activities;
- Positive anthropogenic impact: in addition to natural forcing factors, it includes the subset of human-generated factors needed for the preservation and protection of both the terrestrial and coastal marine environment, thus potentially generating a positive impact basing on the expert opinion, such as protected areas.

Predicted values of natural capital and environmental flows for each scenario were calculated, allowing to define how much the forcing factors affect natural capital and environmental flows and providing an overall assessment of the biophysical consequences on a regional scale.

2.4. Subjective analysis

The data were collected through questionnaires to conduct an experts' opinion survey aimed at addressing the following issues: (1) investigating the perception of existing dependencies (positive or negative) between the attributes of forcing factors (Table 1) and natural capital values; (2) defining whether these attributes have low or high influence on the natural capital value itself (for this purpose, respondents were asked to score the forcing factor from 1, low influence, to 7, high influence); (3) comparing the results obtained through expert judgment with regression analysis, as already experienced in previous

Table 1

Procedures to collect data about natural and anthropogenic forcing factor. Data were gathered from Geoportale Regione Liguria (<https://geoportale.regione.liguria.it/>); Istituto Nazionale di Statistica (ISTAT) (<http://dati.istat.it>); Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) (<https://www.ispambiente.gov.it>) (accessed 10 August 2023).

Forcing factors	Attributes of forcing factors	Biomarine unit on which the forcing factor insists	Data collection source
Weather conditions	Solar radiation intensity Wind speed Rainfall	All units All units All units	Specific meteorological stations located in several municipalities of the Ligurian marine-coastal zone.
Sea conditions	Tidal excursions Wave motion Marine coastal currents Water temperature	All units All units All units All units	
Seabed type (type of substrates in which the habitats live)	Hard seabed Soft seabed Artificial seabed	All units	Raster image (converted from a raster to a vector file using QGIS), in which each pixel reports the average annual temperature of the marine coastal waters of Liguria Coastal habitats Atlas (Diviacco et al., 2020) with habitats classified in hard bottom (e.g., rock and anthropogenic structures), soft bottom (e.g., sand, mud) and artificial one. The surface of each seabed type per biomarine unit was calculated by adding up the surfaces of habitats belonging to each category within each unit. Finally, these values were reported as the percentage of area occupied by each type in relation to the total area of each unit.
Coastline type (type of sediment that characterized the beach along the coast)	Sandy coastline Rocky coastline Gravelly coastline	All units	Coastline was divided into different type according to attributes, obtaining the percentage of them per biomarine unit.
Slopes exposure	Slopes exposure	All units	Raster image from the Digital Terrestrial Model (DTM) of Liguria, from which the exposure values concerning only the coast were obtained.
Geographical coordinates	Latitude, longitude	All units	Using QGIS, the centroid for each biomarine unit were obtained.
Hydromorphological events	Landslide surfaces	All except the units 10, 14, 15, 17, 09_bg_A, 09_bg_Isola, 09_bg_Predani, 09_bg_C, 17_pf_A, 17_pf_B, 18_PF_C east, 22_ct_A Mesco, 24_ct_C	Only the landslides affecting the coastline were considered. Subsequently, each landslide area was assigned to the corresponding biomarine unit considering the coastline segment that the landslide overhangs unit.
Accommodation facilities	Hotels/hostels/inns Bed&breakfast Campsites/villages Hiking refuges	All except the units 22, 09_bg_A, 09_bg_B Isola, 09_bg_B Predani, 09_bg_C, 17_pf_A, 22_ct_A Mesco, 22_ct_B Mesco, 22_ct_B Montenero, 24_pv_C	Data referring exclusively to coastal municipalities, since the action exerted by this forcing factor is assumed to be potentially more relevant on the marine coastal area.
Beaches	Bathing beaches	All except the units 22, 17_pf_A, 17_pf_B, 22_ct_A Mesco, 22_ct_B Mesco, 22_ct_A Montenero, 22_ct_B Montenero, 24_pv_C	The coordinates of the Ligurian bathing beaches were obtained through the analysis of the Ligurian Water Protection Plan and the list of bathing waters whose monitoring is updated by ARPAL (Regional Agency for Environment Protection of Liguria Region).
Scuba diving activity	Diving activity on cave Diving activity above reefs Diving activity on wrecks	All except the units 1, 2, 3, 6, 11, 12, 13, 22, 26, 09_bg_Predani, 17_pf_A, 22_ct_C, 23_ct_A Montenero, 25_pv_C	Coordinates of the diving sites recorded in the Ligurian marine coastal area by divers in the diving logbook and those investigated in the framework of the European Interreg Maritime projects GIREPAM (Integrated Management of Ecological Networks through Parks and Marine Areas) and NEPTUNE (Underwater Natural and Cultural Heritage and Sustainable Management of Recreational Diving).
Infrastructure	Coastal railways	All except the units 4, 17, 20, 22, 24, 26, 09_bg_B Predani, 09_bg_C, 16_pf_C west, 17_pf_A, 17_pf_B, 18_pf_C east, 22_ct_A Mesco, 22_ct_B Mesco, 22_ct_C, 24_pv_C	Total length of railway lines of the Ligurian coastal municipalities located less than 500 m from the coast.
Fish farms	Fish farming Mariculture farming Mussel farming Artificial reefs for fish restocking	Units 1, 3, 6, 7, 8, 9, 15, 16, 19	Location and area occupied by different types of sea farms from local databases.
Sea defence	Sea defences made by sacks, by concrete, by mixed materials, by stones including submerged and emerged sea defences	All except the units 17, 22, 24, 09_bg_A, 09_bg_B Isola, 09_bg_B Predani, 09_bg_C, 17_pf_A, 17_pf_B, 22_ct_A Mesco, 23_ct_A Montenero, 23_ct_B Montenero	Types of structures considered for the sea defences were grouped into categories based on the type of material used for their construction or the site they are located.
Measure to prevent coastal erosion	Beach nourishment	All except the units 1, 14, 20, 22, 24, 25, 01_cm_C, 09_bg_B Predani, 16_pf_C west, 17_pf_A, 17_pf_B, 22_ct_A Mesco, 22_ct_B Mesco, 22_ct_C, 23_ct_A Montenero, 23_ct_B Montenero, 24_ct_C, 24_pv_C, 25_pv_C	Information regarding the sites where beach nourishment was carried out in the years between 2003 and 2007 from regional databases.
Discharges and pipelines	Discharges and pipelines to sea	All except the units 1, 4, 17, 22, 24, 01_cm_C, 09_bg_A, 09_bg_B Isola, 09_bg_B Predani, 09_bg_C, 16_pf_C west, 17_pf_A, 17_pf_B, 22_ct_A Mesco, 22_ct_B Mesco,	1) discharges from coastal municipalities located near rivers and streams that flow into the sea (generally industrial discharges) and 2) discharge pipelines to the sea.

(continued on next page)

Table 1 (continued)

Forcing factors	Attributes of forcing factors	Biomarine unit on which the forcing factor insists	Data collection source
Population density of coastal municipalities	Population density of coastal municipalities	22_ct_C, 23_ct_A Montenero, 23_ct_B Montenero, 24_ct_C, 24_pv_C, 25_pv_C All units	Number of inhabitants in Ligurian coastal municipalities for each biomarine unit: the population density was calculated by summing the inhabitants' numerical values of all coastal municipalities bordering each unit according to the share of coastline of the municipality included in the unit.
Urban land use	Urban, industrial and artisanal areas	All units	The percentage values of urban land use were obtained by considering the coastal municipalities bordering the coastal stretches of the different biomarine units.
SZCs (Special Zones of Conservation)	Marine and terrestrial SZCs	All units	SCIs (Sites of Community Importance) indicate the perimeter of areas characterized by the presence of particular habitats or species (both animal and plant) that need protection. They were created in 1997 by the Region of Liguria in fulfilment of the obligations laid down in the EU Habitat Directive (Presidential Decree no. 357 of 1997). SCIs represent areas particularly suitable for the conservation or restoration of habitat, which are subjected to special rules to maintain biodiversity of flora and fauna according to Council Directive 92/43/EEC. Information on the location and extent of both marine and terrestrial SCIs was obtained. For terrestrial areas, only those located within coastal municipalities were considered. Each SCI was assigned to the biomarine unit to which it belongs based on its location and a percentage value of the protected area proportion on the coastline was calculated. In the case of marine SZCs, their surface areas were divided among the biomarine units to which they belonged and the total surface area for each unit was calculated. These values were then compared to the surface area of the biomarine units in order to obtain the percentage value of the surface area occupied by the SZCs.
Bans	Fishing and anchoring bans	All except units 21, 22, 26, 23_ct_C, 24_ct_C, 25_pv_C	Location of fishing and anchoring bans and their surface areas were obtained and reported in QGIS. Each area was assigned to the biomarine unit within which the ban exists and the total surface area occupied by the ban in each unit was calculated. Obtained data were compared to the surface of the biomarine units in order to obtain the percentage values of bans.

studies (Petrossillo et al., 2010; Rongen et al., 2022).

The questionnaire was first tested by a small group of experts in order to make it understandable and useful for obtaining the results needed for the study. Few changes were therefore made in the questionnaire structure and the way in which the various *forcing factors* were presented, so that the questionnaire was administered to a wider audience of experts of the field in order to carry out the research. The selection of suitable experts is essential for the reliability of subjective analyses (Okoli and Pawlowski, 2004). Experts in the coastal marine field, with a focus on academics, MPA managers and employees, and decision-makers were selected for this study. If the experts cover similar areas and represent a homogeneous sample, as in this study, a group of 10–15 people is representative (Delbecq et al., 1975; Skulmoski et al., 2007). The attributes presented to experts, which were also employed in the regression analysis, are reported in Table 1. The intensity of the effect of the forcings reported by the experts was derived for each biomarine unit through the mean values of the scores given by the experts to each *forcing factors* and the presence of the same in the unit, respecting the subdivision of the forcings in the four scenarios described in Section 2.3.2 in order to assess how much the presence of natural and anthropic forcings can vary the state of the natural capital.

3. Results

3.1. Random Forest dependency analysis

The variance expressed by the RF regression (model accuracy) was 59.49 % for the natural capital values and 66.53 % for the environmental flows values. Each *forcing factor* was considered significant in driving the distribution of natural capital and environmental flows if its removal from the model resulted in an increased percentage of square error greater than 10 %. Anchoring ban, hard seabed and marine SZCs drove natural capital distribution while, similarly, anchoring ban, hard seabed but also artificial coastline and accommodation facilities drove environmental flows.

The ranges of optimal values expected to increase natural capital and environmental flows for each predictive variable were analyzed through the univariate partial dependence plots (Fig. 2 and Fig. 3). Natural capital values increased at growing values of anchoring ban and marine SZCs coverage, up to a maximum when the biomarine units' surfaces were covered for the 60 % by anchoring ban and the 35 % by marine SZC. Furthermore, the natural capital values increased when the seabed was mainly characterized by hard substrate and decreased with the presence of artificial coastline.

Also, the environmental flows values increased on the hard seabed and when biomarine units' surfaces were covered by about 60 %

anchoring ban. Instead, the more artificialization of the coast and the presence of accommodation facilities increased the more natural capital decreased.

The mean biophysical value of natural capital and environmental flows the biomarine units at extensive level (and then considering biomarine units' surface) are shown, for each scenario, in Table 3 and these results report:

- a similarity, for both natural capital and environmental flows, between predicted values of the realistic situation scenario and those calculated in Bordini et al. (2023); predicted values of natural capital differ from those by Bordini et al. (2023) by only $7.97E+17$ sej, equal to a +1.69 %, while environmental flows by only $3.09E+17$ sej, equal to +0.97 %;
- an increase of both natural capital (+46.81 % corresponding to an increase of $2.21E+19$ sej) and environmental flows (+100.00 % corresponding to an increase of $6.38E+19$ sej) values in zero anthropogenic impact scenario;
- a decrease in natural capital values (−12.14 % corresponding to a decrease of $5.72E+18$ sej) and an increase in environmental flows values (+2.07 % corresponding to an increase of $6.60E+17$ sej) in negative anthropogenic impact scenario;
- an increase for both natural capital (+56.69 % corresponding to an increase of $2.67E+19$ sej) and environmental flows (+98.89 % corresponding to an increase of $3.15E+19$ sej) values in positive anthropogenic impact scenario.

In addition, the percent contribution of *forcing factors* on natural capital and environmental flow variations compared to the total of all positive or negative *forcing factors* in the three scenarios was reported in Table 4. This shows urban land use as the *forcing factor* that has the most negative influence on the natural capital (−44.35 %) and environmental flows (−45.35 %), followed by coastal defences (−17.56 %) and SZCs the major positive influence on natural capital (+78.24 %) and bans on environmental flows values (+50.70 %).

3.2. Subjective analysis

Questionnaires were administered to 25 people. Most of the sample (around the 80 %) was filled by university staff with expertise in the marine coastal field, 60 % of which were PhD students, postdoctoral and research fellows, the 16 % were professors and the 4 % were technical administrative staff. In particular, the university staff is composed by personnel working on this specific field for at least ten years. In addition, the remaining 16 % of the sample was equally represented by employees at MPAs, association consultants in cooperation with the university, secondary school teachers, and retired teachers.

3.2.1. Comparison between subjective and objective methodologies

The average scores ascribed by experts to *forcing factors* listed in Table 2 are reported in Fig. 4, together with the importance score assigned by RF. Results from both subjective and objective analyses have been standardized on a scale from 0 (not important) to 7 (highly important) for the sake of clarity.

Despite some of the most important variables pointed out by respondents were in agreement with RF results (e.g., anchoring ban and seabed type) in several cases questionnaires revealed that experts' perceptions differed for some variables by reporting low or no effects on natural capital in contrast to objective analysis. Among others, discharge and pipelines to sea, coastline type, landslide areas and coastal railways were selected as important variables but did not reveal any significant effect on natural capital trend through objective analysis. The Spearman correlation performed between the total scores assigned by experts to *forcing factors* and results obtained by RF did not report significance ($\rho = 0.14$, $n = 26$, $p < 0.5$).

4. Discussion

The implementation of a regression analysis that links values of natural capital and environmental flows to several *forcing factors* opened the way for the development of several scenarios. The proposed scenarios allowed the assessment of the consequences of human activities on natural capital and environmental flows. Since results reported a similarity between predicted natural capital and environmental flows values of the realistic situation scenario and values calculated in Bordini et al. (2023), the scenario that represents the current situation could be taken as the baseline to compare other three scenarios results. Comparing the current situation of the coastal zone with a hypothetical condition that only considers natural *forcing factors* (thus assuming no human influence), indeed, revealed increased values of natural capital and environmental flows (Table 3). On the contrary, if negative anthropogenic *forcing factors* were introduced into the system, in addition to the natural ones, the positive effect of natural factors was counteracted, causing a total natural capital drop by about 40 % (± 36 %) across all biomarine units. The establishment of anthropogenic *forcing factors* with a negative effect is what happened along the Ligurian coast, where urban expansion began in the 1850s through the construction of the main roads and railways (Burgos et al., 2017), but also through the construction of many tourist infrastructures that caused serious changes of the coastline during the XX century (Ferrari et al., 2005). The strong proliferation of urban and industrial structures along coastal regions inevitably impacted and destroyed natural habitats (Bianchi and Morri, 2000; Buonocore et al., 2021; Coll et al., 2010; Montefalcone et al., 2010; UNEP/MAP RAC/SPA, 2010), resulting in a change in the amount of natural capital stored by the habitats themselves. The Ligurian Sea hosts several pressures which may threaten the conservation status of marine coastal habitats, as for instance shipping, fishing, marine litter derived from densely populated areas (Bo et al., 2014; Relini, 1972a, 1972b, 1989) and commercial maritime traffic (Cattaneo-Vietti et al., 2010). In this regard, indeed, the percent contribution of natural capital and environmental flow values obtained considering each positive or negative *forcing factors* compared to the total of the all positive or negative *forcing factors* in the three scenarios was investigated (Table 4): the most negative impact on the natural capital (−44.35 %) and environmental flows (−45.35 %) values was due to the urban land use. The Ligurian region is strongly urbanized along the coast because of the orographic limits as it lies between the sea and the Alps (Romano et al., 2017). This strong and massive urban expansion led to a complete anthropization of lowlands and green areas and to the covering of watercourses that in association with a greater incidence of short and intense rainfall events, has resulted in an increased vulnerability of the Ligurian area to hydrogeological risk (Disse and Engel, 2001; Faccini et al., 2015; Luino et al., 2012, 2014). Beside urban land use, presence of coastal defenses implied natural capital value decrease of 17.56 % while accommodation facilities and artificialization of the coast returned into a decrease of environmental flows values of respectively 21.02 % and 12.97 %.

Therefore, negative anthropogenic impact scenario showed what can be expected to happen to natural capital and environmental flows values in the presence of these types of pressures and could suggest to policy makers some potential measures to prevent and control negative outcomes, for instance by limiting further expansion of the urban land use and reducing or monitoring the settlement of additional coastal defenses.

However, the Liguria government adopted measures to protect and conserve marine habitats through the establishment of SZCs since 2005 (National Decree 25/3/2005) and the increasing imposition of anchoring and fishing bans on valuable habitats worthy of safeguard.

Thus, humans do not only act negatively on the marine coastal zone: they also take conservation and protection measures that provide benefits to a wide variety of species, maintain the ecosystem itself as well as the services it generates for human wellbeing (Gerber et al., 2003;

Table 2
Forcing factors divided into the four predictive scenarios.

Forcing factor		Scenarios			
Type	Name	Realistic situation	Zero anthropogenic impact	Negative anthropogenic impact	Positive anthropogenic impact
Natural	Solar radiation intensity	X	X	X	X
	Wind speed	X	X	X	X
	Rainfall	X	X	X	X
	Tidal excursion	X	X	X	X
	Wave motion	X	X	X	X
	Marine coastal currents	X	X	X	X
	Water temperature	X	X	X	X
	Seabed type (hard and soft)	X	X	X	X
	Coastline type (sandy, rocky and gravelly)	X	X	X	X
	Slope exposure	X	X	X	X
	Latitude Longitude	X	X	X	X
	Landslide areas	X	X	X	X
	Human generated negative	Artificial coast	X		X
Accommodation facilities (hotel, bed&breakfast, etc.)		X		X	
Bathing beaches		X		X	
Beach nourishment		X		X	
Diving activity		X		X	
Coastal railway		X		X	
Fish farms		X		X	
Sea defences		X		X	
Urban and use		X		X	
Discharges and pipelines to sea		X		X	
Population density of coastal municipalities		X		X	
Human generated positive	Marine and terrestrial SZC	X			X
	Fishing ban	X			X
	Anchoring ban	X			X

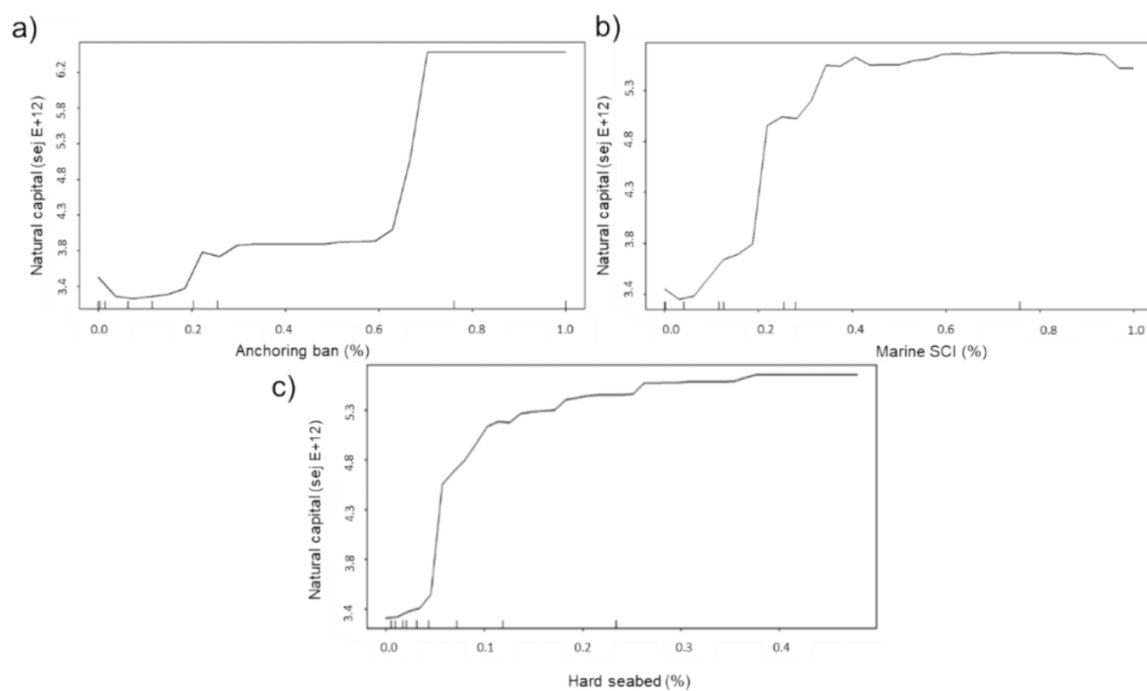


Fig. 2. Partial dependence plots for the main driving forcing factors on natural capital values: (a) anchoring ban, (b) marine SZC, (c) hard seabed.

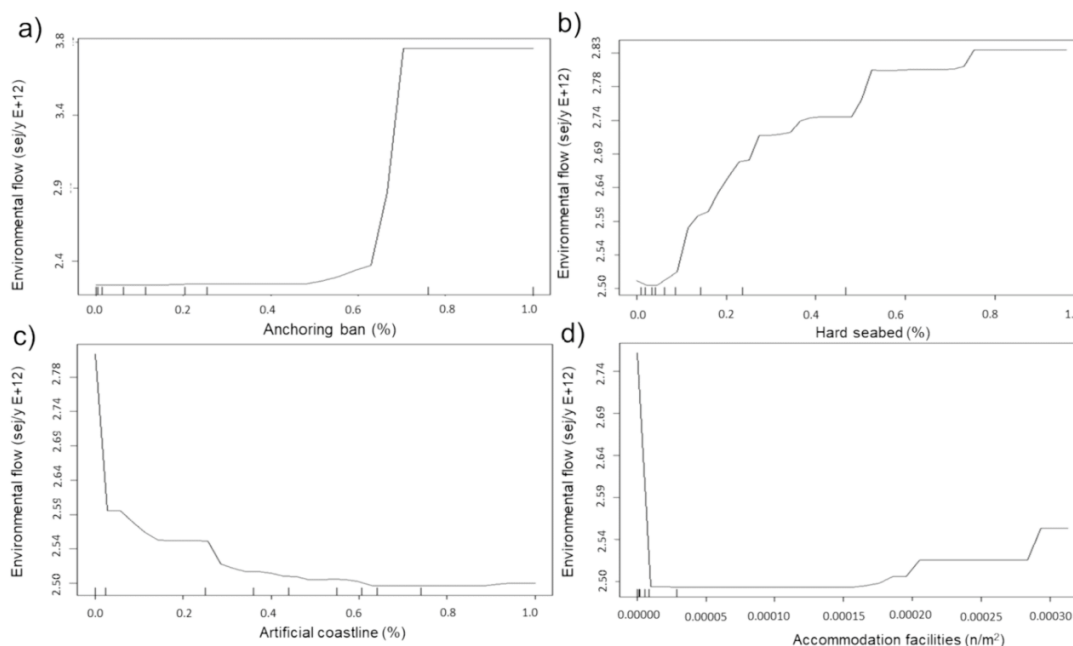


Fig. 3. Partial dependence plots for the main driving forcing factors on environmental flows values: (a) anchoring ban, (b) hard seabed, (c) artificial coastline, (d) accommodation facilities.

Table 3

Natural capital and environmental flows values in extensive terms in the four scenarios. Percentage variations between the calculated values of natural capital and environmental flows and those predicted in the four scenarios is reported in brackets.

	Calculated values (Bordoni et al., 2023)	Scenarios			
		Realistic situation	Zero anthropogenic Impact	Negative anthropogenic impact	Positive anthropogenic impact
Natural capital (sej)	4.71E+19	4.79E+19	6.92E+19	4.14E+19	7.39E+19
Percentage variation (%)		1.69 %	46.81 %	-12.14 %	56.69 %
Quantification of variation (sej)		7.97E+17	2.21E+19	-5.72E+18	2.67E+19
Environmental flows (sej y ⁻¹)	3.19E+19	3.22E+19	6.38E+19	3.26E+19	6.34E+19
Percentage variation (%)		0.97 %	100.00 %	2.07 %	98.89 %
Quantification of variation (sej y ⁻¹)		3.09E+17	3.19E+19	6.60E+17	3.15E+19

Roberts et al., 2006; Dryden et al., 2008; Lynch et al., 2013). In fact, when anthropogenic forcing factors with a positive effect (i.e., anchoring ban and marine SZCs) are put in place, they have a great influence, as shown by model results, which reported a natural capital value increase of 57 % and a growth of 99 % in environmental flows value compared with the Bordoni et al. (2023) values (Table 3). Particularly, the model showed more influence (+78.24 %) of SZCs in the conservation of natural capital and even greater contribution due to both SZCs (+49.30 %) and bans (+50.70 %) on environmental flows values (Table 4). Implementing measures to protect habitats (e.g., *Posidonia oceanica* meadows, coralligenous) through anchoring and fishing bans, in fact, allows for the maintenance of environmental flows annually needed for the storage of natural capital. Thus, the combination of both preservation of bans and conservation of SZCs measures, ensures the natural capital and environmental flows are better safeguarded.

In conclusion, the model predictions for the scenarios provided a useful tool to analyze the influence of natural and anthropogenic forcing factors. The proposed approach could be developed further by incorporating a larger number of forcing factors and more detailed information about their attributes. Furthermore, this model could be further developed for the creation of future scenarios, by analyzing how changes

Table 4

Percent contribution of forcing factors with positive and negative effects on anthropogenic scenarios.

	Influence of forcing factors	
	Natural capital	Environmental flows
Positive anthropogenic impact scenario		
Bans (anchoring, fishing)	21.76 %	50.70 %
ZSCs (marine and terrestrial)	78.24 %	49.30 %
	100.00 %	100.00 %
Negative anthropogenic impact scenario		
Urban land use	-44.35 %	-45.35 %
Artificial coast	-7.62 %	-12.97 %
Diving activity	-8.57 %	-0.01 %
Sea defences	-17.56 %	-7.55 %
Population density of coastal municipalities	-4.79 %	-6.59 %
Bathing beaches	-5.67 %	-4.78 %
Accommodation facilities (hotel, bnb, etc.)	-8.32 %	-21.02 %
Others (discharges and pipelines to sea, fish farms, etc.)	-3.13 %	-1.72 %
	-100.00 %	-100.00 %

in environmental parameters and anthropogenic forcing factors that act on the marine coastal zone could lead to changes in natural capital and environmental flows within the system over time.

4.1. Analysis of the results obtained for comparison between subjective and objective methodologies

The greater influence of anthropogenic forcing factors with positive effect was also highlighted through the administration of questionnaires. In particular, the anchoring and fishing bans and the presence of terrestrial and marine SZCs obtained scores higher than 70 % if compared with the average of all the scores assigned by experts to the other attributes.

Although both the objective and the subjective methods applied agreed on the protection measures benefits, the Spearman correlation did not report any relevant correspondence. This confirmed that human perception about the environment derives not only from human knowledge but also by the combination of various components associated with personal attitudes and the subjective evaluation of present and past events (Bechtel and Jayaram, 1997). Moreover, humans try to adjust their behavior in response to the changes of ecosystems they perceive (Scheffer et al., 2001): as a consequence, people tend to engage in riskier behaviors when a more secure environment is perceived (risk homeostasis) (Petrosillo et al., 2010). Thus, where natural capital needs to be preserved through conservation measures, given for instance its great value or its ability to provide services, the presence of anthropogenic forcings factors, with their possible negative effects, was felt more dangerous than they actually are. Since there were no clear reference systems for assessing the risk of forcing factors in natural capital changes, the experts, once aware of the risk itself, tended to give more conservative answers than the results obtained from the mathematical model. Furthermore, despite the questionnaire was previously tested by a small group of experts so that it could also be made understandable in its structure by e-mail, due to the COVID-19 pandemic restrictions, it reported different perceptions of questions by each expert. Explaining the questionnaire via e-mail also created uncertainty for the experts, who had to answer the questions without the provision of all the necessary information when compared to face-to-face interactions. This

uncertainty emerged also in a previous study (Rongen et al., 2022), involving difficulties in analyzing the answers. Due to the complexity of the questionnaire and communication with experts, this study showed the importance of adding the subjective analysis (questionnaires) only after the quantitative analysis (Random Forest). First, it is necessary to quantitatively estimate the change in the values of natural capital and environmental flows due to the presence of forcing factors. Random forest regression, indeed, allowed to calculate natural capital and environmental flow values due to the presence of different forcing factors. Instead, questionnaire was useful to score the influence of variables on natural capital without actually calculating a changed value due to forcing factors. Therefore, using questionnaires after objective research using mathematical models can be useful to reinforce the results obtained and to be able to confirm whether what is reported by the random forest is commonly acknowledged by experts in the field. This type of approach is indispensable to follow a rational decision-making process characterized by satisfactory quality of environmental information and knowledge.

5. Conclusion

The model developed in this study identifies which forcing factors most influence the value of natural capital and environmental flows in coastal areas, and how by hypothesizing what would happen in the presence of some of them rather than others.

The integration with spatial analysis using a cartographic support, provided information about where natural capital stocks and environmental flows undergo changes as a function of natural or anthropogenic factors. Spatial analysis then allowed, for instance, the identification of areas that most need management or protection measures, thus representing a decision support system to address effective interventions.

The study could be further refined by analyzing a larger number of forcing factors to make the model closer to reality in order to provide more detailed information to both the experts and mathematical models. In conclusion, this study represents a solid basis for the assessment of the marine coastal habitats' situation at regional scale with the potential for future developments and improvements. The refinement of the procedure, as well as its extension to a national or Mediterranean scale,

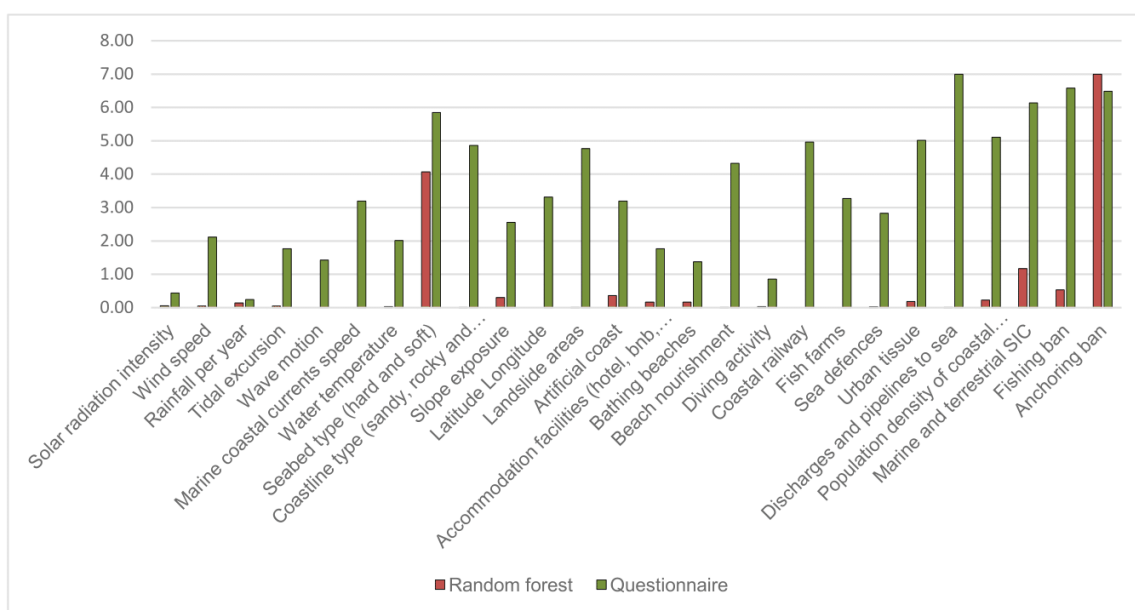


Fig. 4. Comparison of importance scores ascribed by random forest and experts to forcing factors.

could contribute to the identification of areas or regions in Italy that need safeguarding and protection actions for the natural capital of marine coastal habitats. Based on the ecological values identified for each area using scenarios, priority levels for the interventions can be established, in order to define which and how many actions should be undertaken in the area. Furthermore, in a future perspective, this assessment can not only be spatially consolidated but also temporally, to monitor possible changes in natural capital and environmental flows within the system as a function of interaction with external *forcing factors*. This information can become a support tool for local managers in the development of effective sustainable management strategies and implementation of decisions at the regional level that ensure both the protection of nature and human activities.

CRedit authorship contribution statement

Iaria Rigo: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rachele Bordoni:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Conceptualization. **Federico Betti:** Writing – review & editing, Methodology. **Giulia Dapuzo:** Writing – review & editing, Supervision, Formal analysis. **Francesco Massa:** Writing – review & editing, Supervision, Formal analysis. **Chiara Paoli:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Paolo Povero:** Writing – review & editing, Supervision, Formal analysis. **Francesca Ruggeri:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Paolo Vassallo:** Writing – review & editing, Supervision, Formal analysis.

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

All data were sourced from the following sources.
 Solar radiation: <http://www.solaritaly.enea.it/TabelleRad/TabelleRadIt.php>;
 Meteorological data: <https://www.ilmeteo.it/portale/archivio-meteo/Liguria>, <http://servizi-meteo Liguria.arpal.gov.it/boacapomele.html>, https://cmr.earthdata.nasa.gov/search/concepts/C1615905770-OB_DAAC;
 Cartographic data: <https://geoportal.regione.liguria.it/catalogo/mappe.html>, <https://webapp.navionics.com/?lang=#boating@7&key=myflGc~ox%40>, www.arpal.liguria.it/homepage/acqua/acquamarino-costiere/balneazione.html, <https://www.logbookimmersioni.it/guida-punti-immersione/>;
 Population density: https://esploradati.istat.it/databrowser/#/it/dw/categories/IT1,POP,1.0/POP_POPULATION/DCIS_POPRES1/IT1,22_289_DF_DCIS_POPRES1_1,1.0.
 The source natural capital and environmental flows data derived from [Bordoni et al. \(2023\)](#).

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Appendix A

Table A1
 Natural capital and environmental flow values predicted by the model in the four scenarios and compared with that obtained by [Bordoni et al. \(2023\)](#).

Biomarine units	Natural capital (1E+11sej m ⁻²)					Environmental flows (1E+11sej m ⁻² y ⁻¹)				
	Calculated (Bordoni et al., 2022)	Scenario 1 (realistic situation)	Scenario 2 (zero anthropogenic impact)	Scenario 3 (negative anthropogenic impact)	Scenario 4 (positive anthropogenic impact)	Calculated in Bordoni et al. (2022)	Scenario 1 (realistic situation)	Scenario 2 (zero anthropogenic impact)	Scenario 3 (negative anthropogenic impact)	Scenario 4 (positive anthropogenic impact)
01	30.43	32.71	37.46	26.95	42.00	13.67	15.96	32.98	15.96	33.02
01_cm_C	54.82	51.42	57.96	44.35	61.76	17.83	18.49	36.54	18.44	36.56
02	18.34	22.38	36.26	22.39	36.73	13.54	15.44	33.17	15.95	32.88
03	57.89	49.26	37.27	35.27	48.66	15.18	15.77	32.87	15.44	33.25
04	33.98	32.52	37.45	25.33	43.15	15.81	15.48	33.53	15.72	33.27
05	38.40	35.11	37.84	25.86	43.28	15.12	15.04	33.05	15.19	33.13
06	26.50	30.20	36.28	23.04	40.79	13.66	14.38	33.05	14.70	33.15
07	16.42	20.07	34.98	19.98	35.01	13.60	14.43	33.15	14.94	32.66
08	31.01	28.00	35.09	23.00	37.99	14.80	14.96	33.17	15.19	32.71
09	19.78	22.86	36.31	20.27	38.70	15.36	15.72	33.41	15.96	33.04
09_bg_A	125.86	105.14	69.84	75.92	97.15	81.42	66.80	43.04	46.98	61.80
09_bg_B Isola	74.30	78.30	53.71	58.14	74.92	47.32	52.42	35.97	38.98	49.97
09_bg_B Predani	120.19	97.19	69.55	69.02	93.43	57.49	49.82	40.00	35.50	53.68
09_bg_C	21.12	31.26	35.28	28.32	38.58	15.70	23.00	32.99	23.30	32.88
10	26.50	25.58	34.57	21.23	39.92	17.18	17.16	32.62	16.99	32.56
11	16.13	17.99	33.93	16.24	36.62	14.37	15.21	32.73	15.55	32.52
12	22.75	22.64	34.52	18.86	36.62	15.07	15.23	32.65	15.47	32.19
13	11.23	13.93	32.74	14.70	32.26	15.40	15.57	32.39	15.87	31.90
14	10.37	14.05	32.89	14.48	33.07	16.74	16.96	32.55	17.25	32.06
15	15.17	17.95	33.52	16.60	35.35	17.58	16.96	32.76	17.22	32.27
16	68.54	55.56	59.62	44.99	65.99	27.08	23.40	37.32	23.56	37.30

(continued on next page)

Table A1 (continued)

Biomarine units	Natural capital (1E+11sej m ⁻²)					Environmental flows (1E+11sej m ⁻² y ⁻¹)				
	Calculated (Bordoni et al., 2022)	Scenario 1 (realistic situation)	Scenario 2 (zero anthropogenic impact)	Scenario 3 (negative anthropogenic impact)	Scenario 4 (positive anthropogenic impact)	Calculated in Bordoni et al. (2022)	Scenario 1 (realistic situation)	Scenario 2 (zero anthropogenic impact)	Scenario 3 (negative anthropogenic impact)	Scenario 4 (positive anthropogenic impact)
16_pf_C west	67.49	58.76	62.04	52.02	66.83	18.47	21.94	38.26	22.02	38.19
17	18.24	21.89	33.03	20.87	33.66	19.97	22.25	32.70	22.53	32.41
17_pf_A	73.25	73.87	62.47	48.60	86.09	48.94	47.92	39.95	31.82	55.13
17_pf_B	39.17	52.68	61.95	39.44	79.55	29.99	36.28	39.07	27.76	51.48
18_pf_C east	22.94	34.64	61.76	35.10	60.75	16.28	20.28	38.09	20.73	37.39
18	11.33	14.43	32.89	14.45	32.68	13.50	14.88	32.60	15.34	32.11
19	10.27	13.43	32.50	14.15	32.04	13.57	14.02	32.61	14.54	32.17
20	21.50	30.74	51.61	29.88	51.51	16.92	17.80	35.73	18.12	35.24
21	15.46	17.07	32.51	17.13	32.39	15.05	16.17	33.54	16.44	33.06
22	11.33	27.90	36.72	28.28	36.36	14.31	23.94	33.86	24.31	33.52
22_ct_A	97.34	96.33	65.62	64.54	94.63	68.48	60.35	41.51	41.55	59.82
Mesco										
22_ct_B	126.05	102.16	64.57	66.10	94.86	55.83	49.26	39.28	32.29	55.22
Mesco										
22_ct_C	13.25	20.40	31.10	20.45	30.87	21.38	23.54	33.43	23.74	33.19
23_ct_A	99.65	93.38	65.88	63.49	94.40	63.35	59.27	42.35	40.66	60.84
Montenero										
23_ct_B	72.67	74.63	50.13	51.86	72.95	65.59	56.67	38.29	40.43	54.12
Montenero										
23_ct_C	35.23	28.08	32.63	22.38	36.04	33.32	26.17	34.90	26.36	34.45
24_ct_C	25.25	25.66	33.27	26.00	32.94	27.93	27.82	35.40	28.11	35.01
24	7.87	13.20	31.05	13.90	30.59	13.54	16.85	33.99	17.38	33.61
24_pv_C	30.43	45.66	60.60	45.43	60.77	22.24	28.42	39.44	28.99	38.79
25_pv_C	69.31	56.45	52.81	56.62	52.59	20.33	22.37	36.79	22.68	36.50
25	8.64	11.51	31.40	12.32	30.84	15.05	15.40	33.29	15.71	32.80
26	8.06	14.70	32.11	15.49	31.62	15.54	18.07	33.97	18.30	33.52

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4.2 PAPER III

III

**HABITAT SUITABILITY MODELING FOR *POSIDONIA OCEANICA*
DISTRIBUTION ALONG A MEDITERRANEAN REGION (NW ITALY)**

by

Bordoni R., Paoli C., Montefalcone M., Oprandi A., Rigo I., Ruggeri F., Vassallo P.

Habitat suitability modeling for *Posidonia oceanica* distribution along a Mediterranean region (NW Italy)

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ABSTRACT

Posidonia oceanica (L.) Delile, a keystone seagrass species, plays a central role in the ecological balance of coastal areas. Despite their ecological importance, *P. oceanica* meadows are threatened throughout the Mediterranean Sea by increasing human pressures and climate change. Proper management and conservation of coastal marine habitats are challenging and require a comprehensive understanding of their distribution. To address this need, we developed habitat suitability models (HSMs) that, taking into account both natural and anthropogenic factors, assess the suitability of the environment for the presence of *P. oceanica* in the Ligurian Sea (NW Italy).

These models were built up using the Random Forest algorithm in R software. Model response variables included potential seabed areas characterized by *P. oceanica* habitats on soft and rocky bottoms, down to 50 m depth. Explanatory variables included natural factors such as seawater salinity and temperature, as well as variables related to human activities along the coastal strip.

The HSMs showed high accuracy rates of 82% for *P. oceanica* on soft bottom and 99% for *P. oceanica* on rocky bottom. The models predict a substantial increase in *P. oceanica* meadows on soft bottom, from 2448 ha to 11623 ha, and a modest increase on rocky bottom, from 159 ha to 200 ha. The west coast of Liguria was found to have a greater extent of seagrass meadows compared to the east coast.

This study provides valuable guidance for the sustainable management of *P. oceanica* meadows and offers practical tools for scientific research, land managers, stakeholders, and policy makers. These findings are essential for the conservation of a vital marine ecosystem and for promoting prudent and effective land management, ultimately securing the legacy of *P. oceanica* in northwestern Italy.

Keywords: seagrass conservation, Random Forest, coastal management, anthropic influence

1. INTRODUCTION

39 *Posidonia oceanica* (L.) Delile is an endemic and keystone seagrass species of the Mediterranean
40 Sea, where it plays a pivotal role in maintaining ecological balance [1, 2]. Its extensive meadows,
41 covering approximately 1.5% of the surface area of the Mediterranean Sea [3], have long been
42 recognized as a priority habitat for marine flora and fauna [4]. In particular, *P. oceanica* is known to
43 thrive in clear waters, from the surface down to 40 m depth. However, plants have also been found at
44 around 50 m [1].

45 *P. oceanica* meadows are critical coastal marine habitats, due to the ecosystem services and functions
46 they provide [5]. These include wave and current attenuation, sediment retention, shoreline
47 stabilization and protection from erosion, carbon sequestration, and primary production which
48 together support the health of coastal environments [6–14]

49 In addition, *P. oceanica* meadows provide a sheltered habitat for many vagile and pelagic species
50 during their early life stages [1, 15, 16]

51 The presence of seagrass meadows also guarantees provisioning and cultural services, in terms of
52 educational opportunities, and recreational activities such as scuba diving and nature appreciation
53 [17].

54 *P. oceanica* meadows are considered priority habitats worthy of conservation according to several
55 European directives (e.g., [18]).

56 Despite their ecological importance and conservation efforts, *P. oceanica* meadows are threatened.
57 Human activities, including habitat fragmentation, eutrophication, pollution, overfishing, and the
58 introduction of invasive species, combined with climate change, make it difficult to maintain their
59 plasticity (Waycott et al. 2009). As a result, seagrass meadows are declining worldwide at rates
60 ranging from 2% to 5% per year [19, 20].

61 In the Mediterranean basin, especially in the northwestern sector (Ligurian Sea), the conservation
62 status of *P. oceanica* meadows is well documented [9, 21–25]. In particular, in the Ligurian Sea *P.*
63 *oceanica* meadows are reported to have experienced extensive losses in the last century [24, 26–30],
64 although conservation efforts, enforced in recent years, may have curbed this decline [25, 31, 32].

65 The degradation of *P. oceanica* meadows has cascading consequences, leading to changes in
66 ecosystem structure and services, both ecological and socio-economic [16].

67 For instance, the significance of climate in accounting for the distribution of animals and plants was
68 first recognized by pioneers such as [33], and later by [34]. Over the years, understanding these
69 relationships has become increasingly essential, especially in the context of a rapidly changing
70 environment [35].

71 Habitat suitability models (HSMs) have emerged as a valuable tool for unraveling the intricacies of
72 species distributions and their interactions with environmental factors. These models are typically

73 based on various hypotheses about how environmental variables determine the presence or absence
74 of species. They provide predictive insights for geographic modeling, which is particularly relevant
75 for assessing the effects of accelerated land use and other environmental changes on organisms and
76 their distribution. In particular, while a limited number of species have been subjected to detailed
77 analyses of their dynamic responses to environmental change, static distribution modeling often
78 serves as the primary means of exploring the potential effects of a changing environment on species
79 distributions [35].

80 Understanding the spatial distribution of a species is crucial in conservation biology and
81 environmental management [36]. It underpins informed decisions about conservation and sustainable
82 management of ecosystems [37, 38]. Consequently, there has been a noticeable increase in the
83 adoption of modeling approaches, reflecting a growing recognition of the crucial need to comprehend
84 species' spatial distributions. As emphasized by [38], these models provide a powerful toolkit for
85 assessing the compatibility of a given habitat with the requirements of target species.

86 HSM have been widely applied in Mediterranean marine environments (e.g.,[39–41]). Several
87 previous studies have focused on mapping the distribution and habitat suitability of *P. oceanica*
88 meadows [2, 42–47].

89 The main objective of this study is to develop a Habitat Suitability Model (HSM) specifically tailored
90 for *P. oceanica* in a western region of the Mediterranean Sea, able to include information on how
91 both natural and anthropogenic variables influence *P. oceanica* distribution. The goal of this research
92 is to provide a complete, versatile and practical tool not only to the scientific community, but also to
93 local land managers, stakeholders and policy makers to assist the decision-making process in the
94 contest of coastal management.

95

96 **2. MATERIALS AND METHODS**

97 **Study area**

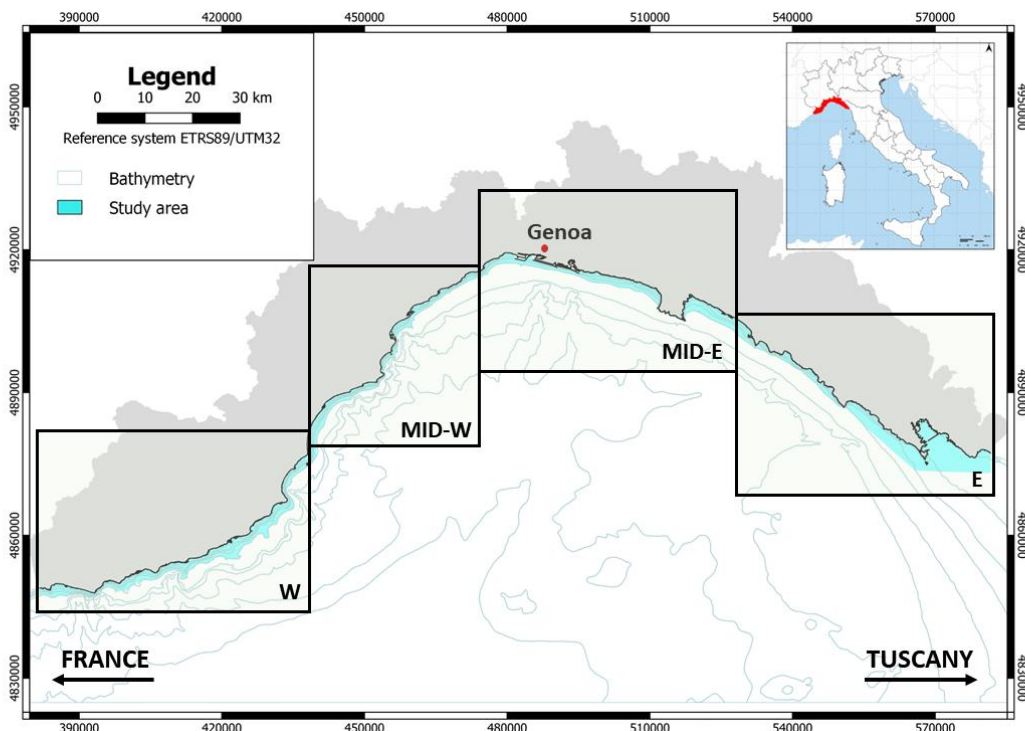
98 In this study, the entire coastal area of Liguria – i.e., from the surface down to 50 m depth - was
99 investigated. Liguria is an administrative region of Italy with 234 municipalities, located in the
100 northernmost part of the western Mediterranean (Fig. 1). Liguria shares its western border with France
101 and its eastern border with Tuscany. It is characterized by a long, narrow stretch of land and sea
102 encompassing approximately 345 kilometers of rocky and sandy coastline [48], and features a
103 continental platform that rapidly descends to depths exceeding 2000 meters.

104 Additionally, Figure 1 offers a comprehensive overview of the study area, highlighting four sections
105 that will be the focus of subsequent figures in this paper. These sections divide the study area into
106 four parts: Western side (W), Mid-Western side (MID-W), Mid-Eastern side (MID-E), and Eastern

107 side (E). This division aims to facilitate a closer examination and provide more detailed observations
108 of key aspects.

109 The Ligurian Sea is known for its unique morphological and biological characteristics, as well as its
110 higher primary production compared to the rest of the western Mediterranean [49]. As a result, it
111 hosts a diverse range of species and habitats that play a crucial role in ecosystem processes.
112 Consequently, Liguria boasts a significant number of Sites of Community Importance (SCIs) and
113 Marine Protected Areas (MPAs), which have been established to safeguard its natural heritage. There
114 are 26 marine SCIs, characterized by the presence of seagrasses like *Posidonia oceanica* and
115 *Cymodocea nodosa*. Additionally, there are three coastal MPAs and two Marine Conservation Areas
116 (MCAs).

117 While Ligurian Sea is a biodiversity hotspot, it is also heavily impacted by human activities [49].
118 According to the Italian National Institute of Statistics (ISTAT), Liguria region has one of the most
119 densely populated coastlines in the 2000s, with the highest level of coastal urbanization. The region's
120 high population density, coupled with the interaction of various productive industries, tourist
121 attractions, urban centers, port activities and multiple sources of pollution poses significant challenges
122 to biodiversity conservation [49]. In addition, the population density increases further during the
123 summer months due to the region's strong tourist appeal and seaside amenities, leading to an increase
124 in recreational activities [50, 51]. This special combination of natural values exposed to a set of human
125 pressures makes Liguria a particularly appropriate area to test and validate the model.
126



127
128 *Figure 1. Ligurian coastal area between 0 m and 50 meters depth divided into the four sections (W, MID-W, MID-E, E)*

129

130 **Spatial analysis**

131 Spatial maps serve as essential tools in the analysis and management of natural environments. They
132 play a crucial role in designing spatial plans and illustrating the results of different management
133 strategies and ecosystem conditions [52–54].

134 Throughout this study a Geographic Information Systems (GIS), the software QGIS (version 3.22.8),
135 was employed to extract, process, and present our findings as georeferenced information. It resulted
136 useful as decision support tools in the field of spatial data. The generation of maps in QGIS followed
137 the ETRS89-ETRF89 reference system with UTM32 cartographic representation, as recommended
138 by the Military Geographic Institute at the European level [55].

139

140 **Grid cells**

141 Once the study area was delineated between depths of 0-50 meters, the QGIS "Create Grid" tool was
142 used to partition the area in a regular grid of 26974 squares measuring 140x140 meters each. These
143 cells served as the basic units on which all subsequent analyses were built.

144

145 **Random Forest**

146 Random Forest (RF) is a powerful machine learning technique introduced by [56] that has gained
147 considerable popularity. It excels at handling both regression and classification problems, and its
148 strength lies in its ability to model response variables. RF achieves this by recursively partitioning
149 datasets into subgroups using decision rules, forming a binary tree structure in which nodes and edges
150 represent information flow between adjacent nodes [57]. Each tree in the forest is grown by randomly
151 selecting explanatory variables and utilizing different random data subsets through bootstrapping
152 [58]. This randomization process enhances model performance by reducing the risk of overfitting and
153 improving generalizability [56].

154 The RF algorithm constructs a forest of decision trees, and individual tree predictions are aggregated
155 to produce the final output. This aggregation can be achieved either by averaging the outputs or by
156 considering weighted votes from each tree [59]

157 One of the key features of RF is its ability to assess the importance of variables in predicting the
158 response. It determines this importance by analyzing the change in mean square error when excluding
159 a variable from the model [56]. This helps researchers understand how each explanatory variable
160 affects the response.

161 The dataset used for training is referred to as the *in-bag* data, while the *out-of-bag* data remains unused
162 during tree construction [56]. However, the "out-of-bag" data plays a crucial role in estimating the

163 generalization error of the model, which consistently converges with increasing the forest size [57].
 164 The choice of the number of trees in the forest should carefully balance computational resources and
 165 model performance [57].

166

167 **Response variables**

168 The response variables in this study include all seabed areas within the study area that feature habitats
 169 of *P. oceanica* on soft bottom (POS) or *P. oceanica* on rocky bottom (POS-R), as indicated by their
 170 locations depicted in Figure 2. Figure 2. Distribution of POS and POS-R in the study area, extracted from Coppo et al., 2020,
 171 with randomly selected zoomed-in views to highlight details. These locations were extracted from The Atlas of the
 172 Marine Coastal Habitats of Liguria [60], an invaluable resource providing essential information about
 173 the Ligurian seabed and its main habitats.

Nomenclature	Surface %	Nomenclature	Surface %	Nomenclature	Surface %
PA - Infralittoral photophilous algae on hard seabed	1.50%	CYM - <i>Cymodocea nodosa</i>	5.84%	DM - Dead Matte	0.79%
PA-A - Infralittoral photophilous algae on artificial seabed	0.37%	CYM-CAU - <i>Cymodocea nodosa</i> and <i>Caulerpa taxifolia</i>	0.49%	MOS - Mosaic of <i>Posidonia oceanica</i>	1.85%
PA-BR - Infralittoral photophilous algae on beach-rock seabed	0.03%	CYM-DENSE - Dense <i>Cymodocea nodosa</i>	0.30%	POS - <i>Posidonia oceanica</i>	7.45%
SAC - Circal-littoral sciaphilous algae	0.11%	CYM-DM - <i>Cymodocea nodosa</i> on dead Matte	0.48%	POS-CAU - <i>Posidonia oceanica</i> and <i>Caulerpa taxifolia</i>	0.05%
SAI - Infralittoral sciaphilous algae	0.27%	CYM-POS - <i>Cymodocea nodosa</i> with <i>Posidonia oceanica</i>	0.06%	POS-R - <i>Posidonia oceanica</i> between and on rock	0.82%
C - Coralligenous	0.42%	DB - Detrital beds	1.40%	UA - Uninvestigated area	2.92%
CAU - <i>Caulerpa taxifolia</i>	0.06%	DB-M - Muddy detrital beds	0.99%	S - Sand	30.33%
C-M - Coralligenous on mud	0.01%	M - Muds	42%	CS - Coarse sediments	1.21%
CYL - <i>Caulerpa cylindracea</i>	0.03%	CA - Caves	0.00%	CS-C - Coarse sands and coralligenous	0.02%

174 Table 1 lists all the coastal marine habitats in the study area as described by the Atlas. To determine
 175 the response variables, the prepared grid cells (paragraph 0) were intersected with the habitat
 176 extensions, ensuring that each cell contains a value for the underlying habitat. If a grid cell intersected
 177 *Posidonia* habitat, even if only a small portion of the cell was occupied by *Posidonia*, the entire cell
 178 was designated as indicating the presence of POS or POS-R. Ultimately, the response variables
 179 selected were those grid cells that indicate the presence of POS and POS-R.

180

Nomenclature	Surface %	Nomenclature	Surface %	Nomenclature	Surface %
--------------	-----------	--------------	-----------	--------------	-----------

PA - Infralittoral photophilous algae on hard seabed	1.50%	CYM - <i>Cymodocea nodosa</i>	5.84%	DM - Dead Matte	0.79%
PA-A - Infralittoral photophilous algae on artificial seabed	0.37%	CYM-CAU - <i>Cymodocea nodosa</i> and <i>Caulerpa taxifolia</i>	0.49%	MOS - Mosaic of <i>Posidonia oceanica</i>	1.85%
PA-BR - Infralittoral photophilous algae on beach-rock seabed	0.03%	CYM-DENSE - Dense <i>Cymodocea nodosa</i>	0.30%	POS - <i>Posidonia oceanica</i>	7.45%
SAC - Circal-littoral sciaphilous algae	0.11%	CYM-DM - <i>Cymodocea nodosa</i> on dead Matte	0.48%	POS-CAU - <i>Posidonia oceanica</i> and <i>Caulerpa taxifolia</i>	0.05%
SAI - Infralittoral sciaphilous algae	0.27%	CYM-POS - <i>Cymodocea nodosa</i> with <i>Posidonia oceanica</i>	0.06%	POS-R - <i>Posidonia oceanica</i> between and on rock	0.82%
C - Coralligenous	0.42%	DB - Detrital beds	1.40%	UA - Uninvestigated area	2.92%
CAU - <i>Caulerpa taxifolia</i>	0.06%	DB-M - Muddy detrital beds	0.99%	S - Sand	30.33%
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CYL - <i>Caulerpa cylindracea</i>	0.03%	CA - Caves	0.00%	CS-C - Coarse sands and coralligenous	0.02%

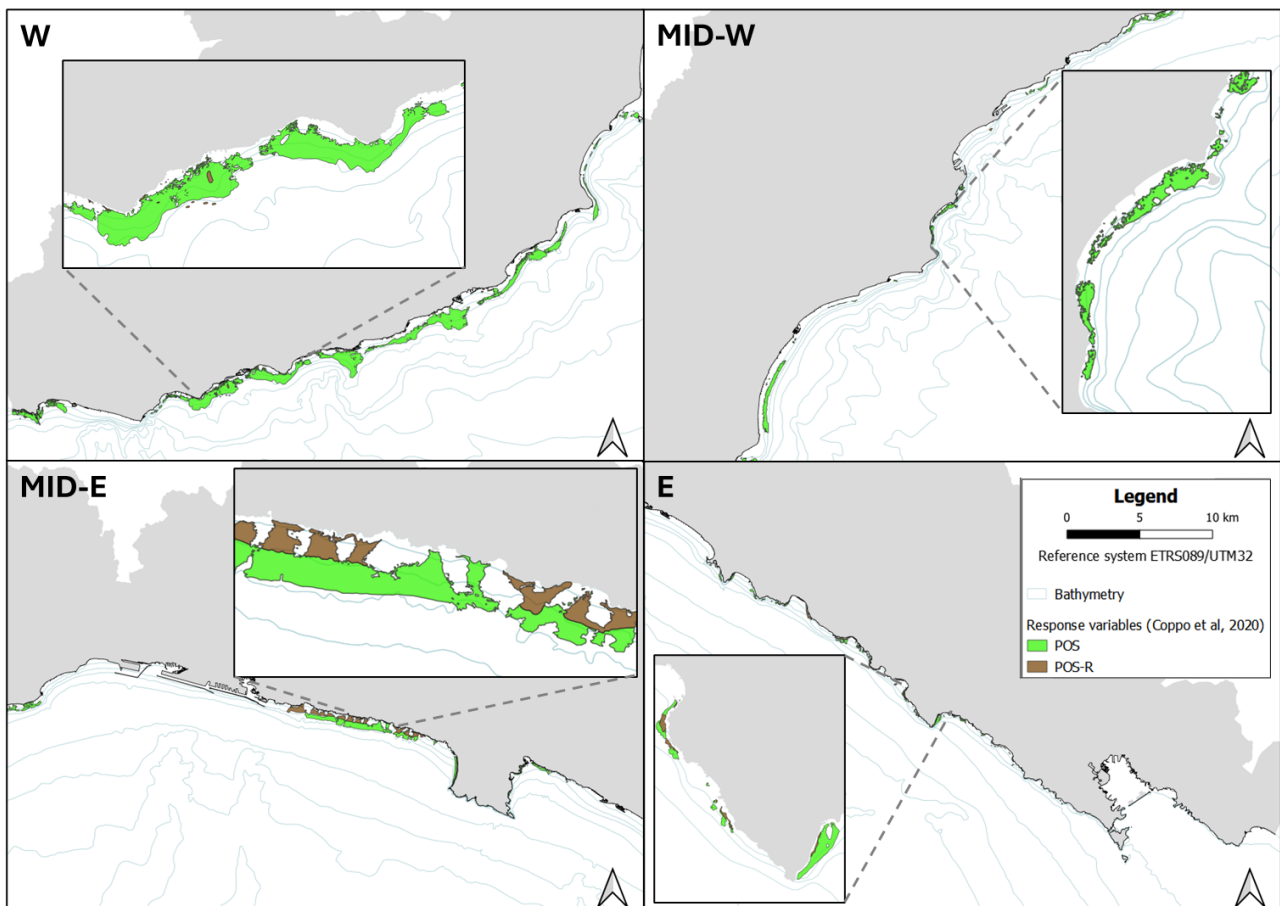
Table 1. Ligurian marine coastal habitats between 0 m and 50 meters depth (Coppo et al., 2020).

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Figure 2. Distribution of POS and POS-R in the study area, extracted from Coppo et al., 2020, with randomly selected zoomed-in views to highlight details.

188

189

Explanatory variables

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Explanatory variables represent factors that exert their influence within the studied area. The selection of these variables was based on those previously tested in other HSMs according to the literature (e.g., [40, 41, 44–46]. Additionally, variables not previously tested but known to potentially have an influence, such as the presence of railways along the coastline [61], were also included.

Similarly to the response variables, they were subsequently associated with each grid cell previously created. The considered explanatory variables include both natural variables, such as seawater salinity and temperature, and variables related to human activities (e.g. fishing ban, anchoring ban or harbor presence) along the coast that are expected to advantage or disadvantage the presence of *P. oceanica*. Human-related activities can be associated, for example, with the distance between their location and the grid cells, their mere presence, and the impact they can exert within a certain range of influence.

200

Table 8, reported in

201 **APPENDIX** provides a comprehensive list of 31 explanatory variables considered.
 202 It should be noted that in the RF classification, all these variables were taken into account and tested
 203 for their importance and relevance for the response variables. However, only the six variables yielding
 204 the most significant results are discussed in this study.

205

206 **Classification details**

207 Overall, two classifications were run using the same explanatory variables but different response
 208 variables. The first classification considered POS, while the second used POS-R. For both
 209 classifications, two-thirds of the respective datasets were allocated to the training process, while the
 210 remaining one-third was used for testing.

211 The R software (version 4.2.0) was used for this RF analysis [56], as it provides a useful tool for
 212 implementing RF algorithms [62]. In this study, 500 trees were used, and the mean square error was
 213 calculated from the predictions with the test dataset, averaged over all trees using the out-of-bag error.
 214 For this classification task, the *randomForest* package [62] was applied: the number of predictors
 215 considered at each split was set equal to the square root of the number of explanatory variables
 216 ($\sqrt{31} \approx 6$), and the minimum number of records in the terminal nodes was set to 1. Predictor
 217 importance was assessed using permutation-based importance as calculated by the *randomForest*
 218 package. The models' outputs were a probability value between 0 and 1, representing the likelihood
 219 of the presence of POS and POS-R. The classification threshold of 0.8 was used to distinguish
 220 between absence (0) and presence (1).

221 Using the RF algorithm, the dataset can be used to make predictions, resulting in a classification into
 222 four categories. These categories are summarized in a confusion matrix (

223 Table 2), which is a two-by-two table that tabulates the outcomes of a binary classifier: *true presences*

Confusion matrix		Prediction	
		Presences	Absences
Observation	Presences	TP The model correctly identifies cells as having the same presence as observed	FA The model fails to predict the presence of an attribute in cells observed in the real dataset
	Absences	FP The model predicts the presence of an attribute in cells not observed in the real dataset	TA The model accurately identifies cells as lacking the observed feature

224 (*TP*), *true absences (TA)*, *false presences (FP)*, *false absences (FA)*.

225

Confusion matrix	Prediction
------------------	------------

		Presences	Absences
Observation	Presences	<p>TP</p> <p>The model correctly identifies cells as having the same presence as observed</p>	<p>FA</p> <p>The model fails to predict the presence of an attribute in cells observed in the real dataset</p>
	Absences	<p>FP</p> <p>The model predicts the presence of an attribute in cells not observed in the real dataset</p>	<p>TA</p> <p>The model accurately identifies cells as lacking the observed feature</p>

Table 2. Confusion matrix

226

227

228 From the confusion matrix, several fundamental performance metrics assessing the quality of
 229 prediction can be derived, each offering valuable insights into the model's effectiveness:

230

- 231 1. Error Rate (ERR): The error rate is the ratio of all incorrect predictions to the total number of
 232 instances in the dataset. ERR ranges from 0.0, indicating a model with perfect accuracy, to
 233 1.0, signifying a model that is completely inaccurate

234

$$ERR = \frac{FP + FA}{TP + TA + FP + FA};$$

235

- 236 2. Accuracy (ACC): ACC represents the ratio of all correct predictions to the total number of
 237 instances in the dataset. A perfect model has an accuracy score of 1.0, while a model with no
 238 correct predictions scores 0.0

239

$$ACC = \frac{TP + TA}{TP + TA + FP + FA};$$

240

- 241 3. Sensitivity (SN): Sensitivity is calculated as the ratio of correct positive predictions to the
 242 total number of positive instances. It ranges from 0.0, indicating a model that fails to recognize
 243 any positives, to 1.0, signifying a model that accurately identifies all positive cases

244

$$SN = \frac{TP}{TP + FA};$$

245

- 246 4. Specificity (SP): Specificity is determined by the ratio of correct negative predictions to the
 247 total number of negative cases. SP ranges from 0.0, illustrating a model that cannot effectively
 248 discriminate between positives and negatives, to 1.0, representing a model with excellent
 249 negative prediction accuracy

250

$$SP = \frac{TA}{TA + FP};$$

251

- 252 5. Precision (PREC): Precision is the ratio of correct positive predictions to the total number of
 253 positive predictions made by the model. The best precision score is 1.0, indicating a model

254 that exclusively makes correct positive predictions, while the lowest score is 0.0, reflecting a
 255 model that lacks precision in positive predictions

256
$$PREC = \frac{TP}{TP + FP};$$

257
 258 6. False Positive Rate (FPR): FPR is derived by dividing the number of incorrect positive
 259 predictions by the total number of negative instances. The FPR score ranges from 0.0,
 260 illustrating a model that never produces false positive predictions, to 1.0, indicating a model
 261 that consistently produces incorrect positive predictions when faced with negative instances

262
$$FPR = \frac{FP}{TA + FP};$$

263
 264 Although these metrics provide a comprehensive view of the model's performance, the Kappa statistic
 265 [63] is another commonly used metric that assesses the agreement between predicted and observed
 266 classifications, taking into account chance. In similar studies [64], the Kappa statistic is often used as
 267 a performance measure for classification models. Kappa ranges from -1 (perfect disagreement) to 1
 268 (perfect agreement), with 0 indicating agreement no better than chance. The interpretation of the
 269 results, as suggested by [63], is: values ≤ 0 as indicating no agreement, 0.01-0.20 as none to slight,
 270 0.21-0.40 as fair, 0.41-0.60 as moderate, 0.61-0.80 as substantial, and 0.81-1.00 as near perfect
 271 agreement.

272
$$\kappa = \frac{P_o - P_e}{1 - P_e}$$

- 273 • P_o = observed agreement (i.e., the proportion of times the classifier agrees on the
 274 classification).
 275 • P_e expected agreement (i.e., the proportion of times agreement is expected by chance, based
 276 on the marginal sums of the confusion matrix)
 277

278 **3. RESULTS**

279
 280 shows the number of grid cells containing habitats of POS and POS-R. It includes both observed

Grid cells	n. of observed cells	Observed hectars	n. of predicted cells	Predicted hectars
POS	1249	2448	5930	11623
POS-R	81	159	102	200

281 cells, derived from The Atlas of the Marine Coastal Habitats of Liguria [60], and model-predicted
 282 cells, along with their corresponding areas in hectares. For POS, there were 1,249 observed cells

283 (2448 ha) and 5,930 predicted cells (11623 ha). For POS-R, the number of cells increased from 81
 284 observed cells (159 ha) to 102 predicted cells (200 ha).

285

Table 3. Comparison between observed and predicted cells, along with their respective hectares, for both POS and POS-R models.

Grid cells	n. of observed cells	Observed hectares	n. of predicted cells	Predicted hectares
POS	1249	2448	5930	11623
POS-R	81	159	102	200

286

287 The explanatory variables with the most significant impact on the classification are consistent for
 288 both *P. oceanica* habitats, whether on soft or rocky bottom, however reporting different order of their
 289 importance. These variables and their respective percentages of importance are detailed in Table 4
 290 (POS) and Table 5 (POS-R). In both scenarios, the variable of greatest influence is the minimum
 291 distance from the rocky shoreline (25% for POS; 20% POS-R), followed by the minimum distance
 292 from the sandy shore (20% for POS; 28% for POS-R).

293

Table 4. The explanatory variables with the most significant influence, as classified by the random forest classification for POS.

POS most influential explanatory variables	Importance
Min. distance from rocky shoreline	25%
Min. distance from sandy shoreline	20%
Min. distance from artificial shoreline	15%
Bathymetry	14%
Min. distance from railway	13%
Min. distance from harbors and marinas	13%

294

295

Table 5. The explanatory variables with the most significant influence, as classified by the random forest classification for POS-R.

POS-R most influential explanatory variables	Importance
Min. distance from rocky shoreline	35%
Min. distance from sandy shoreline	28%
Min. distance from railway	14%
Bathymetry	9%
Min. distance from harbors and marinas	8%
Min. distance from artificial shoreline	5%

296

297 The values of the confusion matrix and the corresponding accuracies for both models are displayed
298 in

299 Table 6. The model for POS bottom predicts 4736 new cells (FP) with values of POS, while the model

300 for POS-		TP	TA	FP	FA	Total grid cells	R predicts The cells
301 21 FP.	POS	1194	20989	4736	55	26974	
302 predicted	POS- R	81	26872	21	0	26974	

303 representing FA are limited, with 55 cells for the POS model and none for the POS-R model. Table
304 7 shows the metrics that can be derived from the confusion matrix for both sets of predictions. The
305 accuracy values are 82% (ERR = 0.18) for POS and 99% (ERR = 0.00) for POS-R. The maximum
306 values of sensitivity (SN) and specificity (SP) (both reaching 1) are achieved by the POS-R model,
307 while relatively high values are also observed for the POS model, with SN at 0.96 and SP at 0.82. In
308 terms of precision (PREC), the POS model exhibits a value of 0.20, while the POS-R model reaches
309 a PREC of 0.79. Lastly, the false positive rate (FPR) is 0.05 for the POS model, and there are no false
310 positive predictions for the POS-R model.

311 For the POS model, Kappa was found to be 0.27, indicating fair agreement between the predicted and
312 actual presence of POS. For the POS-R model, Kappa was 0.73, indicating good agreement between
313 the predicted and actual absence of the species.

314

315

Table 6. Confusion matrix for both classifications.

316		TP	TA	FP	FA	Total grid cells
317	POS	1194	20989	4736	55	26974
318	POS- R	81	26872	21	0	26974

320

Table 7. Measures of classification quality derived from the confusion matrix.

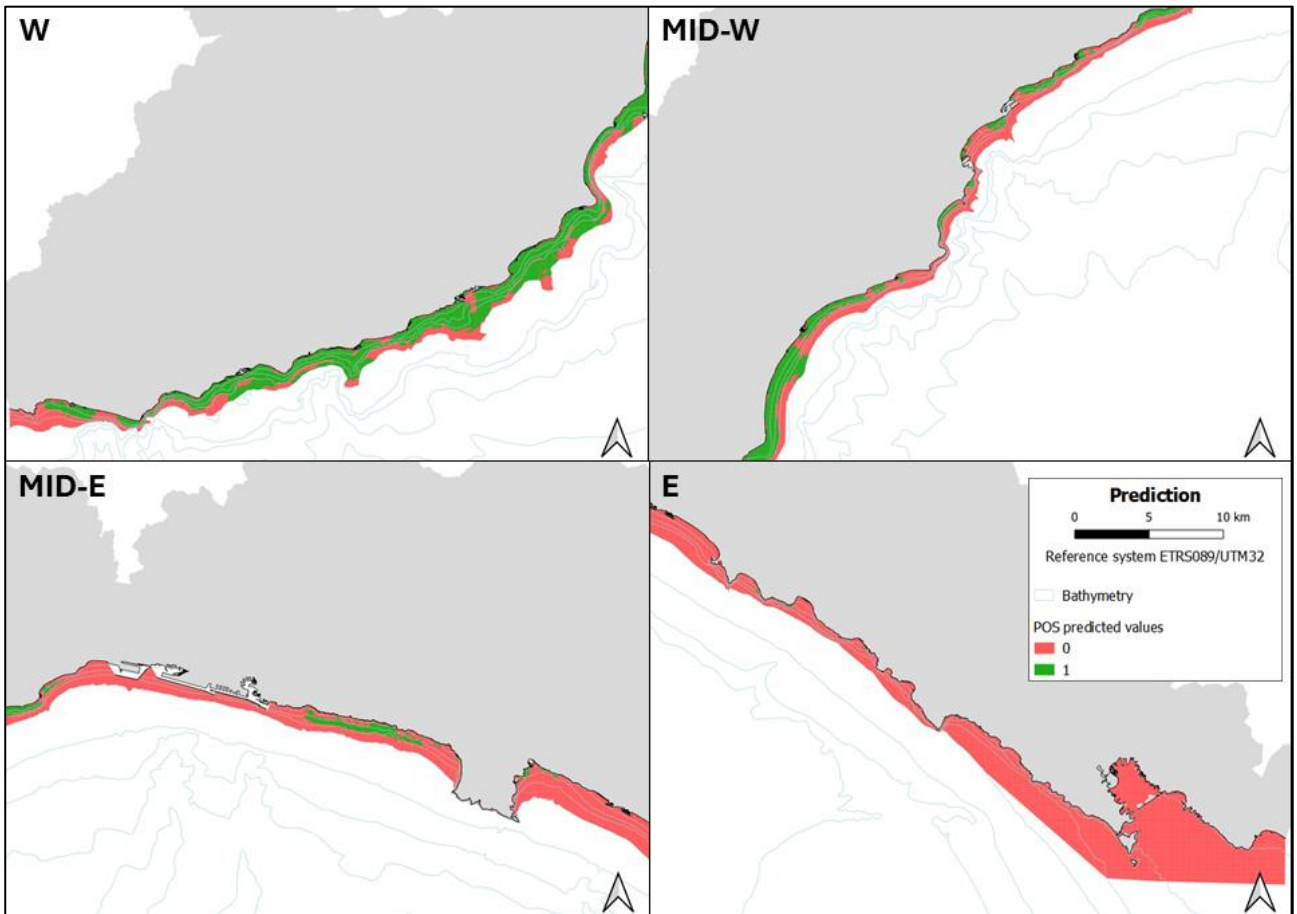
321		ERR	ACC	SN	SP	PREC	FPR	κ
322	POS	0.18	0.82	0.96	0.82	0.20	0.05	0.27
323	POS- R	0.00	0.99	1.00	1.00	0.79	0.00	0.73

324

325 Figure 3 displays the distribution of predicted values over the whole study area for the POS model,
326 where a higher number of cells with predicted values is observed along the western coast of Liguria.

327 In contrast, illustrates the same for the POS-R model, where the majority of cells with predicted
328 values are located along the eastern coast.

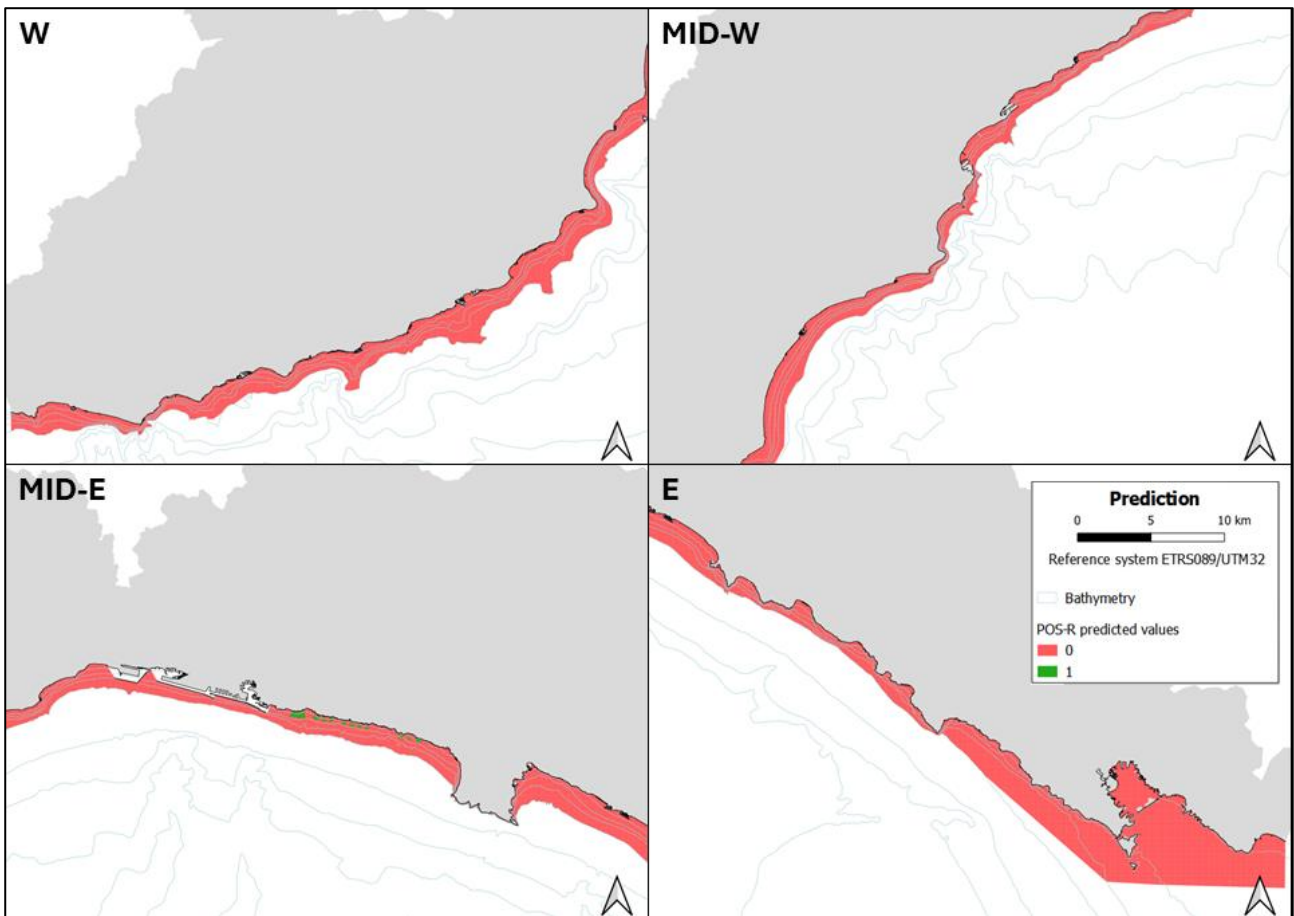
329



330

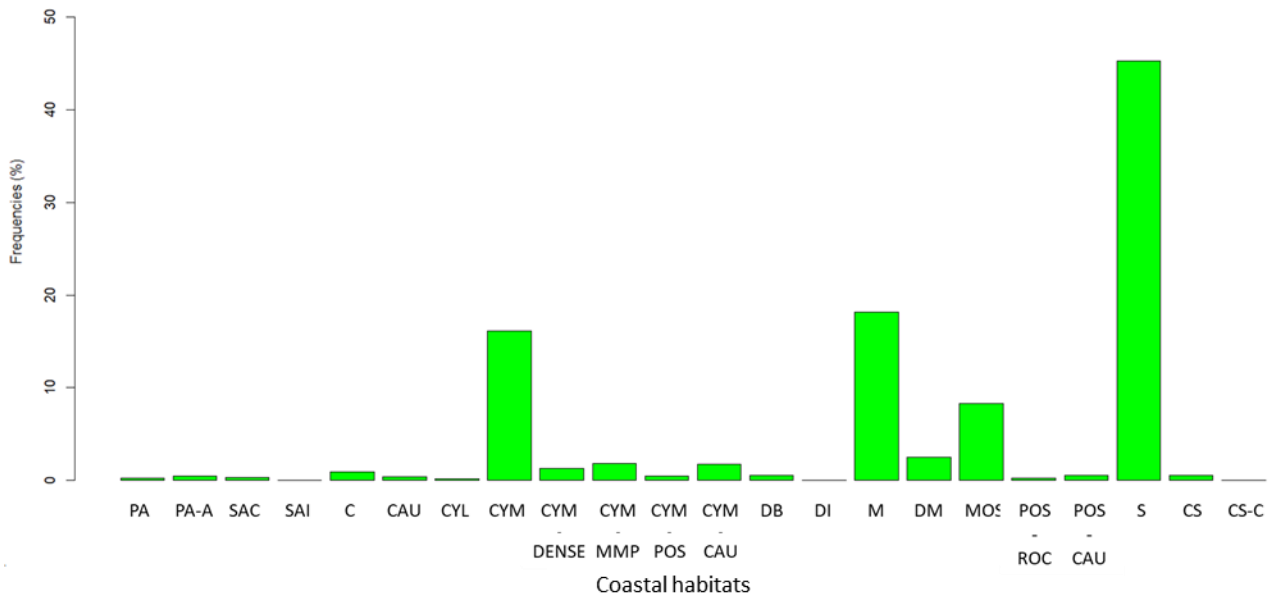
331

Figure 3. Distribution of predicted values for POS.



333
334
335
Figure 4. Distribution of predicted values for POS-R.

336 Figure 5 and Figure 6 depict the frequencies of FP grid cells for POS and POS-R, respectively. These
 337 figures show where the model predicted the presence of *P. oceanica*, but other actual habitats were
 338 found instead. In the case of the predictions made by the model for POS (Figur), four habitats are the
 339 most common: sand (S, 45%), mud (M, 18%), *Cymodocea nodosa* (CYM, 16%), and mosaic of *P.*
 340 *oceanica* (MOS, 8%). As for the scenario of POS-R (**Error! Reference source not found.**), almost
 341 90% of the frequencies are attributed to infralittoral photophilous algae on hard seabed (PA, 50%),
 342 infralittoral photophilous algae on artificial seabed (PA-A, 23%), and infralittoral sciaphilous algae
 343 (SAI, 14%).



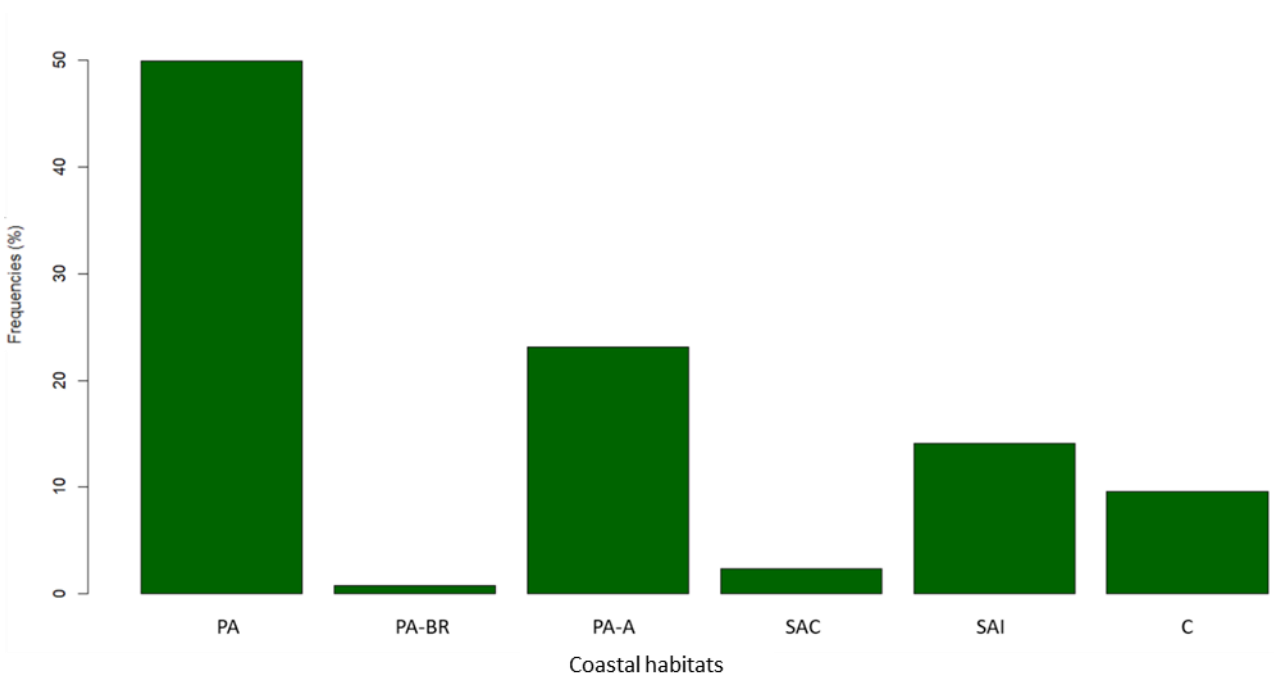
344

345

346

Figure 5. The percentage frequencies of coastal habitats potentially replaced by POS are shown, with percentages represented on the y-axis and the coastal habitats displayed on the x-axis. The habitats' acronyms are explicated in Table 1.

347



348

349

350

Figure 6. The percentage frequencies of coastal habitats potentially replaced by POS-R are shown, with percentages represented on the y-axis and the coastal habitats displayed on the x-axis. The habitats' acronyms are explicated in Table 1.

351

352 4. DISCUSSION

353 The model predicts a substantial increase of +374% cells with predicted presence of POS, while POS-

354 R show a more modest increase of 26% (

355).

Grid cells	n. of observed cells	Observed hectars	n. of predicted cells	Predicted hectars
POS	1249	2448	5930	11623
POS-R	81	159	102	200

356 It's worth noting that the historical extent of *P. oceanica* in Liguria was much greater in the past,
357 covering the entire coastline. In the 1910s, the estimated meadows' surface of *P. oceanica* in Liguria
358 was approximately 7000 hectares [24]. However, the decline of *P. oceanica* in this region began in
359 the 19th century, coinciding with the onset of road and railway construction projects. As documented
360 by [29], construction materials were sourced from the beaches and rivers, and rock excavated for
361 tunnels and infrastructure was often dumped into the sea, resulting in the formation of ephemeral
362 beaches. Moreover, this material was used to build seawalls to prevent coastal erosion, which may
363 have been exacerbated by the construction work itself. The construction of harbors and small marinas
364 in the following decades led to a further loss of seagrass beds. Additionally, the channelization of
365 rivers and streams to prevent flooding increased water flow and sediment transport, ultimately leading
366 to the burial of *P. oceanica* meadows [29]. This historical context highlights the substantial reduction
367 of *P. oceanica* in Liguria over the years due to human intervention.

368 In general, both current cartography [60] and model results indicate a greater extent of seagrass
369 meadows along the western coast of Liguria compared to the eastern coast. This difference in
370 seagrass extent has already been noted in the Atlas of Marine Phanerogams of Liguria [61], which
371 reported a three times greater surface of marine phanerogams along the western coast compared
372 to the eastern coast, along with the additional observation that individual meadows tend to be
373 smaller along the eastern coast. In the last 40 years or so, there has been a remarkable expansion
374 of seagrass meadows along the western coast of Liguria, reflecting a positive trend in their extent.
375 Conversely, in the central region of Liguria, there has been a subtle reduction in meadow coverage.
376 However, along the eastern coast, the presence of seagrass meadows has remained consistently
377 lower than in the western one, and this difference is probably due to various natural factors [61].
378 This difference in seagrass meadow dynamics has been more pronounced highlighting the complex
379 interplay of ecological and environmental factors in shaping the distribution and trends of *P.*
380 *oceanica* in Liguria [24]. This, associated with the model results of this study, may suggest that since
381 some of these impacts occurred some time ago and the pressure they exert is no longer as intense,
382 there may be a slow recovery of the *Posidonia* meadows, which, however, is not yet possible to
383 observe in detail.

384 An interesting observation emerges when examining the behavior of the variables related to the
385 minimum distance from sandy and rocky shores. POS tend to be in closer proximity to sandy
386 shoreline, mainly within a range up to 5 km, which can be attributed to the remarkable ability of *P.*
387 *oceanica* to form its own bottom, known as a matte, on soft and sedimentary bottoms [65]. The matte
388 consists of intertwined roots and rhizomes with sediment trapped between them, as described in
389 studies by [66]. This adaptation allows the plant to anchor itself securely even in areas with less stable
390 bottoms.

391 Conversely, POS-R is predominantly located within 0.5 km of rocky shores, with some even
392 positioned very close to the rocky shoreline. This proximity to rocky shoreline can be explained by
393 the ability of *P. oceanica* to withstand the challenging conditions of hard and strong rock layers, as
394 confirmed in the study by [24]. Studies by [2] suggest that the plant can colonize even in the active
395 hydrodynamic surf zone of rocky shoreline. Waves can dislodge shoots from the underlying meadow,
396 which then become lodged in cracks and crevices of the rock, where they establish and survive,
397 effectively acting as pipelines [67].

398 As reported in Table 5, three other variables show interesting behavior when compared to each other:
399 the minimum distance from railroads, the minimum distance from artificial shorelines, and the
400 distance from harbors. The minimum distances from artificial shorelines and railroads may be
401 somewhat correlated, as in some cases, the presence of a railroad may require an artificial shoreline
402 to support the railroad itself.

403 It appears that *P. oceanica* meadows on soft and rocky bottoms tend to be located at shorter distances,
404 ranging from near the shoreline to less than 2000 meters, in the case of artificial shoreline and
405 railways. However, they are found at greater distances from harbors, ranging from 1500 meters to
406 over 3500 meters.

407 This difference can be interpreted in terms of environmental impact. Railways and artificial shorelines
408 may have a more "acute" impact because the construction and maintenance phases can result in
409 significant disturbance to the surrounding ecosystem, such as earth movement, excavation, and
410 potential pollution associated with rail traffic. These acute impacts may occur concurrently with the
411 construction or maintenance phases of railroads, making the overall impact more "acute" and
412 immediate. It's worth mentioning that the construction of railways in Liguria took place many
413 decades ago, especially in the late 19th and early 20th centuries.

414 On the other hand, harbors tend to generate a more "chronic" impact. The impact of harbors extends
415 over time because they often operate for many years and can continuously affect the marine
416 environment, including navigation-related pollution, sediment accumulation, and changes in the

417 dynamics of ocean currents. These impacts accumulate over time, leading to a "chronic" effect on the
418 surrounding ecosystem.

419 Furthermore, regarding the behavior of these two habitats in relation to the bathymetry in which they
420 are located, we observe that POS tends to be found predominantly within depths approaching 20
421 meters. However, it is worth noting that under no turbidity water conditions, *P. oceanica* has been
422 observed at depths of almost 50 meters [1]. In contrast, *Posidonia oceanica* on rocky bottom is mainly
423 found within the first 10 meters of depth, with meadows occasionally extending to depths between
424 10 and 20 meters. This distribution is largely due to the availability of rocky seabeds at certain depths.

425 Evaluation metrics derived from the confusion matrix (

426 Table 6, Table 7) for the two *P. oceanica* HSMs provide nuanced insights into their predictive

	TP	TA	FP	FA	Total grid cells
POS	1194	20989	4736	55	26974
POS-R	81	26872	21	0	26974

427 capabilities. For the model predicting POS, an ERR rate of 18% suggests a moderate degree of
428 misclassification. While a remarkable ACC of 82% was achieved, it is crucial to consider sensitivity
429 and specificity. The high SN of 96% indicates the effectiveness of the model in correctly identifying
430 areas suitable for POS. Notably, the low PREC of 20% implies a significant number of false presences
431 (FP), revealing areas predicted as suitable where *P. oceanica* may not actually be present. This can
432 be seen as an advantageous feature, drawing attention to potential areas for further ecological
433 exploration or targeted monitoring efforts. The FPR of 5% highlights the tendency of the model to
434 predict suitable habitat in areas not observed, providing valuable insights for habitat expansion or
435 restoration considerations.

436 The Kappa coefficient for the POS model (0.27), which indicates fair agreement suggests that while
437 the model performs reasonably well, there is still room for improvement, particularly in reducing
438 false presences and improving model precision.

439 Conversely, the model for POS-R shows remarkable performance with an error rate of 0% and an
440 outstanding accuracy of 99%. SN and SP both reach optimal values of 100%, indicating the model's
441 ability to accurately predict both presence and absence cases. The PREC of 79% underlines the
442 reliability of presence predictions. The lack of false presences (0% FPR) suggests a conservative
443 approach, with the model tending to be cautious in predicting habitat suitability.

444 The high Kappa coefficient (0.73) for the POS-R model demonstrates strong reliability in predicting
445 areas where POS-R is not present, highlighting the model's effectiveness in distinguishing absence
446 accurately.

447 Of note is the extremely low number of false absences (
 448 Table 6) for both predictions. There are only 55 false absences for the POS, representing only 0.2%

449 of the
 450 elements,

	TP	TA	FP	FA	Total grid cells
POS	1194	20989	4736	55	26974
POS-R	81	26872	21	0	26974

total
and

451 remarkably, there are zero false absences in the model for POS-R. False absences refer to elements
 452 for which the model does not predict the presence of the response variable, but in reality, such a
 453 variable is observed.

454 Shifting our focus to the false presences (
 455 Table 6), which are cases where the model predicts the presence of the response variable, but it is not

456 actually
 457 allowed
 458 perform a
 459 detailed

	TP	TA	FP	FA	Total grid cells
POS	1194	20989	4736	55	26974
POS-R	81	26872	21	0	26974

observed,
us to
more
spatial

460 analysis. This analysis allowed to identify the coastal habitats that are actually present but are
 461 considered by the model to be suitable for the presence of *Posidonia oceanica* on soft bottom and
 462 rocky bottom.

463 POS is predicted in a greater number of distinct habitats compared to POS-R, specifically 23 habitats
 464 versus 7 for the latter. In the case of POS, the most common predictions relate to habitats such as
 465 littoral sand, mud, *Cymodocea nodosa*, and mosaic of *Posidonia oceanica*. These habitats share the
 466 common characteristic of soft bottom, which is an ideal environment for the growth of *P. oceanica*
 467 on sandy terrain. Regarding predictions for the *Cymodocea nodosa* habitat and the *Posidonia*
 468 *oceanica* mosaic, there are few considerations to be made. As widely acknowledged [23, 24, 61],
 469 these two habitats often represent the degradation of former *P. oceanica* meadows. The reason why
 470 the model reports this situation could be explained by two hypotheses: 1) the model used in this study
 471 may not account for one or more explanatory variables that could indicate a different situation, and
 472 this issue may no longer be relevant; 2) assuming that the variables used are sufficient, the model
 473 may suggest that in the areas where *Cymodocea nodosa* and the mosaic are currently observed, they
 474 are experiencing improved conditions. The threats and impacts that facilitated their development may
 475 no longer be present, thus allowing *P. oceanica* to recover. These hypotheses can only be tested and
 476 potentially validated with further and deeper analyses.

477 Regarding POS-R, the model predicts its presence mainly in situations where habitats, of littoral
 478 photophilic algae or artificial bottoms are present. These assemblages are typical of shallow waters,

479 and the observation of the responses and behaviors of variables related to the depth of the seabed and
480 the minimum distance from artificial shoreline confirms the potential presence of POS-R.
481 Furthermore, it should be noted that the significantly high number of false presences, especially in
482 the case of POS, prevents the model from reaching the maximum level of accuracy (100%).
483 The models developed have allowed us to identify anthropogenic variables that significantly
484 influence the presence of POS and POS-R. These findings are crucial for conservation strategies of
485 these seagrass meadows. Understanding the anthropogenic factors that either facilitate or hinder the
486 presence of *P. oceanica* allows for targeted measures to mitigate negative impacts. For example,
487 regulatory or control measures can be implemented to protect against activities that threaten these
488 critical marine formations.
489 In addition, future research could benefit from incorporating methodologies, such as those proposed
490 by [68], that utilize advanced survey technologies and in situ measurements of ecosystem
491 functionality. These data could, for example, improve the spatial resolution of models and better
492 represent habitat heterogeneity, leading to improved predictive accuracy of HSMs. Another critical
493 aspect is the use of HSMs as a navigation tool for planning *P. oceanica* restoration activities. These
494 models identify coastal areas with a high potential to support *Posidonia oceanica* meadows, while
495 also providing detailed information on the type of bottom in these areas. This knowledge can be
496 invaluable to land managers and environmental restoration professionals, allowing them to focus
497 restoration efforts on areas with a higher probability of success. In addition, knowledge of the current
498 substrate can guide decisions about the type of intervention needed to restore a suitable habitat for *P.*
499 *oceanica*.

500

501 **5. CONCLUSION**

502 In conclusion, the model for habitat suitability model developed in this study for *P. oceanica*
503 meadows along the Ligurian coast serves as a crucial foundation for advancing our understanding of
504 seagrass ecology in the region. The identification of natural and anthropogenic variables influencing
505 the presence of *P. oceanica* on different substrates is crucial for conservation efforts, allowing
506 targeted actions to address threats and protect these important marine formations. Furthermore, the
507 study highlights the utility of HSMs as a strategic tool for planning restoration activities, providing
508 valuable insights into potential restoration sites and bottom characteristics. Overall, the models
509 developed provide essential guidance for sustainable management, helping both scientists and
510 stakeholders make informed decisions to conserve *P. oceanica* meadows and promote effective land
511 management practices.

512

513 **Author contributions**

514 Rachele Bordoni: Conceptualization, Methodology, Formal analysis, Data curation, Validation,
515 Writing – original draft, Writing – review & editing.

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518 Ilaria Rigo: Data curation, Formal analysis, Writing – review & editing

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520 Alice Oprandi: Investigation, Writing – review & editing.

521 Paolo Vassallo: Conceptualization, Methodology, Formal analysis, Supervision, Validation, Funding
522 acquisition, Writing – review & editing.

523

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529

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APPENDIX

Table 8. List of explanatory variables employed in the classification analysis.

Variables	Rational	Reference
Average sea water temperature	<i>P. oceanica</i> is highly sensitive to temperature fluctuations. Rising seawater temperatures alter its functions and distribution by increasing respiration, growth, and flowering rates, as well as enhancing microbial metabolism. [69]	Nasa https://giovanni.gsfc.nasa.gov/giovanni/
Salinity	Salinity levels influence the physiological processes of <i>P. oceanica</i> , which is highly sensitive to salinity increases. Such changes can significantly alter the community structure and affect ecosystem stability.[69, 70].	EMODnet https://emodnet.ec.europa.eu/en
Bathymetry	Depth is a critical factor for <i>P. oceanica</i> as it requires adequate light availability to support photosynthesis, which diminishes with increasing depth.	Geoportale Liguria https://geoportal.regione.liguria.it/

Type of seabed (hard, soft)	The rhizome structure of <i>P. oceanica</i> requires specific substrate types for anchoring and demonstrates adaptability based on the characteristics of the seabed, influencing its distribution and stability.	
Chemical status of the seawater	Poor chemical status often caused by heavy metals, hydrocarbons and nutrients in excess often deteriorates water quality, causing increased turbidity and thus impairing the growth conditions of <i>P. oceanica</i> by reducing light availability.	
Marine Protected Areas (MPA)	Protective measures aim to protect <i>P. oceanica</i> from mechanical damage, such as those caused by anchors and fishing gear. In addition, MPAs help reduce pollution and other environmental threats by restricting various human activities.	
MPA's zonation		
Fishing ban		
Anchoring ban		
Minimum distance from coastal defence structures	Elements and features present along the coast that can or have previously altered sediment flow (e.g., the construction of the railway that took place between the late 19th and early 20th centuries), as well as the physico-chemical characteristics of the environment. Coastal structures, infrastructure, and settlements can disrupt sediment dynamics and light availability. <i>P. oceanica</i> meadows have often been buried during coastal development or construction or have experienced delayed decline due to altered conditions near ports, including changes in hydrodynamics, nutrient loading, epiphyte growth, and pollution. Surviving meadows typically exhibit reduced productivity and abundance as a result of these disturbances. [71]	
Minimum distance from railroads		
Minimum distance from type of shoreline (sand, gravel, rock, artificial)		
Minimum distance from harbors and small marinas		
Effect due to the proximity of rivers and streams		Elements and features present along the coast that can or have altered sediment

<p>Effect due to the proximity of sewage</p>	<p>flow and the physico-chemical characteristics of the environment. Nutrient enrichment from freshwater inputs and sewage can lead to eutrophication, resulting in loss of <i>P. oceanica</i> due to deterioration of light, sediment and water conditions. [69, 72]</p>	
<p>Effect due to the proximity of beach nourishment projects</p>	<p>Elements and features present along the coast that can or have altered sediment flow and the physico-chemical characteristics of the environment. Sediments used in these projects can increase turbidity and also bury <i>P. oceanica</i> meadows. [69, 72]</p>	
<p>Percentage of land cover near areas of interest:</p> <ul style="list-style-type: none"> Estuaries Public services Olive groves and vineyards Rivers Port areas Urban greenery Accommodation facilities Industrial zones Railways Roads Rocks and cliffs Beaches Urban fabric Vegetation Cultivated areas <p>Fire-affected areas</p>	<p>Coastal elements and features can directly or indirectly alter the conditions of the marine environment. For example, these features may contribute to coastal erosion, changes in sediment dynamics, and variations in water quality. Such altered conditions may negatively affect the presence and survival of <i>P. oceanica</i> [69, 72]</p>	

4.4 RESEARCH I

I

HABITAT SUITABILITY MODELS AS A PRIORITIZATION TOOL FOR ENHANCING THE RESTORATION SUCCESS OF *ERICARIA* *AMENTACEA*

by

Bordoni R., Paoli C., Asnaghi, V., Chiantore, M., Farina L., Gaino, F., Rigo, I., Ruggeri, F.,
Vassallo, P.

Habitat Suitability Models as a prioritization tool for enhancing the restoration success of *Ericaria amentacea*

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ABSTRACT

Ecological restoration is increasingly recognized as crucial for addressing global environmental challenges, including biodiversity loss, ecosystem degradation and climate change. Restoration efforts, such as those outlined in the European Biodiversity Strategy and the UN Sustainable Development Goals, are gaining momentum worldwide. Additionally, the EU's recently entered into force the Regulation (EU) 2024/1991 on nature restoration and amending Regulation (EU) 2022/869 which sets ambitious targets for restoring degraded habitats.

In the Mediterranean, brown macroalgae belonging to the *Cystoseira s.l.* complex (including *Cystoseira*, *Gongolaria*, and *Ericaria*) play an important role as "ecosystem engineers" in coastal habitats, although their populations have declined due to anthropogenic pressures. Restoration efforts are essential to support the conservation of the forests they form, restoration efforts are essential. In this context, Habitat Suitability Models (HSMs) provide an effective tool for guiding restoration strategies by mapping the distribution of suitable habitats. By establishing correlations between species distribution and environmental conditions, HSMs provide insights into potential restoration sites, helping to optimize conservation efforts. In this regard, this study develops a habitat suitability model (HSM) for the species *Ericaria amentacea* along the Ligurian coast (NW Mediterranean). Using presence-absence data combined with environmental and anthropic variables, the Random Forest algorithm predicted 920 sectors suitable for *E. amentacea* beyond the 313 where it is present. The Habitat Quality model (INVEST Workbench), along with an assessment of proximity to harbors and marinas, was used to further refine and prioritize the sectors predicted by the model that are most likely to succeed in restoration success, based on accessibility and habitat quality. These findings offer

a valuable tool for enhancing biodiversity conservation and restoration efforts in Mediterranean coastal ecosystems.

Keywords: Habitat Suitability Model, Random Forest, biodiversity conservation, Habitat Quality, Nature Restoration and Regulation Law

1. INTRODUCTION

Addressing pressing global environmental challenges and ensuring the provision of ecosystem services essential to human well-being will require concerted efforts to increase both the extent and functionality of ecosystems. Achieving this goal requires a balanced approach that integrates environmental protection with active ecological restoration (Gann et al., 2019).

As recognition of the need for environmental restoration grows, ecological restoration initiatives are increasing worldwide (Gann et al., 2019). The Biodiversity Strategy to 2020 (European Commission (EC), 2011) supported habitat restoration by promoting the reintroduction of species to areas where they historically occurred, provided that the causes of their initial decline have been addressed. These goals have been reinforced by the Biodiversity Strategy to 2030 (EC, 2020), including legally binding targets, integrating climate resilience, and aligning more closely with the EU's Green Deal objectives. Similarly, the Convention on Biological Diversity (2016) emphasizes the restoration of degraded natural and semi-natural ecosystems to reverse biodiversity loss, restore connectivity, increase ecosystem resilience, improve ecosystem services, and mitigate the effects of climate change. The United Nations Sustainable Development Goals (SDGs) for 2030 also prioritize ecosystem restoration for marine, coastal (Goal 14), and terrestrial ecosystems (Goal 15). These goals aim to protect, restore, and promote sustainable land use, ensure sustainable forest management, fighting desertification, and halt and reverse land degradation and biodiversity loss.

Since the restoration of degraded coastal habitats has been increasingly recognized as an effective strategy (Abelson et al., 2020), especially in light of the UN Decade of Ecosystem Restoration (2021-2030), the EU Nature Restoration Law (Regulation (EU) 2024/1991 on nature restoration and amending Regulation (EU) 2022/869) recently entered into force, as an effort to address biodiversity loss and ecosystem degradation. It sets specific targets: by 2030, at least 30% of marine ecosystems in poor condition must be restored, increasing to 60% by 2040 and 90% by 2050, as quantified in national restoration plans.

In this context, Mediterranean macroalgal forests, predominantly composed of canopy-forming species within the complex *Cystoseira* sensu lato (*Cystoseira*, *Gongolaria*, and *Ericaria*),

emerge as targets for restoration efforts due to their large ecological role in supporting biodiversity and ecosystem functioning and providing services to humans (Sauvageau, 1912; Feldmann, 1937; Ercegović, 1952; Molinari Novoa and Guiry, 2020).

The complex *Cystoseira s.l.*, classified among the brown algae of the order *Fucales*, spans the Mediterranean and Atlantic coasts and grows from the intertidal to the lower sublittoral zones (Falace et al., 2018). Ecologically, *Cystoseira s.l.* complex is recognized as an "ecosystem engineer" due to its pivotal role in regulating spatial habitat heterogeneity, productivity, and nutrient cycling in temperate rocky environments (Falace et al., 2018). By forming dense canopies and intricate three-dimensional structures, *Cystoseira s.l.* creates essential habitats that provide food and shelter for several species (Bulleri et al., 2002; Rodríguez-Prieto et al., 2013). *Cystoseira s.l.* species are listed as "of Community interest" under the Habitats Directive (92/43/EEC) and serve as indicators of environmental quality in Mediterranean coastal waters, as defined by the Water Framework Directive (2000/60/EC). Several species are also protected by the Bern Convention, prioritized by the Barcelona Convention and considered vulnerable by international organizations such as IUCN, RAC/SPA and MedPan.

Cystoseira s.l. habitats provide a number of ecosystem services. Contributing significantly to carbon sequestration and nutrient cycling, these algae are essential for maintaining ecological balance and mitigating climate change (Boudouresque, 1972; Verlaque, 1987; Ballesteros, 1988, 1989, 1990a, 1990b; Sales and Ballesteros, 2012; Piazzini et al., 2018; De La Fuente et al., 2019; Pinna et al., 2020). In addition, these habitats support fish stocks that benefit both commercial and recreational fisheries, providing significant economic and cultural value (Costa-Domingo et al., 2022; Friedrich et al., 2022).

The brown algae *Cystoseira s.l.* are widespread throughout the Mediterranean Sea (Rodríguez-Prieto et al., 2013), facing numerous disturbances that have led to a decline in their abundance in many coastal areas (Airoldi et al., 2008; Mineur et al., 2015). The main threats consist of habitat destruction, sedimentation, low water quality, human activities (e.g. coast cementing, trampling), overgrazing by herbivores and eutrophication (Bellan-Santini, 1965; Munda, 1993; Sala, Boudouresque and Harmelin-Vivien, 1998; Cormaci and Furnari, 1999; Thibaut et al., 2005; Arévalo, Pinedo and Ballesteros, 2007; Mangialajo et al., 2008; Perkol-Finkel and Airoldi, 2010; Sales et al., 2011; Pinedo et al., 2013; Vergés et al., 2014; Ivesa et al., 2016).

After degradation, a natural recovery of *Cystoseira s.l.* populations is a rare event (Chapman, 1995; Soltan et al., 2001; Sales et al., 2011; Capdevila et al., 2018a; Riquet et al., 2021), although there have been instances of such recovery (Ivesa et al., 2016). Limited natural

recovery is primarily due to the poor dispersal ability of *Cystoseira s.l.* species, which results from the fast fertilization of their large eggs and the fast sinking of zygotes (Falace et al., 2018). Given these challenges, active restoration methods have emerged as one of the few viable strategies for reestablishing lost *Cystoseira s.l.* forests (Smith et al., 2023). A critical first step in these restoration efforts is the identification of restoration needs (*i.e.*, areas where *Cystoseira s.l.* species are in regression or lost compared to past distribution) and suitable sites for intervention (*i.e.*, areas suitable for *Cystoseira s.l.* presence, where main stressors have been removed; Gianni et al., 2013; Frascetti et al., 2021; Fabbrizzi et al., 2023). In this context, Habitat Suitability Models (HSMs) support the geographic perspective of conservation strategies by producing maps of the distribution of suitable habitats (Barbosa 2003; Rondinini et al. 2005; Pearce and Boyce 2006).

HSMs are used in a variety of ecological studies and are particularly useful in cases where data on species presence and absence are available, that allows researchers to establish correlations between species distribution and several environmental conditions, thereby identifying potential new habitats or assessing changes in habitat suitability over time (Franklin, 1995; Guisan and Zimmermann, 2000; Hirzel and Le Lay, 2008).

In the Mediterranean marine environment, HSMs have proven to be invaluable for a wide range of applications. For example, these models have been used to assess the distribution and conservation status of several marine species and habitats (e.g., Falace et al., 2015; Carlucci et al., 2016; Vassallo et al., 2018). A notable recent application of HSMs in the Mediterranean context is the work of Fabbrizzi et al. (2020), which focused specifically on assessing the distribution of macroalgal forests at the Mediterranean scale. These studies used HSMs to understand habitat distribution and to predict how environmental changes might affect marine biodiversity and ecosystem services.

Overall, HSMs are a powerful tool for ecological research and conservation planning. Their ability to predict habitat suitability based on empirical data allows researchers to make informed decisions about species management and habitat restoration (Franklin, 1995; Guisan and Zimmermann, 2000).

This study aims to develop a comprehensive HSM for *Ericaria amentacea* (*C.Agardh*) *Molinari & Guiry 2020*, a brown macroalgae species belonging to the *Cystoseira s.l.* complex thriving in shallow rocky reefs, at its northern limit in the Mediterranean region: the Ligurian coast. The main objective is to use existing knowledge on the distribution of *E. amentacea* to identify areas of potential habitat suitability and to support conservation efforts for this species.

The Ligurian coast provides an exemplary setting for this study due to its historical role as a pilot area for the Italian CARLIT methodology (Ballesteros et al., 2007). The CARLIT index (CARtography of LITtoral and upper-sublittoral benthic communities), established under the Water Framework Directive (2000/60/EC), provides a comprehensive framework for the assessment of coastal water quality in the Mediterranean Sea. This index evaluates the health of the marine environment based on the composition of macroalgal assemblages along rocky coastlines, providing a valuable baseline for monitoring and management efforts (Ballesteros et al., 2007). In the Liguria region, this methodology has been widely applied since 2006, generating a long-term dataset containing information on the presence and absence of various marine species, including *E. amentacea*. ARPAL, the Regional Agency for Environmental Protection in Liguria, is responsible for assessing the CARLIT index in designated water bodies (WBs) along the Ligurian coast. Each WB, as described in the national methodology report (Mangialajo et al., 2008), is divided into 50 m segments, with a subset of these segments monitored annually to ensure that each WB is assessed every three years.

The HSM developed in this study uses the CARLIT dataset along with additional environmental and anthropic variables to predict suitable habitats for *E. amentacea* using the Random Forest (RF) algorithm, a robust machine learning technique introduced by Breiman, 2001.

The RF model integrates these variables to map potential areas where *E. amentacea* may be found, providing insight into areas where this species has not been studied and pointing out those areas that might be in need for restoration activities.

Once the RF model identifies potential locations for *E. amentacea*, additional criteria are applied to refine the list of potential restoration sites. These criteria are designed to assess habitat quality and prioritize sites based on their suitability for restoration efforts. From the results of this assessment, only those sites located in areas with a better ecological integrity and easier access from a port are selected for further consideration in order to prioritize restoration activities in areas that are easy to reach and operate.

2. MATERIAL AND METHODS

2.1 Study area

The study area encompasses the northwestern Mediterranean region, with a particular focus on the coastline of Liguria (NW Italy). It extends approximately 731 kilometers from the western border with France to the eastern border adjacent to the administrative region of Tuscany.

Figure 1 provides a detailed overview of the study area and illustrates its division into four distinct sub-regions: Western Liguria (W), Mid-Western Liguria (MID-W), Mid-Eastern

Liguria (MID-E), and Eastern Liguria (E). These sections are always represented in the following figures of this paper for the sake of a clearer representation of results and to allow a more detailed study and observation of the coastal environments of the region.

The Ligurian coast is renowned for its rich biodiversity, reflecting the Mediterranean's status as a global biodiversity hotspot. However, this region also faces significant anthropic pressures due to high population densities and the convergence of various human activities, including tourism, urban development, and commercial enterprises (Cattaneo-Vietti et al., 2010). These activities can cause both physical damage to rocky coastal ecosystems and changes in the chemical and biological conditions of seawater, with potentially serious ecological consequences (Mangialajo et al., 2007).

To assess the distribution of *E. amentacea* along the Ligurian coast, the entire coastline was segmented, each averaging approximately 50 meters in length, reporting a total of 15550 sectors. This segmentation was carried out using the open-source Geographic Information System QGIS software (version 3.22.8) and adhered to the European Geodetic Reference System ETRS89-ETRF89 with UTM32 cartographic representation.

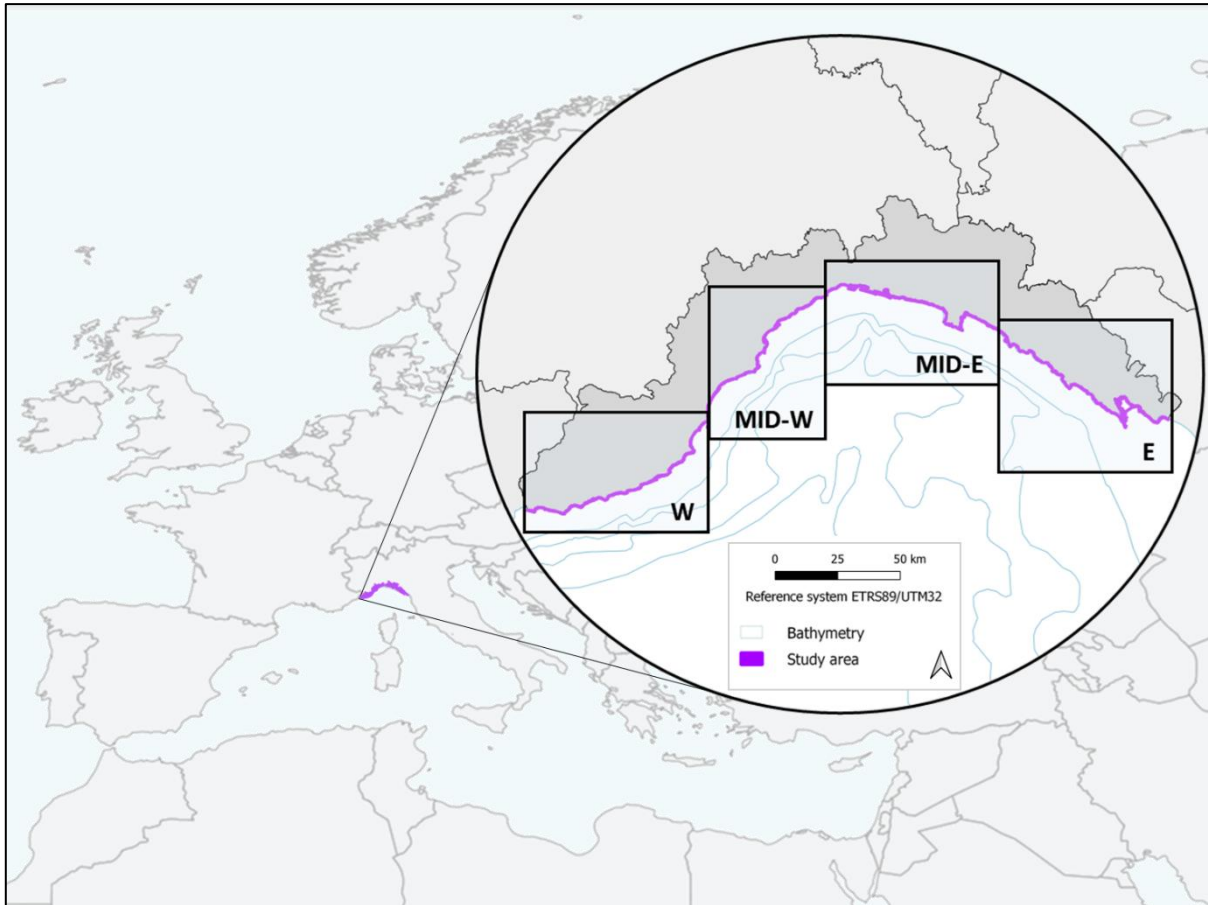


Figure 1. Study area divided into sub-regions: Western Liguria (W), Mid-Western Liguria (MID-W), Mid-Eastern Liguria (MID-E) and Eastern Liguria (E).

2.2 Habitat suitability model for *E. amentacea*

Figure 2 illustrates the structure of the HSM process, detailing how the steps (i.e., the classification analysis and the definition of criteria to determine the best set of sectors for restoration activities) are interrelated to achieve the selection of proposed sites for restoration activities implementation.

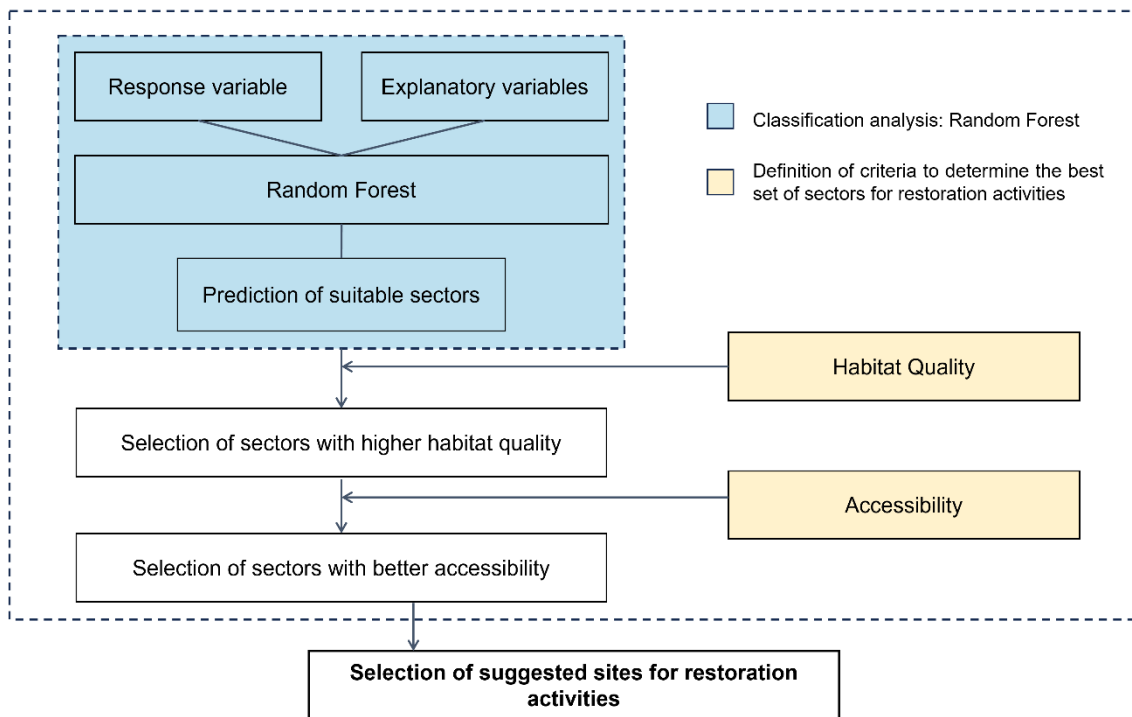


Figure 2. Schematic representation of the HSM process

2.2.1 Classification analysis: Random Forest

a. Response variable: Collection of georeferenced data of *E. amentacea*

To assess the distribution of *E. amentacea*, data were collected through:

- the collaboration with the regional environmental agency (ARPAL), which calculates the CARLIT index that provided comprehensive information on macroalgal assemblages along the Ligurian WBs;
- the use of the Geoportale Regione Liguria (www.geoportale.regione.liguria.it) to obtain precise geographic coordinates for the recorded locations of *E. amentacea*.

For this study, data from the last three years available and relevant for the calculations of the CARLIT methodology were selected for data collection (2019, 2020, and 2021).

Finally, all *E. amentacea* distribution information was digitized (Figure 3) and associated with coastal sectors (thus identified as presence and absence sectors), resulting in 313 sectors where the species is recorded.

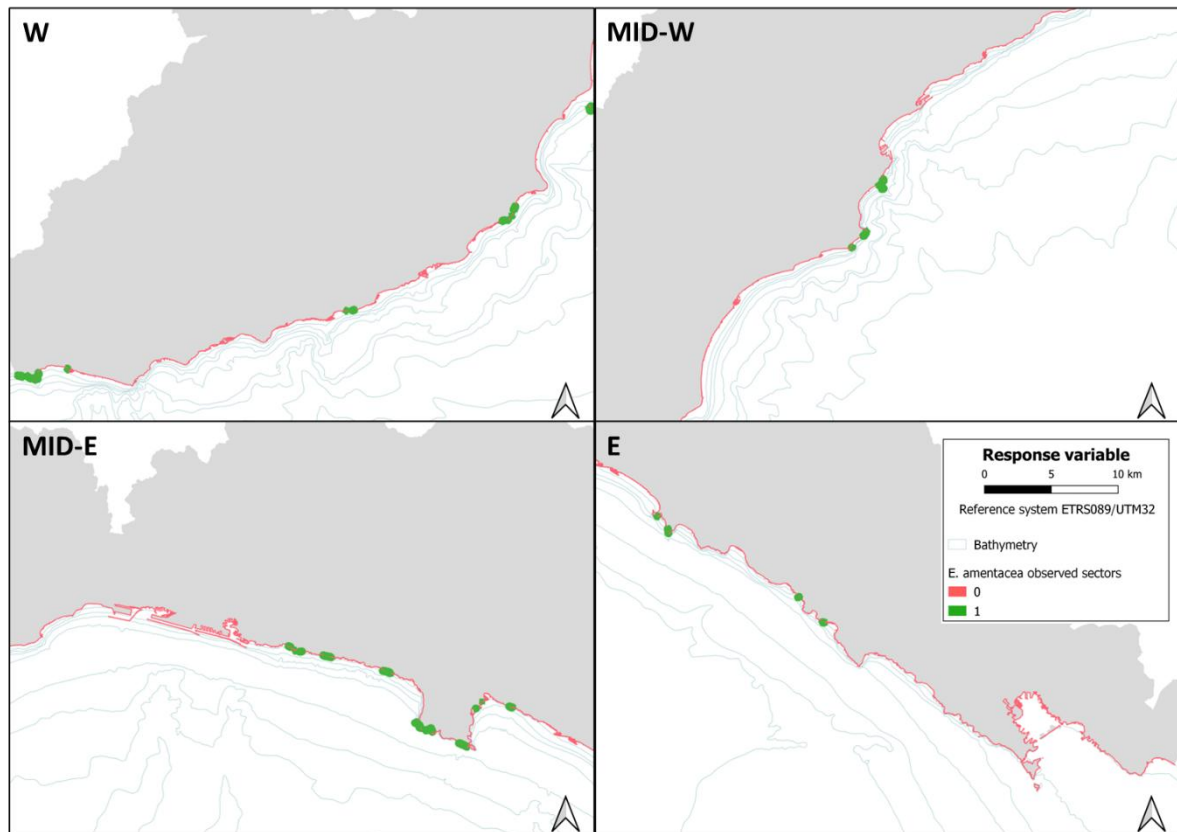


Figure 3. Distribution of *E. amentacea* in the study area, based on ARPAL monitoring for the calculation of the CARLIT Index (years 2019 – 2020 - 2021).

b. Explanatory variables: natural and anthropogenic pressures

A set of predictor variables (Appendix, Table 5) were associated with the dataset containing the presence and absence of *E. amentacea* in each sector. Several environmental and anthropic characteristics were considered as inputs for the modeling procedure. The elaboration of these variables was done using QGIS (version 3.22.8) and MATLAB (version R2024b).

These variables represent factors affecting the study area and include both natural and anthropogenic pressures and elements. Natural variables include seawater salinity, temperature, and other environmental conditions, while anthropic variables include factors such as the proximity of human activities to the sectors and their potential impacts (e.g., minimum distance from harbors and small marinas, proximity to rivers and streams). The selection of these variables was based on identifying those already used in similar model-based approaches (e.g., Fabbri et al., 2020; Rigo et al., 2024; Bordoni et al., 2024) and those that, based on expert judgment, could potentially influence the species.

c. Random Forest

Random Forest (RF) is a machine learning technique that can handle complex data sets with several variables and effectively identify the most influential factors for predicting outcomes. Derived from regression tree methodology, RF builds a large number of decision trees to model the relationship between explanatory variables and a response variable by partitioning the data into subsets (Breiman et al., 1984; Clark and Pregibon, 1992; Verbyla, 1987).

The RF algorithm grows a collection of decision trees, each based on different random subsets of the data, a process that begins with partitioning the data into two distinct sets: a training set and a test set (Breiman, 2001). The training set, known as the "in-bag" data, is used to develop the trees, while the "out-of-bag" data remains unused during tree development and plays a critical role in evaluating the model's generalization error (Breiman, 2001). This out-of-bag data allows for an unbiased evaluation of the model's performance, with the generalization error decreasing as the number of trees increases and eventually stabilizing as the forest size increases (Hartshorn, 2016).

One of the features of RF is its ability to assess the importance of predictor variables in determining the response variable. This is accomplished by observing changes in the accuracy of the model when individual variables are excluded, which reveals how each variable influences the predictions (Breiman, 2001). Understanding the importance of variables helps researchers to determine which factors are most important in influencing response outcomes. To further explore these relationships, partial dependence plots can be used, which graphically represent the effect of individual variables on the predicted probabilities of the response variable (Hastie et al., 2001).

Using the RF algorithm, predictions are made and categorized into four different outcomes, which are summarized in a confusion matrix. This matrix is a two-by-two table that compares the model's predictions with actual observations. The categories are defined as follows:

- True Presences (TP): Instances where the model correctly predicts the presence of a feature.
- True Absences (TA): Instances where the model correctly predicts the absence of a feature.
- False Presences (FP): Instances where the model incorrectly predicts the presence of a feature.
- False Absences (FA): Instances where the model incorrectly predicts the absence of a feature.

From this confusion matrix, several performance metrics can be derived:

- Error Rate (ERR): The ratio of incorrect predictions (both false presences and false absences) to the total number of observations. A lower ERR indicates a more accurate model.

$$ERR = \frac{FP + FA}{TP + TA + FP + FA};$$

- Accuracy (ACC): The ratio of correct predictions (both true presences and true absences) to the total number of observations. It measures how often the model is correct overall.

$$ACC = \frac{TP + TA}{TP + TA + FP + FA};$$

- Sensitivity (SN): Also known as the True Positive Rate, it measures the proportion of true presences that are correctly identified by the model.

$$SN = \frac{TP}{TP + FA};$$

- Specificity (SP): Also known as the True Negative Rate, it measures the proportion of true absences that are correctly identified by the model.

$$SP = \frac{TA}{TA + FP};$$

- Precision (PREC): This metric indicates the proportion of true presences predictions out of all presence predictions made by the model.

$$PREC = \frac{TP}{TP + FP};$$

- False Positive Rate (FPR): It measures the proportion of absences instances that are incorrectly classified as presences.

$$FPR = \frac{FP}{TA + FP};$$

These metrics are essential for evaluating the effectiveness of the RF model in predicting the presence or absence of a feature. The confusion matrix and its derived metrics provide valuable insight into the performance of the model and help identify areas for improvement (Breiman, 2001).

In the context of this study, the RF model aggregates the results of multiple decision trees to classify areas based on the presence or absence of *E. amentacea*. For the study, the RF model was implemented using R software (Liaw and Wiener, 2022), with the data set divided into a

training set and a test set. The training set consists of two thirds of the sectors showing the presence of *E. amentacea* and an equal number of sectors showing the absence of *E. amentacea*. The test set consists of the remaining one-third of the sectors with the presence of *E. amentacea* and an equal number of sectors with the absence of *E. amentacea*.

A total of 1500 trees were used in the forest to ensure robust model performance.

The RF approach used here involved evaluating various predictor variables for their significance in relation to the presence or absence of *E. amentacea*. While the RF model tested all variables for relevance, this study specifically examines those variables that had the most significant impact on the model's predictions.

2.2.2 Definition of criteria to determine the best set of sectors for restoration activities

The planning process for *E. amentacea* restoration activities used a two-step strategy to identify the most effective sectors for intervention.

The first step of the strategy was to exclude sectors where *E. amentacea* presence prediction coincided with detected presence, identified as "True Presence" (TP) sectors. By excluding these TP sectors, the focus shifted to areas identified as suitable for the species but not yet supporting its natural populations (False Presences, FP), with the aim of focusing restoration efforts on sectors that could benefit most from intervention, according to Habitat Quality and Accessibility.

In fact, in the next step, the FP sectors were evaluated based on the two primary criteria, Habitat Quality and Accessibility.

a. Habitat Quality

To identify the most promising sectors for successful restoration of *E. amentacea*, the environmental conditions of the remaining sectors were assessed to ensure that restoration efforts would have the greatest positive impact on the species. This assessment was critical because the loss and degradation of natural habitats is a major driver of biodiversity decline (Butchart et al., 2010; Sharma et al., 2018; Van der Biest et al., 2020). Habitat quality, which reflects the ability of an environment to support the survival and reproduction of organisms, was assessed using the InVEST Habitat Quality Model (version 3.11.10) (Terrado et al., 2016; Huang et al., 2020, Bao et al., 2016).

This model requires various inputs, including land use data, stressors, sources of stress, and parameters related to habitat sensitivity and semisaturation (Table 1 and Table 2). The habitat

types used in this model were obtained from the Atlas of the Marine Coastal Habitats of Liguria (Coppo et al., 2020) and are described in the Appendix in Table 5, while the land use information was obtained from the Geoportale Regione Liguria (<http://www.geoportale.regione.liguria.it>).

Habitat quality was quantified using the following equation:

$$Q_{xj} = H_{xj} \times \left[1 - \left(\frac{D_{xj}^2}{D_{xj}^2 + k^2} \right) \right]$$

Where:

- Q_{xj} represents the habitat quality of grid cell x for land-use type j ;
- H_{xj} is the habitat suitability of grid cell x for land-use type j ;
- D_{xj} denotes the degree of habitat degradation for grid cell x in land-use type j ;
- k is the half-saturation constant, set to 0.5
- The scale constant z was taken as 2.5, a standard value for such models (Chiang et al., 2014).

In this model, Q_{xj} values range from 0 to 1, where the minimum value indicates poor habitat quality and maximum value stands for 100% habitat quality. The model's output provided a detailed evaluation of habitat conditions across the study area, guiding the selection of sectors for *E. amentacea* restoration.

Table 1. Threat factors and weight in the study area.

MAX_DIST	WEIGHT	THREAT	DECAY
2	0.1	Olive groves and vineyards	linear
10	0.9	Urban landscape	exponential
5	0.6	Railways	linear
2	0.2	Accommodation facilities	linear
10	0.9	Harbor areas	exponential
8	0.7	Industrial zones	exponential
3	0.4	Roads	linear
2	0.1	Cultivated areas	linear

Table 2. The sensitivity of land use to each threat habitat in the study area.

NAME	Olive groves and vineyards	Urban landscape	Roads	Cultivated areas	Industrial zones	Harbor areas	Railways	Accommodation facilities
PA	0.1	0.8	0.2	0.1	0.7	0.9	0.3	0.2
PA-A	0.1	0.8	0.2	0.1	0.7	0.9	0.3	0.2
PA-BR	0.1	0.8	0.2	0.1	0.7	0.9	0.3	0.2

SAC	0.1	0.8	0.1	0.1	0.7	0.9	0.1	0.1
SAI	0.1	0.8	0.1	0.1	0.7	0.9	0.1	0.1
C	0	0.2	0	0	0.4	0.5	0	0
C-M	0	0.2	0	0	0.3	0.5	0	0
CYL	0.1	0.8	0.1	0.1	0.7	0.9	0.2	0.1
CYM	0.1	0.8	0.1	0.1	0.7	0.9	0.3	0.1
CYM-CAU	0.1	0.8	0.1	0.1	0.7	0.9	0.3	0.1
CYM-DENSE	0.1	0.8	0.1	0.1	0.7	0.9	0.4	0.1
CYM-DM	0.1	0.8	0.1	0.1	0.7	0.9	0.4	0.1
CYM-POS	0.1	0.8	0.1	0.1	0.7	0.9	0.5	0.2
M	0	0.2	0	0	0.2	0.4	0.4	0
DM	0.1	0.8	0.1	0.1	0.7	0.9	0.5	0.2
MOS	0.1	0.8	0.1	0.1	0.7	0.9	0.5	0.2
POS	0.1	0.8	0.1	0.1	0.7	0.9	0.5	0.2
POS-CAU	0.1	0.8	0.1	0.1	0.7	0.9	0.5	0.2
POS-R	0.1	0.8	0.1	0.1	0.7	0.9	0.5	0.2
OR	0	0	0	0	0	0.2	0	0
S	0	0.2	0	0	0.2	0.4	0.4	0
CS-C	0	0.3	0	0	0.2	0.4	0.2	0
UA	1	1	1	1	1	1	1	1
CAU	0	0	0	0	0	0	0	0
CA	0	0.2	0	0	0	0.4	0.1	0
CS	0	0.2	0.1	0	0.2	0.4	0.2	0
DB	0	0.2	0.1	0	0.2	0.4	0.2	0
DB-I	0	0.2	0.1	0	0.2	0.4	0.2	0

Thus, obtained results of the RF analysis allowed to identify several geographic sectors predicted to be favorable for the *E. amentacea* distribution. Specifically, the focus was on sectors where the habitat quality was rated above 90%, indicating that these areas are among the best possible environments for the survival and well-being of *E. amentacea*. Given their high-quality habitat conditions, these sectors are ideal locations for targeted restoration efforts to ensure the long-term conservation of *E. amentacea*.

b. Accessibility

This study considered also the logistical aspects of reaching potential restoration sites by evaluating their proximity to access points (i.e., harbors and marinas).

In Liguria, where the rocky coastline is often difficult to access by land due to the lack of suitable roads, proximity to a harbor or marina can greatly facilitate the transportation of the necessary restoration equipment and teams. Figure 4 shows a map with the locations of all

harbors and marinas in the study area, based on data obtained from the Geoportale of the Liguria Region (www.geoportal.regione.liguria.it).

For the previously selected high-quality sectors, the minimum distance to the nearest harbor or marina was then calculated to help guide restoration efforts.

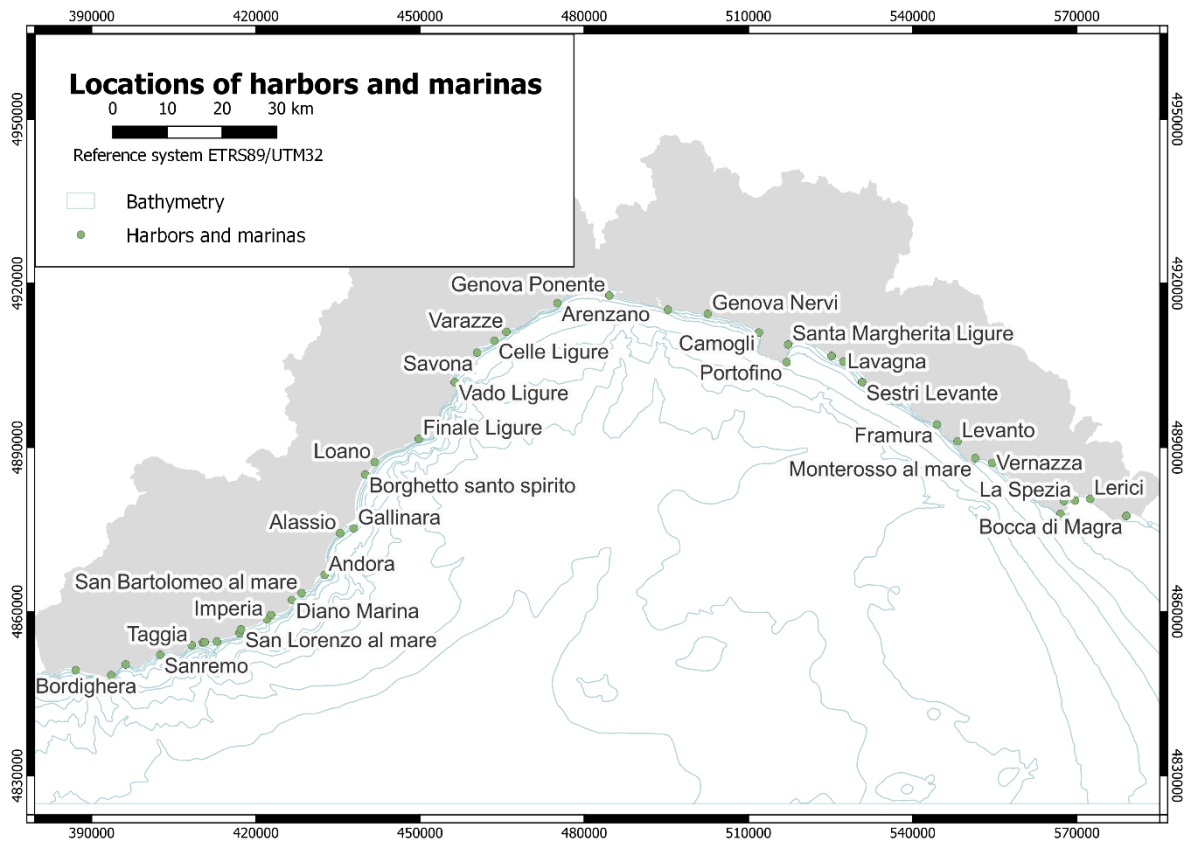


Figure 4. Location of harbors and marinas along Ligurian coast.

By integrating these criteria, this study aimed to streamline the selection of restoration sites to focus on those that offer the best balance of high habitat quality and practical accessibility. This method ensures that the most promising areas for species recovery are targeted, while also facilitating the practical implementation of restoration activities.

3. RESULTS

3.1 Habitat suitability model for *E. amentacea*

3.1.1 Classification analysis: Random Forest

The importance of the most influential explanatory variables and their partial plots obtained through the RF application are illustrated in Figure 5. Importance of explanatory variables in determining the response variable and related partial dependence plots. The most influential variable is human population density (80%), indicating that the presence of *E. amentacea* is more likely where relatively low population densities is registered. As population

density increases, the presence of the species becomes less detectable, with the trend reaching a plateau at around 900 people/km². Both the proximity to beach nourishment projects and the percentage of beaches in the sector show a similar trend, but their importance in the prediction differs, being 61% and 31%, respectively. Particularly, the greater the impact of beach nourishment and the greater the percentage of beaches, the more likely the absence of *E. amentacea*. In addition, the minimum distance from railroads (54% importance) and the minimum distance from coastal defense structures (52% importance) follow a similar trend: the further away from railroads and coastal defense structures, the more likely the presence of *E. amentacea*.

Finally, two other variables show a similar trend. Both Marine Protected Areas (48% importance) and high coast (cliffs; 26% importance) favor the presence of *E. amentacea*.

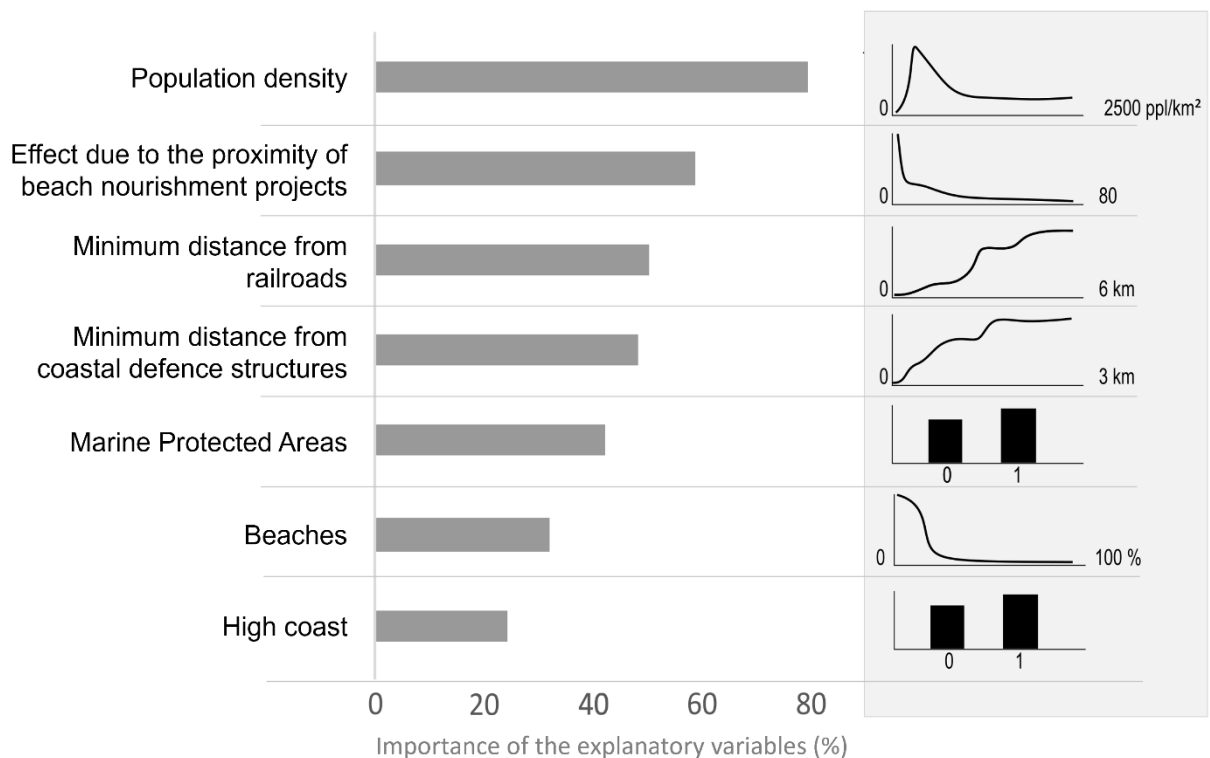


Figure 5. Importance of explanatory variables in determining the response variable and related partial dependence plots.

The model identified a total of 1201 sectors as potentially suitable for the presence of *E. amentacea*: 281 sectors corresponded to actual observations of the species (TP), while 920 sectors were predicted as suitable, since they were sites where the species is absent although conditions seems suitable for its occurrence (FP). Additionally, 32 sectors were predicted as false absences (FA), since they were sites where the species was actually recorded (Table 3).

Table 3. Confusion matrix for the classification analysis.

TRUE PRESENCES	TRUE ABSENCES	FALSE PRESENCES	FALSE ABSENCES	TOTAL SECTORS
281	14317	920	32	15550

The metrics derived from the confusion matrix for both prediction sets are summarized in Table 4. The model achieves an overall accuracy of 94%, with an error rate of 6% (ERR = 0.06). Sensitivity (SN) and specificity (SP) are both relatively high, respectively 0.90 and 0.94. Precision (PREC) is significantly lower (at 0.23), and the false positive rate (FPR) stands at 0.02.

Table 4. Measures of classification quality derived from the confusion matrix.

ERR	ACC	SN	SP	PREC	FPR
0.06	0.94	0.90	0.94	0.23	0.02

Figure 6 displays the spatial distribution of the predicted sectors in the study area, revealing a higher concentration of predicted sectors, almost 70% of the sectors, along the eastern coast of Liguria.

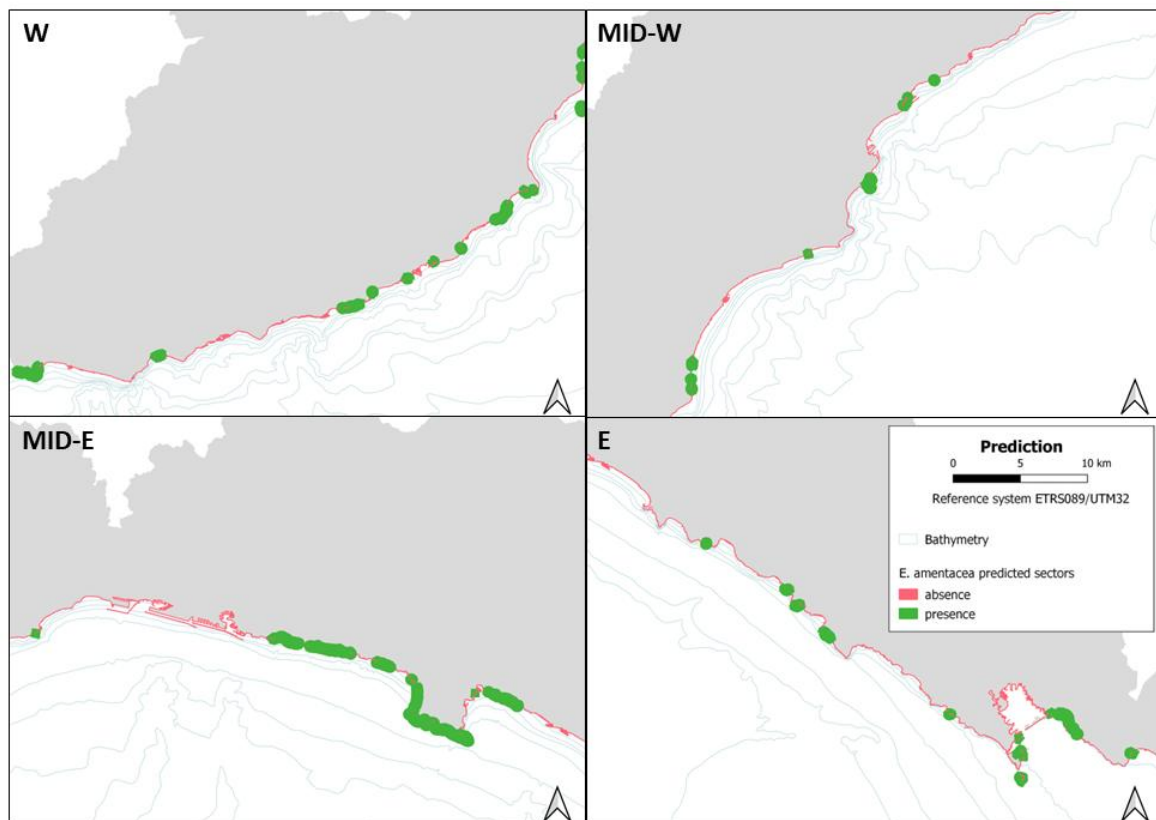


Figure 6. Distribution of predicted sectors for *E. amentacea*.

3.1.2 Application of criteria to determine the best set of sectors for restoration activities

The Habitat Quality model assessed the habitat quality in a range between approximately 50% and 100%. Excluding sectors corresponding to true presences (TP), there were 154 predicted sectors with habitat quality greater than 90%. Among these, 142 sectors are located within areas designated as Marine Protected Areas (MPAs). In addition, the distance between each sector and the nearest harbor or marina was calculated, showing that 43 sectors are within 2 km of the nearest harbor or marina, 107 sectors are between 2 km and 5 km away, and 4 sectors are between 5 km and 8 km from the nearest harbor or marina.

Figure 7 illustrates these results, showing the distribution of habitat quality and proximity to harbor and marinas and the resulting sectors.

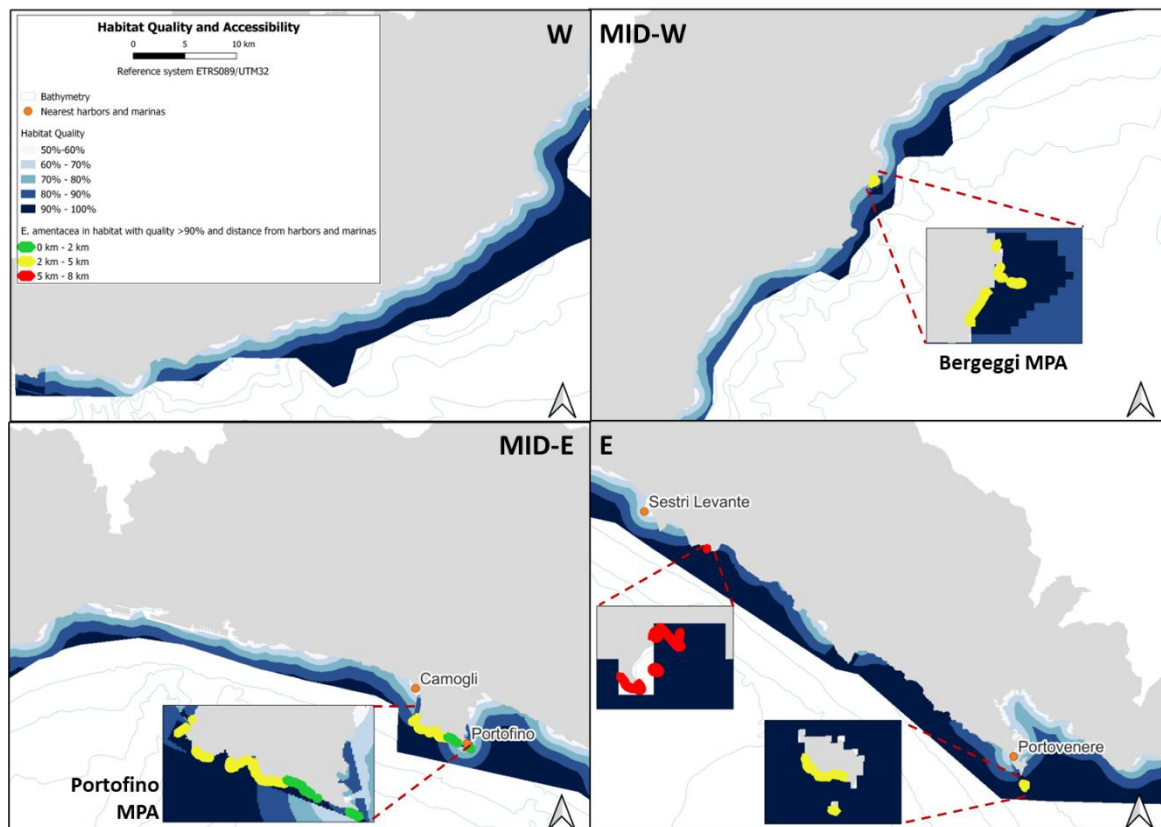


Figure 7. Habitat Quality and Accessibility.

4. DISCUSSION

The Random Forest model shows a high overall accuracy (94%) in predicting the presence of *E. amentacea* along the Ligurian coast. The high sensitivity (90%) and specificity (94%) values suggest that the model is able to correctly identify both the presence and the absence of the species. However, the low precision (23%) indicates a significant number of false presences, where the model predicts *E. amentacea* in sectors where it is not present or verified. Despite

the low precision, the model identifies 920 sectors where presence is predicted while not verified. These sectors represent areas that may be suitable for *E. amentacea*, and therefore need further investigation in a restoration perspective. For these sites, specific field surveys would allow to verify if the prediction of the model is correct (Vassallo et al., 2018). In fact, the predicted sectors may represent new sites where the species can potentially survive and thrive, or these sectors may already host the species, but there are no existing records to confirm its presence due to survey limitations.

The methodology used in this study to assess the presence/absence of *E. amentacea* based on the CARLIT index is biased. This bias is due to the fact that the CARLIT surveys are conducted year after year in the same areas, following a hierarchical sampling design, that means that only a subset of representative stretches of coast are surveyed for each area (Mangialajo et al., 2007; Asnaghi et al., 2009; De La Fuente et al., 2018). As a result, potential new occurrences in unexplored sectors remain unrecorded, leading to an incomplete understanding of the true distribution of the species. Thus, a punctual analysis of the presence of *E. amentacea* and the water quality status through the CARLIT index application, which differs from year to year, could be useful in order to obtain the best prediction result from the model. Looking at the distribution of *E. amentacea*, it is evident that most of the sectors are located in the eastern part of the Ligurian coast, specifically in sub-regions E and MID-E of Figure 6.. This pattern can be attributed to the fact that the eastern coast is rockier than the western coast. The rocky nature of the eastern Ligurian coast creates a favorable environment for *E. amentacea*, a canopy-forming algae important for habitat formation in shallow subtidal and intertidal rocky zones. (Reed and Foster, 1984; Santelices and Ojeda, 1984; Dayton, 1985; Duggins and Dethier, 1985; Benedetti-Cecchi and Cinelli, 1992).

When analyzing the predictor variables (paragraph 3.1.1) to determine the response variable and its associated partial plots, population density emerges as the most influential factor with an importance score of 80%. Specifically, lower population density correlates with a higher probability of finding *E. amentacea*. Conversely, as population density increases, the presence of this species tends to decrease, reaching a plateau around 900 ppl/km². Lower population densities are often associated with less urbanization and reduced human activities, leading to lower levels of pollution and creating a more favorable environment for *E. amentacea*. Several studies have shown that human pressures are increasingly limiting the distribution of *E. amentacea* and similar species (Chrysovergis and Panayotidis, 1995; Rodríguez-Prieto and Polo, 1996; Soltan et al., 2001; Arevalo et al., 2007; Mangialajo et al., 2007; Sales et al., 2011). In recent decades, the populations of *Cystoseira s.l.* species have declined significantly,

especially near urban areas (Benedetti-Cecchi et al., 2001; Soltan et al., 2001; Thibaut et al., 2005, 2015; Ballesteros et al., 2007; Mangialajo et al., 2007, 2008; Perkol-Finkel and Airoidi, 2010). In addition, natural habitats are more likely to be preserved in relatively low-density areas than in densely populated areas. One of the other significant variables in this study is the presence of protected areas, which accounts for 48% of the importance score. MPAs are, in fact, recognized as important tools for the conservation of vulnerable species such as *E. amentacea* (Mangialajo et al., 2007; Cannarozzi et al., 2023). In Liguria, Marine Protected Areas (MPAs) are located in areas with lower population densities compared to large urban centers, and the presence of an MPA may improve the survival chances of *E. amentacea*. The MPA variable is in accordance with the population density variable, reinforcing the assumption that *E. amentacea* thrives in less densely populated areas.

When examining the effect of increasing human population density, it is observed that the presence of *E. amentacea* decreases, although beyond a certain population density threshold, the presence of the species remains relatively stable.

In this study, we find important to exclude areas of very low population density from our analysis. In these cases, *E. amentacea* is often absent, and this scenario is underrepresented in the data. In addition, tourism is typically concentrated in coastal areas, which attract 30% of international tourist arrivals (Candia et al., 2018). In Liguria, areas with very low population density often experience high levels of tourism, which significantly increases the effective population size. During the summer, arrivals to tourist accommodation are almost three times higher than during the winter months, resulting in a significant influx of tourists along the Mediterranean coasts (Candia et al., 2018, Vassallo et al., 2009). Large-scale mass tourism is a major driver of ecological loss and environmental degradation in the region, particularly affecting coastal and marine areas (Candia et al., 2018). This phenomenon complicates the study of the relationship between population density in low-density areas and the presence of *E. amentacea*.

Focusing on the proximity to beach nourishment projects (61% importance) and the percentage of beaches in the sector (31% importance), the higher the impact of beach nourishment and the higher the percentage of beaches, the more likely the absence of *E. amentacea*.

The reason for this negative association can be attributed to the role of sedimentation, which is one of the main pressures affecting the presence of *E. amentacea* (Perkol-Finkel and Airoidi, 2010). Beach nourishment projects, in which sediment is added to beaches to combat erosion, can lead to increased sedimentation in nearby marine environments. Similarly, a higher

percentage of beaches in a given sector often indicates more extensive areas of sediment accumulation and transport, further exacerbating sedimentation pressures.

In addition, the minimum distance from railroads (54% importance) and coastal defense structures (52% importance) shows that greater distances from these features increase the likelihood of finding *E. amentacea*. The absence of *E. amentacea* in these areas can be attributed to habitat fragmentation caused by coastal development, water pollution and high sediment loads. These stressors, associated with the intense excavation activities of the early 20th century, which focused primarily on the extraction of materials for railroad and highway construction, are most likely the cause of *E. amentacea* regression and loss in the easternmost side of the Ligurian sea (De La Fuente et al., 2019). Although these destructive activities have significantly decreased in recent decades, the changes they have caused in the river basin and sediment loads continue to affect this sensitive species, which remains absent from these coastal areas (De La Fuente et al., 2019).

Finally, the high coast (cliffs; 26% importance) is more likely to host *E. amentacea*, both because habitat preference but also because lower direct accessibility to humans (Reed and Foster, 1984; Santelices and Ojeda, 1984; Dayton, 1985; Duggins and Dethier, 1985; Benedetti-Cecchi and Cinelli, 1992).

The model results for Habitat Quality show a gradient from the coast to offshore areas. Near the coast, Habitat Quality is generally lower, with the lowest values around 50%, compared to the offshore areas where values can reach up to 100%. This variation is mainly due to human activities along the coast, which do not affect the more remote offshore areas.

However, there are still some coastal areas with higher habitat quality due to protection status or because of proximity to more rural areas that are less influenced by human pressures.

Habitat quality and distance from access point were chosen in the present study as criteria for identifying potential restoration sites because they are spatially explicit factors. Another important criterion that could be considered is the operability of the site. For species such as *E. amentacea*, which has a low dispersal capacity (Mangialajo et al., 2012), *ex situ* outplanting restoration techniques are considered the more appropriate (Falace et al., 2018; De La Fuente et al., 2019; Clausing et al., 2022, 2024). This method requires specific materials, a dedicated team, and resources for site operations, such as drilling into rocks to attach tiles colonized by the species (De La Fuente et al., 2019). These techniques have been tested for shallow species in low hydrodynamic conditions (Verdura et al., 2018) and for species in mid-littoral habitats (De La Fuente et al., 2019). From an operational point of view, it is essential to identify suitable support points for the implementation of these restoration activities. While this study did not

include field operability as a criterion due to a lack of available data, it is recommended that future evaluations assess which identified sectors are most suitable for practical restoration efforts.

5. CONCLUSION

The HSM model developed in this study serves several purposes. It is a valuable tool for evaluating new potential sites for *E. amentacea*, providing insight into those areas not previously explored with the CARLIT methodology. By integrating ecological, environmental and anthropogenic variables through the Random Forest algorithm, the model produces a detailed map of restoration needs and suitable sites along the Ligurian coast. This not only fills gaps in the current knowledge on *E. amentacea* distribution, but it also informs strategic conservation planning by highlighting areas for targeted restoration. This model brings together habitat quality and strategic location to better optimize restoration efforts and enhance the efficiency of conservation initiatives.

While the study highlights potential restoration sites, it also highlights the need to address ongoing anthropogenic pressures such as urbanization, sedimentation and coastal development that continue to threaten these ecosystems. The integration of habitat quality and accessibility criteria into restoration planning adds an operational dimension, but future work should expand on this by incorporating practical, site-specific considerations to enhance restoration success.

Acknowledgments

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Appendix

Table 5. Explanatory variables.

Variables	Descriptions	References
Type of coast	Rocky, sandy, gravel or artificial coast	Geoportale Liguria: https://geoportal.regione.liguria.it/
High coast	Presence of cliffs	Geoportale Liguria: https://geoportal.regione.liguria.it/
Average seawater temperature	Average annual temperature of the sea (°C)	Nasa Giovanni satellite: https://giovanni.gsfc.nasa.gov/giovanni/
Air temp	Average annual temperature of the air (°C)	Nasa Giovanni satellite: https://giovanni.gsfc.nasa.gov/giovanni/
Salinity	Average annual salinity of the sea (PSU)	EMODnet: https://emodnet.ec.europa.eu/en
Chemical status of the seawater	Chemical status of superficial waters	Geoportale Liguria: https://geoportal.regione.liguria.it/
Population density	Population density of the coastal municipalities	Istat: https://www.istat.it/
Minimum distance from harbors and small marinas	Effect due to the proximity to harbor and marinas, considering a maximum distance of 500m from harbor and 200m from marinas. Scale of effects: 0 (greatest distance, minimum effect)-10 (shortest distance, maximum effect)	Geoportale Liguria: https://geoportal.regione.liguria.it/
Effect due to the proximity of rivers and streams	Effect due to the proximity to rivers and streams' mouth, considering a maximum distance of 500m from rivers' mouth and 200m from streams' . Scale of effects: 0 (greatest distance, minimum effect)-10 (shortest distance, maximum effect)	Geoportale Liguria: https://geoportal.regione.liguria.it/
Effect due to the proximity of sewage	Effect due to the proximity to sewage, considering a maximum distance of 300m from sewage . Scale of effects: 0 (greatest distance, minimum effect)-10 (shortest distance, maximum effect)	Geoportale Liguria: https://geoportal.regione.liguria.it/
Minimum distance from railroads	Minimum distance between each coastline segment and railways	Geoportale Liguria: https://geoportal.regione.liguria.it/
Minimum distance from coastal defence structures	Minimum distance between each coastline segment and coastal defences	Geoportale Liguria: https://geoportal.regione.liguria.it/
Effect due to the proximity of beach nourishment projects	Effect due to the proximity to beach nourishment, considering a maximum distance of 300m from a nourished beach . Scale of effects: 0 (greatest distance, minimum effect)-10 (shortest distance, maximum effect)	Geoportale Liguria: https://geoportal.regione.liguria.it/

Exposure	Average and median orientation	Elaboration on QGIS (v. 3.22.8) and MATLAB (v. 2024a)
Marine Protected Areas (MPA)	Presence of marine protected areas	Geoportale Liguria: https://geoportal.regione.liguria.it/
Percentage of land cover near areas of interest: Estuaries Public services Olive groves and vineyards Rivers Port areas Urban greenery Accommodation facilities Industrial zones Railways Roads Rocks and cliffs Beaches Urban lanscape Vegetation Cultivated areas Fire-affected areas	Percentage occupation of Elements and features of the coastal terrestrial area adjacent to the study area that can alter, either directly or indirectly, the conditions of the marine environment under study.	Geoportale Liguria: https://geoportal.regione.liguria.it/

Table 6. Ligurian marine coastal habitats (Coppo et al., 2020).

Nomenclature	Nomenclature
PA	Infralittoral photophilous algae on hard seabed
PA-A	Infralittoral photophilous algae on artificial seabed
PA-BR	Infralittoral photophilous algae on beach-rock seabed
SAC	Circal-littoral sciaphilous algae
SAI	Infralittoral sciaphilous algae
C	Coralligenous
CAU	<i>Caulerpa taxifolia</i>
C-M	Coralligenous on mud
CYL	<i>Caulerpa cylindracea</i>
CYM	<i>Cymodocea nodosa</i>
CYM-CAU	<i>Cymodocea nodosa and Caulerpa taxifolia</i>
CYM-DENSE	Dense <i>Cymodocea nodosa</i>

CYM-DM	<i>Cymodocea nodosa</i> on dead Matte
CYM-POS	<i>Cymodocea nodosa</i> with <i>Posidonia oceanica</i>
DB	Detrital beds
DB-M	Muddy detrital beds
M	Muds
CA	Caves
DM	Dead Matte
MOS	Mosaic of <i>Posidonia oceanica</i>
POS	<i>Posidonia oceanica</i>
POS-CAU	<i>Posidonia oceanica</i> and <i>Caulerpa taxifolia</i>
POS-R	<i>Posidonia oceanica</i> between and on rock
UA	Uninvestigated area
S	Sand
CS	Coarse sediments
CS-C	Coarse sands and coralligenous
OR	Offshore rock

4.5 RESEARCH II

II

SPATIAL RISK EVALUATION OF COASTAL AND MARINE ECOSYSTEM SERVICES EXPLOITATION IN AN ITALIAN COASTAL AREA

by

Bordoni R., Paoli C., Rigo I., Vassallo P

Spatial risk evaluation of coastal and marine ecosystem services exploitation in an Italian coastal area.

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ABSTRACT

This study presents a spatial risk assessment framework for coastal ecosystem services, focusing on the balance between ecosystem service supply and theoretical human pressure. Coastal and marine ecosystems provide essential services but face increasing pressures from human activities that threaten their sustainability. The developed model calculates relative risk by comparing ecosystem service capacity (supply) and demand (theoretical pressure) across spatial cells, identifying areas where demand may exceed supply, resulting in potential risks to ecosystem health.

A case study in the marine and coastal area of Liguria demonstrates the adaptability of the model, using scenarios that adjust the number of berths in ports to observe impacts on three key ecosystem services: recreational fishing, professional fishing, and boating. Results show that increasing berths shifts more cells into high-risk classifications, while decreasing berths expands low-risk zones. Spatial analysis reveals distinct patterns of risk, with elevated risk levels in the western region suggesting a need for targeted management, while unknown risk areas in the eastern region indicate data gaps or unclear dynamics. This framework provides a valuable tool for guiding ecosystem management and supporting decision-making by illustrating potential outcomes of local changes. Expanding this approach to include additional ecosystem variables could further enhance adaptive management in response to environmental pressures.

1. INTRODUCTION

Marine and coastal areas are essential for biodiversity, human health and economic growth. These regions provide critical nursery grounds for marine life, opportunities for recreation and education, and significant economic benefits through industries such as fisheries and tourism.

In the European Union, more than 40% of people, nearly half of the total population, live in coastal areas, and the growth rate in these regions exceeds that of other EU regions (Eurostat, 2011). However, increasing pressures and demands on coastal resources have led to habitat loss, degradation, pollution and overexploitation, all of which contribute to the decline of coastal ecosystems (EEA, 2010). According to the first report by EU Member States on nature conservation under the EU Habitats Directive, more than two-thirds of coastal habitats and more than half of coastal species are classified as in an *unfavourable* condition (European Commission, 2009). This environmental degradation has significant social and economic consequences.

Ecosystem services (i.e., the benefits provided by natural ecosystems that contribute to human well-being) are increasingly under threat from this degradation. Coastal ecosystems are estimated to account for 36% (Costanza, 1999) to 77% (Martínez et al., 2007) of the total global value of ecosystem services.

As highlighted in the 2050 vision of the Convention on Biological Diversity (CBD, 2010), there is an urgent need to conserve and restore ecosystems that support human health, livelihoods and well-being, and to ensure the continued provision of essential benefits to people. In response to these challenges, the EU Biodiversity Strategy to 2020 (European Commission, 2011) reflects the commitments made by the EU under the CBD in 2010. The strategy aims to prevent further biodiversity loss, including efforts to assess, map and value all ecosystem services across the EU. Mapping the supply and demand for ecosystem services is essential to identify priority areas and understand the trade-offs between different services and stakeholders (Burkhard et al., 2012, 2013; Naidoo et al., 2008; McPhearson et al., 2013). This approach facilitates effective natural resource management and guides spatial planning decisions.

There are various methods for mapping ecosystem services, which can be broadly categorized as biophysical metrics (e.g., Burkhard et al., 2012; Maes et al., 2012; Stürck et al., 2014; Vihervaara et al., 2010b) or economic valuations (e.g., Costanza et al., 1997; Kubiszewski et al., 2013; La Notte et al., 2012). The spatial scale of analysis can also influence the perception and importance of ecosystem services, as stakeholders at different scales may have different interests in land use and service provision (Hein et al., 2006). Furthermore, mapping these services can help to communicate research findings to policy makers and support environmental planning, land use decisions, and resource management (Alkemade et al., 2014; Maes et al., 2012; van Berkel and Verburg, 2014).

Despite the growing importance of ecosystem services, methods for identifying and mapping these services using freely available data while considering the different dimensions of service

provision remain inadequate (Xu et al., 2017; Keeler et al., 2019; Mitchell et al., 2021). A critical challenge in identifying priority areas for ecosystem service provision is to understand that this provision depends not only on the presence of natural ecosystems, but also on complex interactions between ecosystems and human needs, and on people's ability to access and use these services (Mace et al., 2012). Ecosystem service provision therefore depends on two key elements: the capacity of ecosystems to provide a service and the demand for that service by humans (Mitchell et al., 2015). Provisioning occurs at the intersection of capacity and demand. For example, freshwater ecosystems can provide clean water, but provision only occurs when human demand for water exists and hydrological linkages allow downstream users to access water from upstream sources (Brauman et al., 2007). Importantly, the flow of ecosystem services linking capacity and demand is often spatially complex.

Although there is an increasing focus on ecosystem services, there are few examples that integrate both capacity and demand to identify priority areas for service provision (Verhagen et al., 2017a). Information that enables decision-makers to understand where and how natural areas provide benefits to people-and where these benefits may be most threatened by human action-is a critical need.

Several studies have reported widespread decline and unsustainable use of ecosystem services worldwide (WRI, 2001; MEA, 2005). To ensure the continued provision of ecosystem services, it is essential to carefully manage areas that are important for maintaining ecosystem functions and services. Such management is necessary to ensure that ecosystem services are available both now and in the future (van Jaarsveld et al., 2005; Chan et al., 2006; Egoh et al., 2007).

This study proposes a method for mapping the relative capacity of ecosystems to provide ecosystem services and the theoretical pressure exerted by humans accessing and demanding for these services. As outlined in Rigo et al. 2024, using different approaches to achieve the same result can often lead to different outcomes. For this reason, the approaches chosen for this analysis incorporate a more "subjective" perspective in defining both the supply of ecosystem services, partly due to data limitations, and the theoretical pressures on ecosystems. This study seeks to emphasize that the use of certain ecosystem services is not always a conscious choice made by users; instead, various factors such as accessibility, convenience, and amenity can often guide and influence user behavior, thereby affecting the actual engagement with these services.

Ultimately, when both supply and theoretical pressure are assessed together, the result is a measure of the risk that ecosystems face in meeting demand for these services, highlighting the potential challenges when ecosystem capacity and human demand converge.

In technical terms, *risk* refers to the probability of a negative outcome occurring within a given period due to a specific adverse event. Risk, therefore, is a parameter based on both the likelihood of an event happening and the extent of its potential consequences on people, the environment, or assets. It is commonly represented as the product of three parameters: $R = H \times V \times E$, where H stands for hazard, V for vulnerability, and E for exposure.

In this formulation:

- Hazard (H) is the likelihood of a specific event occurring with a certain intensity in a particular area and timeframe.
- Exposure (E) measures everything that could be lost if an adverse event were to occur in a given area.
- Vulnerability (V) expresses the fraction of exposed assets or values that could be lost because of an adverse event.

This definition aligns with that adopted by the European Community (EN 1050, 1996), which considers risk associated with a specific hazard as a function of the potential damage magnitude and the probability of its occurrence. This probability, in turn, depends on factors such as the frequency and duration of exposure, the likelihood of the hazardous event, and the ability to prevent or mitigate the damage.

In the context of our study, this risk framework was applied across the study area to develop a spatial decision support system to inform coastal zone managers about ecosystem services supply and exploitation and address environmentally sound development strategies.

. Here, we adapt the parameters as follows:

- $H \times E$ represents our theoretical pressure indicating the cumulative potential demands on the ecosystem from ecosystem services activities such as fishing, boating or diving.
- V reflects the ecosystem services supply, capturing the capacity of the habitats to provide these services sustainably under current conditions.

By comparing $H \times E$ (theoretical pressure) and V (supply) across different cells in the study area, we assess various levels of ecosystem risk. While overexploitation represents the most severe and critical scenario, other potential risk levels are also evaluated, providing a comprehensive view of where pressure might exceed supply and threaten ecosystem health and sustainability. This approach allows us to evaluate spatial risk patterns and offers insights for managing the ecosystem services sustainably in areas with different levels of exposure and vulnerability.

Finally, a case study approach is employed to demonstrate the practical use of this analysis as a decision-making tool for territorial management, showing how changes in theoretical pressure could alter the associated risk.

1. MATERIALS AND METHODS

Study area

In this study, the coastal area of Liguria was investigated, based on the extension of the Marine-Coastal Habitat Atlas of Liguria (Coppo et al., 2020).

The Ligurian Sea, a biodiversity hotspot like most of the Mediterranean Sea, faces significant anthropogenic pressures due to its high population density and extensive human activities, including tourism, urbanization and industry (Cattaneo-Vietti et al., 2010). These pressures have contributed to habitat degradation (Rigo et al., 2024). Since the 1960s, coastal areas have experienced intensified residential, industrial, and tourist development, further exacerbated by shipping, fishing, and marine debris from densely populated areas (Bianchi and Peirano, 1995; Bo et al., 2014, Relini, 1972a, 1972b, 1989). The combined effects of overexploitation of environmental resources and land consumption for tourism have implications for urban development and environmental sustainability (Lombardini, 2017).

Figur provides a comprehensive view of the study area, which is divided into four distinct sections: Western Liguria (W), Mid-Western Liguria (MID-W), Mid-Eastern Liguria (MID-E), and Eastern Liguria (E). This regional division not only allows a clearer spatial presentation of the results of the study, but is also consistently referred to in the following figures throughout the paper. By dividing the Ligurian coastline into these distinct sections, the study allows for a more detailed examination of the region's coastal environments, ensuring accurate observations of ecosystem services and habitat characteristics.

In addition, for further clarity, enlarged views of specific parts of the study area are included in the following figures.

Once the study area was delineated, a regular grid was created using the QGIS Create Grid tool, resulting in 43592 individual cells, each 140x140 meters in size. These grid cells formed the basic spatial units for all subsequent analyses. Each cell contains varying proportions of different habitat types, meaning that within a given cell there may be multiple habitats, each covering a specific area. The presence and extent of these habitats were quantified and included in further analyses to ensure that the habitat composition within each cell was fully considered in the assessment of ecosystem services and their provision.

The location and extent of habitats were derived from the Marine-Coastal Habitat Atlas of Liguria (Coppo et al., 2020), obtained from Geoportale Regione Liguria (<https://geoportal.regione.liguria.it/>). Table 1 shows the habitat nomenclature and the corresponding class.

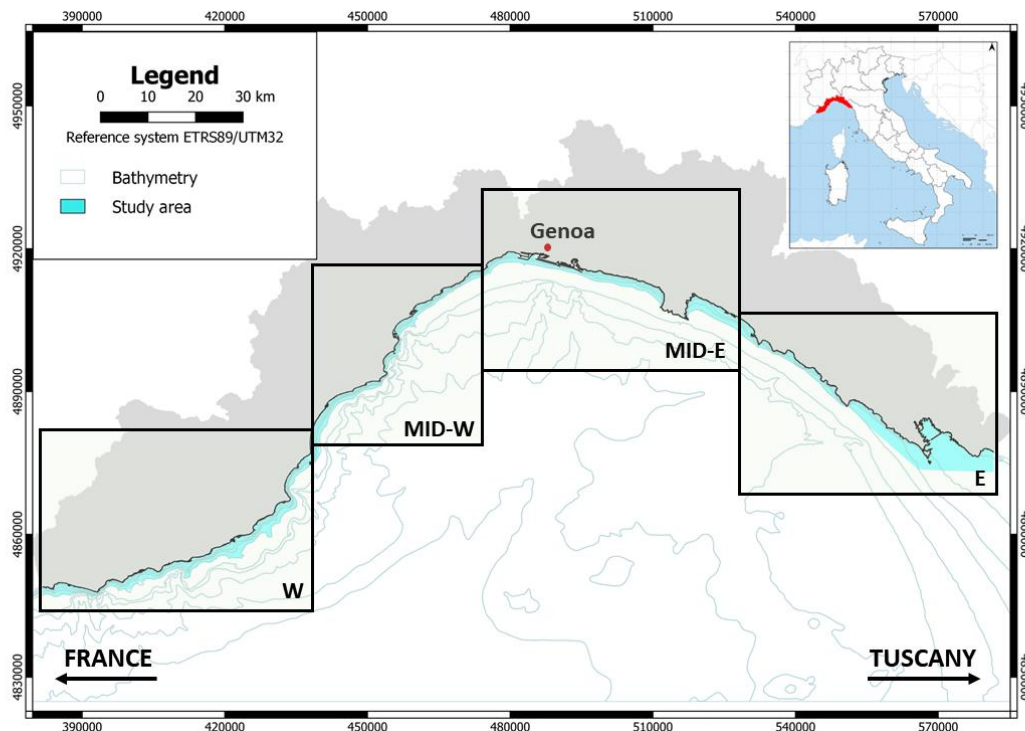


Figure 1.. Study area divided into sections: Western Liguria (W), Mid-Western Liguria (MID-W), Mid-Eastern Liguria (MID-E) and Eastern Liguria (E).

Table 1. Ligurian marine coastal habitats between 0 m and 50 meters depth (Coppo et al., 2020).

<i>Class</i>	<i>Nomenclature of this study</i>	<i>Class</i>	<i>Nomenclature of this study</i>	<i>Class</i>	<i>Nomenclature of this study</i>
PA	Infralittoral photophilous algae on hard seabed	CYM	<i>Cymodocea nodosa</i>	DM	Dead Matte
PA-A	Infralittoral photophilous algae on artificial seabed	CYM-CAU	<i>Cymodocea nodosa</i> and <i>Caulerpa taxifolia</i>	MOS	Mosaic of <i>Posidonia oceanica</i>
PA-BR	Infralittoral photophilous algae on beach-rock seabed	CYM-DENSE	Dense <i>Cymodocea nodosa</i>	POS	<i>Posidonia oceanica</i>
SAC	Circal-littoral sciaphilous algae	CYM-DM	<i>Cymodocea nodosa</i> on dead Matte	POS-CAU	<i>Posidonia oceanica</i> and <i>Caulerpa taxifolia</i>
SAI	Infralittoral sciaphilous algae	CYM-POS	<i>Cymodocea nodosa</i> with <i>Posidonia oceanica</i>	POS-R	<i>Posidonia oceanica</i> between and on rock
C	Coralligenous	DB	Detrital beds	R	Rock
CAU	<i>Caulerpa taxifolia</i>	DB-M	Muddy detrital beds	S	Sand
C-M	Coralligenous on mud	M	Muds	CS	Coarse sediments
CYL	<i>Caulerpa cylindracea</i>	CA	Caves	CS-C	Coarse sands

Evaluation of Ligurian ecosystem services and their supply

A comprehensive list of ecosystem services provided by the Ligurian habitat was compiled with the help of expert judgement provided by the Systems Ecology Research Group of the University of Genoa.

The classification of ecosystem services used to identify those in the study area is the Common International Classification of Ecosystem Services (CICES). CICES was formulated by the working group of the European Environment Agency (EEA) and the United Nations Statistical Division (UNSD), known as the System of Economic and Environmental Accounts (SEEA).

The CICES classification identifies three categories of services:

- provisioning services: tangible and marketable goods (materials and energy) directly consumed by humans and produced by ecosystems.
- maintenance and regulating services: those functions that control and modify the abiotic and biotic compartments of ecosystems and from which environments suitable for human life emerge.
- cultural and social services: all non-material outputs of ecosystems with symbolic, cultural and intellectual significance.

The process carried out by the System Ecology Research Group from University of Genoa identified the following services related to the Ligurian habitat. Apart from the climatic regulation services (CR), which belong to the category of "maintenance and regulation services", all the other services identified belong to the category of "cultural and social services" and they are: professional fishing (PF), recreational fishing (RF), diving (D), snorkeling (S), scientific research (SR) and dissemination activities (DA).

Once the services were identified, each habitat type in the Ligurian region was evaluated and assigned a score from 0 to 5, representing its contribution to each service, with a score of 0 indicating no contribution and a score of 5 indicating full provisioning.

To generate a spatial assessment, an overall ecosystem service score was calculated for each grid cell by aggregating a weighted average for each ecosystem service based on the area occupied by each habitat within the cell. These scores, standardized from 0 to 5, were then mapped to reveal spatial patterns in the distribution of ecosystem services across the study area. In this study, five of the seven identified services - PF, RF, D, S and SR - are analyzed in detail based on the availability of spatial and quantitative data. The remaining two services (CR and DA) will be investigated in future work.

Evaluation of Ligurian theoretical pressure on ecosystem services

This study provides an in-depth analysis of five key ecosystem services in the Ligurian region, based on improved spatial and quantitative data. Specifically, the services considered are PF, RF, D, S and SR. In addition to these ecosystem services, we also consider boating (B) as a relevant activity. Although boating is not a service directly provided by natural habitats, its interactions with these ecosystems ask for examination due to potential impacts and dependencies on local habitats.

The following sections outline the methods used to calculate the theoretical pressure, including the data sources, spatial analysis techniques and quantitative metrics.

Diving

The theoretical pressure on the ecosystem service of diving is assessed by evaluating the spatial proximity between designated diving centers and habitat areas. A Euclidean distance calculation was used to determine the distance between the midpoint of each habitat area and each dive center. Only distances within a defined threshold (10 nautical miles) were retained to focus on habitat areas within a meaningful range for diving activities. Each distance was then converted to its inverse, so that shorter distances would correspond to proportionally higher theoretical pressure.

Only cells with designated dive sites were assigned a final pressure score, while those without dive sites or in unstudied areas were excluded from the assessment. The location of existing dive sites in the Ligurian Sea can be accessed via <https://www.logbookimmersioni.it/>.

Snorkeling

The theoretical pressure on snorkeling related ecosystem services was assessed by evaluating the proximity of habitat areas to nearby beaches suitable for swimming. This analysis results in a pressure score that reflects the theoretical pressure from snorkeling activities. Spatial data for bathing beaches were obtained from Geoportale Regione Liguria (<https://geoportal.regione.liguria.it/>).

A Euclidean distance calculation was used to measure the proximity between each habitat midpoint and each beach midpoint. Only distances within a defined threshold (500 meters) were considered, focusing on cells that were potentially accessible for snorkeling. The inverse of each distance was then calculated, so that shorter distances would exert a proportionally higher theoretical pressure.

These inverse distance values were weighted by the area of each beach, giving larger beaches more weight in the final score.

Finally, cells classified as unsuitable (i.e. those with soft, sedimentary substrates) were excluded to ensure that the final pressure scores represented only suitable cells for snorkeling related services.

Professional fishing

Theoretical pressure from commercial fishing activities was assessed by calculating the spatial proximity between designated fishing ports and relevant habitat areas.

A Euclidean distance calculation was used to determine the proximity between each habitat midpoint and port location. Distances exceeding a threshold of 20 nautical miles were excluded to maintain relevance to professional fishing activity. For each valid distance, the inverse of the distance was calculated, with shorter distances yielding higher values. This distance-based pressure was further weighted by the fishing effort (<https://globalfishingwatch.org/>) exerted in the area and the number of berths in each port (<https://www.yachtdigest.com/porti-liguria/>), providing a composite measure of pressure on habitats.

Further adjustments were made on the basis of MPA zonation (<https://geoportal.regione.liguria.it/>): habitats within Zone A were excluded from the assessment due to strict protection, while reductions of 70% and 30% were applied to zones with partial protection, Zone B and Zone C respectively. Habitat areas within designated Sites of Community Interest (SIC) (<https://geoportal.regione.liguria.it/>) were also excluded from the assessment of commercial fishing pressure.

Recreational fishing

Theoretical pressure from recreational fishing was assessed using the spatial proximity between habitat mid-points and local harbors with berths for recreational boats. The Euclidean distance between each habitat midpoint and port was calculated, disregarding distances greater than 10 nautical miles to maintain a realistic range for recreational fishing activities. Each qualifying distance was then inverted, giving greater weight to closer distances.

The resulting values were weighted by the number of recreational berths in each port.

Additional adjustments were made to reflect the zonation of MPAs: habitats within Zone A were excluded from the scoring, while habitats within Zones B and C, which allow some recreational fishing, were assigned a reduced pressure (20%).

Boating

The theoretical pressure exerted by boating areas is assessed by analyzing the proximity of habitat areas to designated ports. The Euclidean distance is calculated between the mid-points of each habitat area and the port locations. Distances greater than 10 nautical miles are ignored in order to focus on areas within a feasible range for boat access.

To enhance the significance of closer distances, the inverse of the distance is calculated, with shorter distances yielding higher values. This measure is then multiplied by the number of berths available in each port, reflecting the relative capacity of each port to accommodate boating activities.

In addition, pressure on the boating ecosystem service comes not only from boating itself, but also from anchoring, which can cause physical damage to the habitat.

Additional adjustments are made based on the designation of protected areas: habitats within Zone A were excluded from the assessment due to strict protection, while reductions of 90% and 50% were applied to zones with partial protection, Zone B and Zone C respectively. Habitats within designated Sites of Community Importance (SIC) were also excluded.

Scientific research

For the scientific research service, the number of publications related to each habitat (Table 2) was retrieved from ScienceDirect (<https://www.sciencedirect.com/>), focusing on articles that directly or indirectly study the habitats.

Table 2. Number of publications related to each habitat (form ScienceDirect)

<i>Class</i>	<i>Number of publications</i>	<i>Searched terms</i>
<i>PA</i>	38	infralittoral photophilous algae
<i>PA-A</i>	21	photophilous algae artificial bottoms
<i>PA-BR</i>	3	photophilous algae beachrocks
<i>SAC</i>	19	sciaphilous algae circalittoral
<i>SAI</i>	31	sciaphilous algae infralittoral
<i>C</i>	483	coralligenous
<i>CAU</i>	624	<i>Caulerpa taxifolia</i>
<i>C-M</i>	130	coralligenous muddy bottoms
<i>CYL</i>	288	caulerpa cylindracea
<i>CYM</i>	1266	<i>Cymodocea nodosa</i>
<i>CYM-CAU</i>	83	<i>Cymodocea nodosa Caulerpa taxifolia</i>
<i>CYM-DENSE</i>	445	dense <i>Cymodocea nodosa</i>

<i>CYM-DM</i>	68	<i>Cymodocea nodosa</i> dead matte
<i>CYM-POS</i>	751	<i>Cymodocea nodosa Posidonia oceanica</i>
<i>DB</i>	1885	detrital sandy bottoms habitats
<i>DB-M</i>	996	detrital muddy bottoms habitats
<i>M</i>	8480	muddy bottoms habitats
<i>CA</i>	7690	dark marine caves
<i>DM</i>	1252	dead matte
<i>MOS</i>	207	mosaic of <i>Posidonia oceanica</i>
<i>POS</i>	3466	<i>Posidonia oceanica</i>
<i>POS-CAU</i>	165	<i>Posidonia oceanica Caulerpa taxifolia</i>
<i>POS-R</i>	721	<i>Posidonia oceanica</i> in rocky bottoms
<i>R</i>	7390	offshore rocky bottoms
<i>S</i>	19549	sandy bottoms habitat
<i>CS</i>	69429	marine coarse sediments
<i>CS-C</i>	128	marine coarse sediments coralligenous

Standardization and total theoretical pressure evaluation

Once the raw scores for each ecosystem service (D, S, PF, RF and B) had been calculated, they were standardized on a scale from 0 to 5 to ensure consistency and comparability between the different services. This process produced standardized scores for each service, which were then aggregated into a comprehensive final dataset.

A weighted average was then calculated for each cell, taking into account both the ecosystem service scores and the area occupied by each habitat within the cell. The total theoretical pressure value for each cell was determined by summing the values of all ecosystem services present in that cell. This total was then further standardized on a scale of 0 to 5 to facilitate interpretation and comparison of ecosystem service contributions between different habitats.

Evaluation of the risk

The assessment of risk associated with ecosystem services is illustrated in Figure 2. This matrix categorizes levels of risk based on the interplay between the supply of ecosystem services and the theoretical pressure on these services, both derived from the methods outlined above.

The classification results in four different risk classes:

- high risk: occurs when both ecosystem service supply and theoretical pressure are high (≥ 2.5), indicating an increased risk of overexploitation and the need for immediate management action.

- unknown risk: defined by low supply (< 2.5) and high pressure (≥ 2.5), indicating possible information gaps or unclear dynamics that make effective management difficult.
- moderate risk: occurs with high supply (≥ 2.5) and low pressure (< 2.5), indicating that while services are abundant, lower pressure reduces risk, although protective measures may still be recommended.
- low risk: both supply and pressure are low (< 2.5), reflecting minimal risk of overexploitation due to limited availability and demand for ecosystem services.




THEORETICAL PRESSURE SUPPLY	Low	High
	Low	 LOW RISK
High	 MODERATE RISK Potential need of protection	 HIGH RISK Potential overexploitation

Figure 2. Risk matrix.

Case study: creation of scenarios

A case study approach is used to illustrate the practical application of this analysis as a decision-making tool for territorial management. Specifically, it seeks to answer the question: how would changes in the number of berths in local ports affect the theoretical pressure on ecosystem services and, consequently, the associated risk levels?

Adjusting the number of berths requires recalculating the theoretical pressure on three ecosystem services: PF, RF and B, as the number of berths directly influences the pressure values for these services.

In this analysis, six ports were selected as examples: two ports in the central-eastern region and four in the western region of the study area. Two scenarios were developed to model these potential interventions:

- Increased berths scenario (IBS): A 20% increase in the number of berths, representing increased pressure from increased boat capacity.

- Decreased berths scenario (DBS): A 20% reduction in the number of berths, representing a reduction in pressure with fewer berths available.

By examining the effects of these scenarios, this study aims to illustrate how changes in port infrastructure could alter the theoretical pressure on ecosystem services and, in turn, the level of risk across the study area.

RESULTS

Evaluation of Ligurian ecosystem services and their supply

Table 3 displays the values assigned to ecosystem services supplied by the habitats in the study area, as determined by a survey conducted by the System Ecology Research Group. The habitats with the highest overall scores are those associated with *Posidonia oceanica* (POS, POSR-R, MOS, and POS-CAU), followed by habitats related to coralligenous formations and caves (C and CA) and those associated with *Cymodocea nodosa* (CYM, CYM-DENSE, CYM-CAU).

Table 3. Values of ecosystem services supplied by the habitats in the study area.

Habitat (Diviacco et al., 2020)	PF	RF	CR	S	D	SR	DA
PA	1	1	3	5	3	2	1
PA-A	1	1	3	5	0	2	1
PA-BR	1	1	3	5	3	2	3
SAC	1	1	1	0	1	1	0
SAI	1	1	1	0	1	1	0
C	2	2	1	0	5	5	5
CAU	3	3	1	0	0	4	4
C-M	1	1	1	0	4	4	4
CYL	3	3	1	0	0	4	4
CYM	2	2	4	3	2	4	4
CYM-CAU	3	3	3	2	1	4	4
CYM-DENSE	2	2	4	3	2	4	4
CYM-DM	2	2	2	2	1	4	4
CYM-POS	3	3	4	2	2	4	4
DB	0	0	0	0	0	0	0
DB-M	0	0	0	0	0	0	0
M	0	0	0	0	0	0	0
CA	2	2	1	3	5	5	4
DM	1	1	0	2	1	5	5
MOS	3	3	4	3	2	5	5
POS	5	5	5	4	5	5	5
POS-CAU	4	4	3	2	2	5	5

<i>POS-R</i>	5	5	5	4	5	5	5
<i>R</i>	0	0	0	0	0	0	0
<i>S</i>	0	0	0	0	0	0	0
<i>CS</i>	0	0	0	0	0	0	0
<i>CS-C</i>	1	1	1	0	3	3	3

Figure 3 shows the spatial distribution of these values across the study area, corresponding to the locations of specific habitats. Cells with higher values, approaching 5, are predominantly occupied by habitats with the highest supply scores. These high-scoring habitats are generally located closer to the coastline (within 30 meters of depth) and are more concentrated on the western side of the area, with 1193 out of 1525 cells scoring above 4.

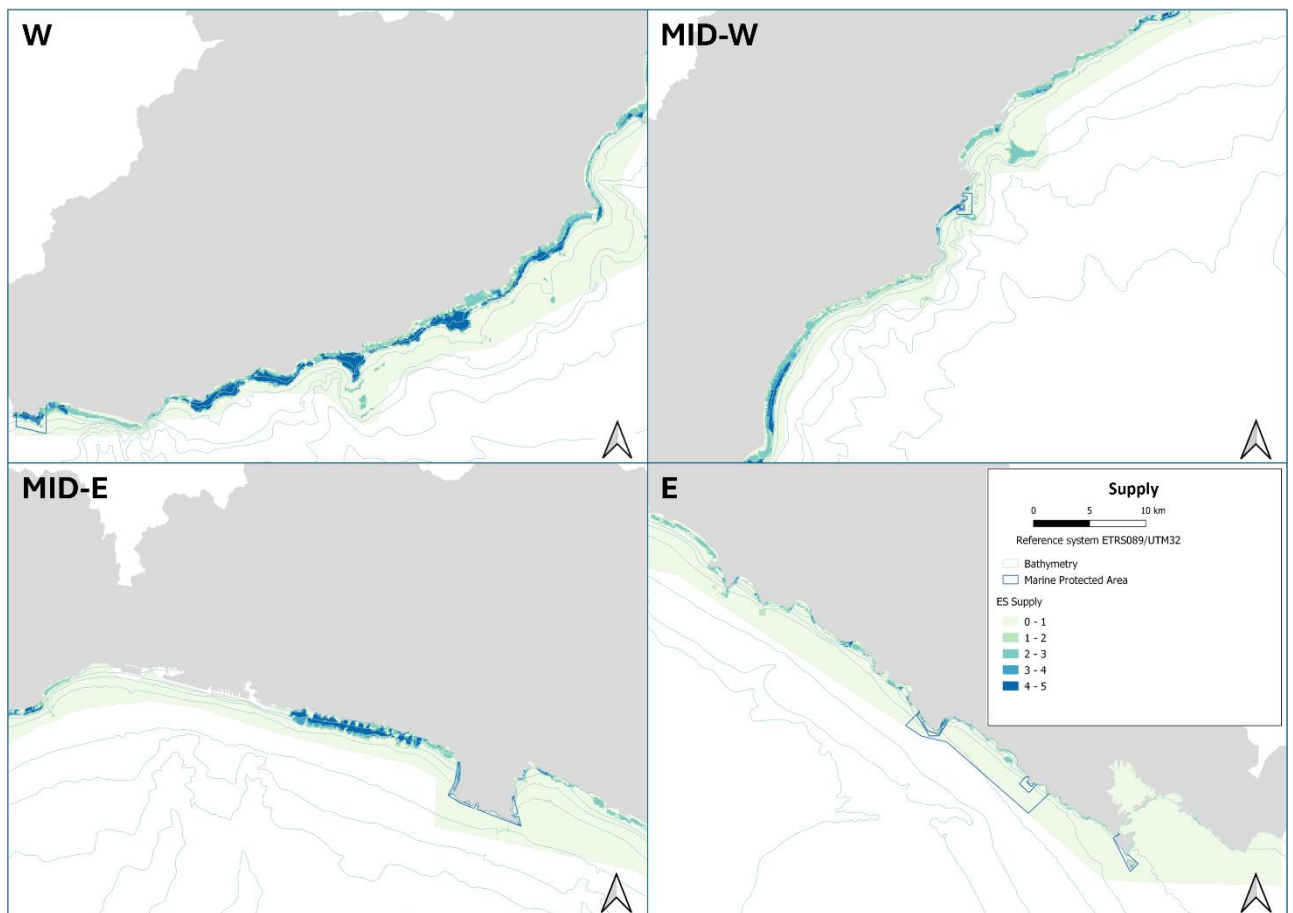


Figure 3. Spatial distribution of ecosystem services supply.

Evaluation of Ligurian theoretical pressure on ecosystem services

The spatial distribution of total theoretical pressure values across the study area is illustrated in Figure 4.

Specifically, 98 cells have a pressure value above 4, 19463 cells fall between values of 2 and 4, and 24031 cells have values below 2.

RF exerts the greatest influence on the total theoretical pressure for an average cell, accounting for 46% of the overall score. This is followed by contributions from PF and boating B, each contributing roughly 19%. In contrast, snorkeling exerts minimal pressure, contributing only 0.01% to the overall score.

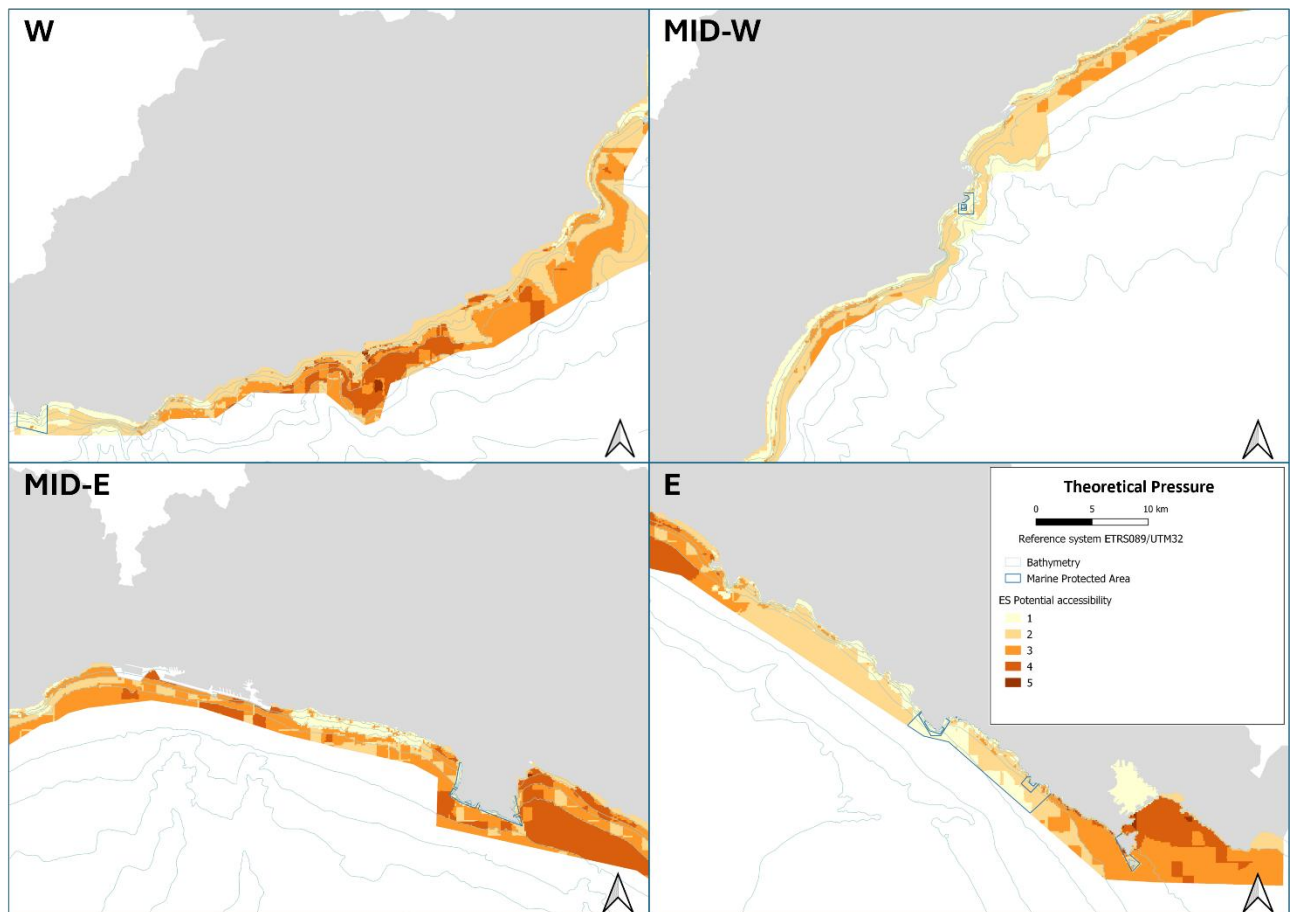


Figure 4. Spatial distribution of theoretical pressure values.

Evaluation of the risk

Figure 5 displays the four risk classes and their distribution across the study area. In total, approximately 63.89% (27848 cells) of cells are classified as low risk; 27.52% (11997 cells) fall under unknown risk, 8.25% (3595 cells) as moderate risk, and 0.35% (152 cells) as high risk.

The spatial distribution of risk classes reveals regional variations. Moderate and high risk cells are more concentrated on the western side of the study area, making up 70.96% (2551 cells) and 77.63% (118 cells) of their respective totals. In contrast, low risk cells are also slightly more prevalent on the western side, representing 57.52% (15741 cells) of all low risk cells,

compared to 43.48% (12017 cells) in the east. Finally, cells with unknown risk are more common on the eastern side, representing 67.71% (8123 cells) of the total in this category.

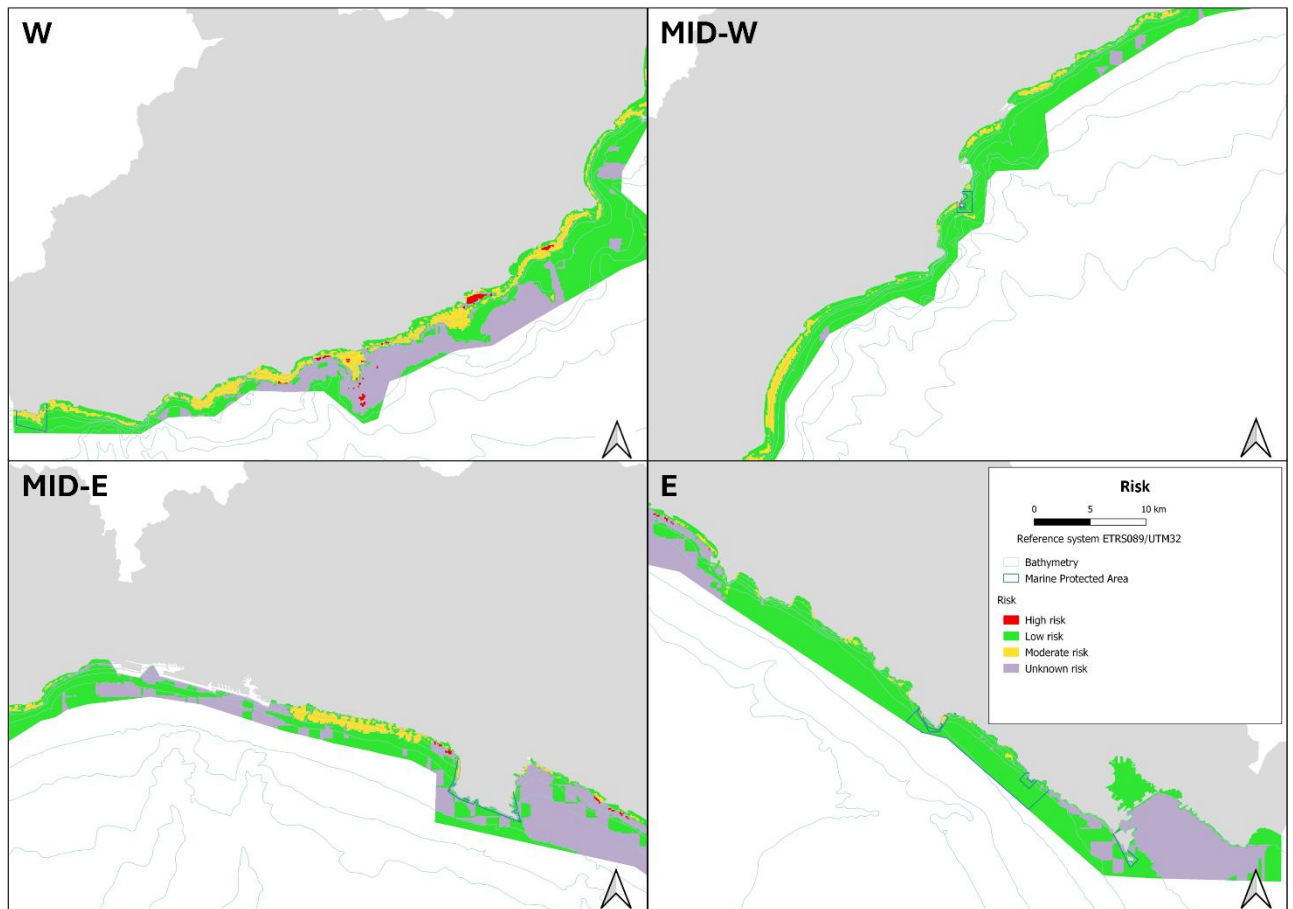


Figure 5. Spatial distribution of the risk classes in the study area.

Case study: creation of scenarios

Figure illustrate theoretical pressure distribution for the IBS scenario: 253 cells show pressure scores higher than 4, 19676 cells fall between scores of 2 and 4, and 23663 cells have scores below 2. Recreational fishing remains the primary pressure contributor in this scenario, accounting for 45.65% of the average cell score. This is followed by PF (20.61%) and B (19.35%), with snorkeling again contributing minimally at 0.01%.

Risk class distribution for the IBS scenario is shown in Figure 7.

Here, approximately 61.91% (26992 cells) of cells are categorized as low risk, 29.48% (12853 cells) as unknown risk, 8.23% (3588 cells) as moderate risk, and 0.36% (159 cells) as high risk. Moderate and high-risk cells remain more concentrated in the west, accounting for 71% (2545 cells) and 77% (124 cells) of their respective totals. Low-risk cells are slightly more common on the west coast at 56% (15285 cells), while unknown-risk cells are more prevalent in the east, comprising 66% (8523 cells) of this category.

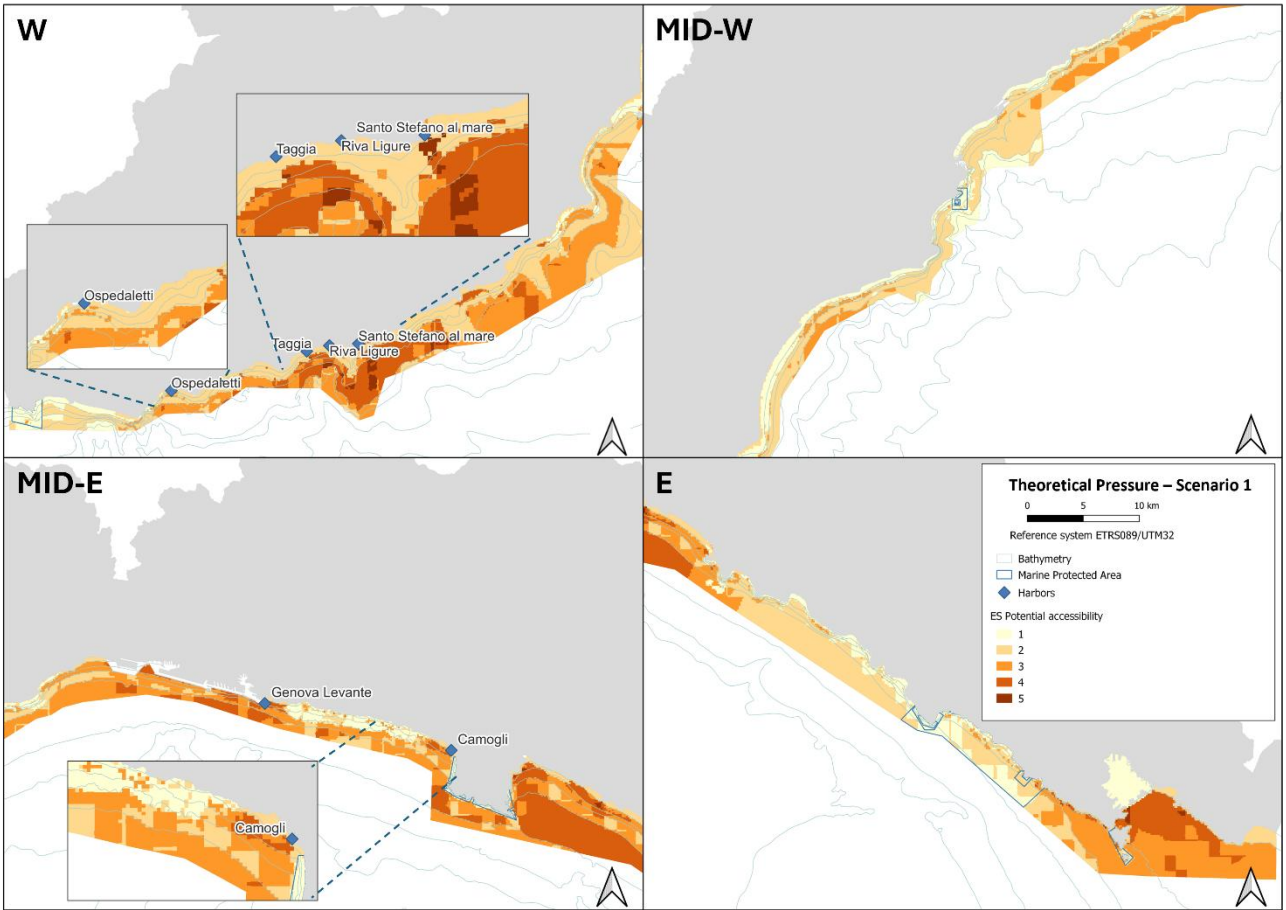


Figure 6. Spatial distribution of theoretical pressure values for the IBS scenario.

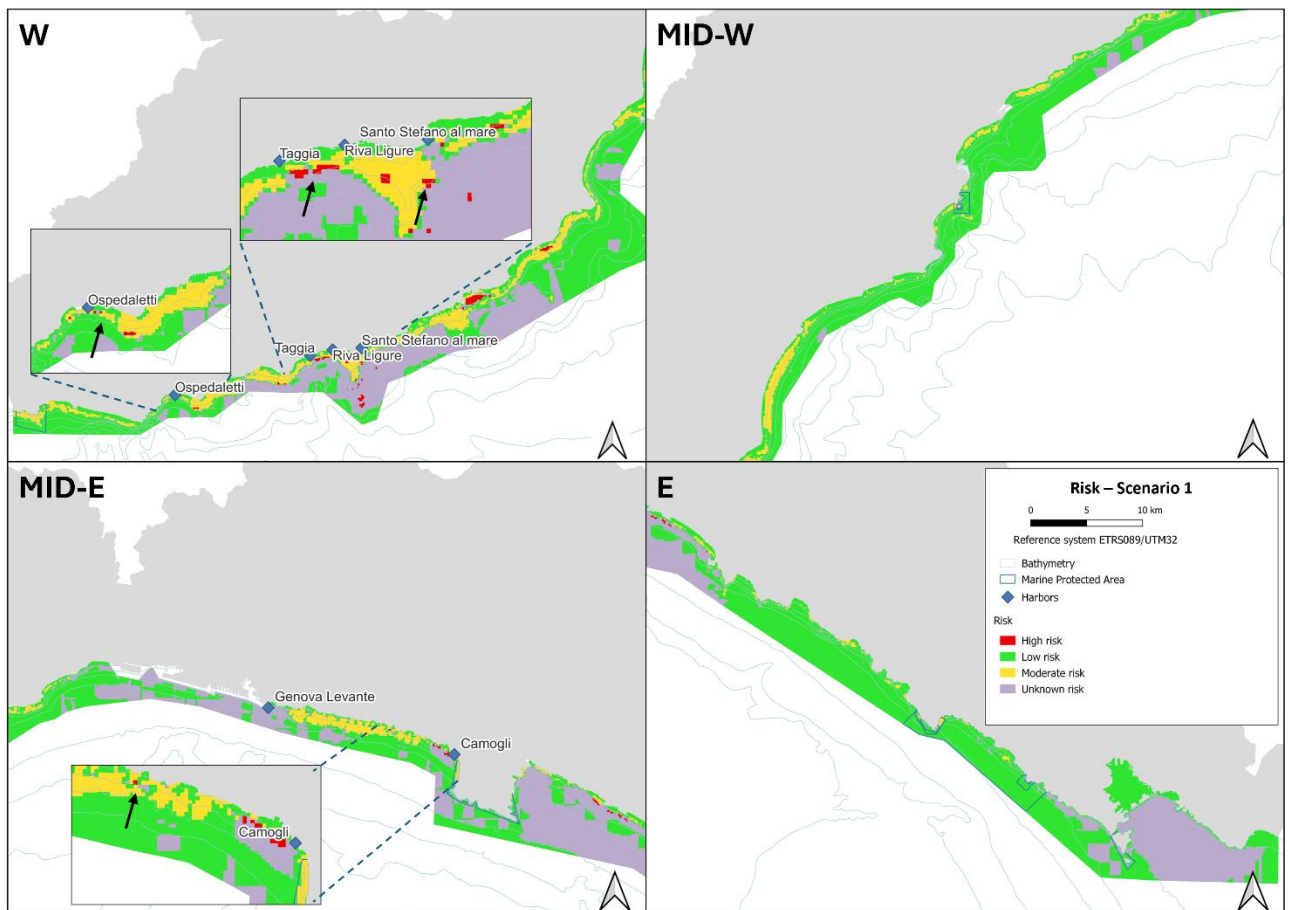


Figure 7. Spatial distribution of the risk classes in the study area for the IBS scenario.

In the DBS scenario (Figure 8), 46 cells show pressure scores above 4, while 18753 cells have scores between 2 and 4, and 24793 cells are below 2. In this scenario, RF again exerts the most pressure (45.53%), followed by PF (20.30%) and B (19.37%), with snorkeling contributing only 0.01%.

For the DBS scenario, risk class distribution is presented in Figure 9.

Here, 66.06% (28798 cells) of cells fall into the low risk category, 25.34% (11047 cells) into unknown risk, 8.28% (3609 cells) into moderate risk, and 0.32% (138 cells) into high risk.

As in previous scenario, moderate and high-risk cells are more concentrated on the west side, comprising 71% (2565 cells) and 75% (104 cells) of their respective totals. Low-risk cells are more common on the west coast at 56% (16264 cells), while unknown-risk cells are more concentrated on the east, accounting for 69% (3351 cells) of this category.

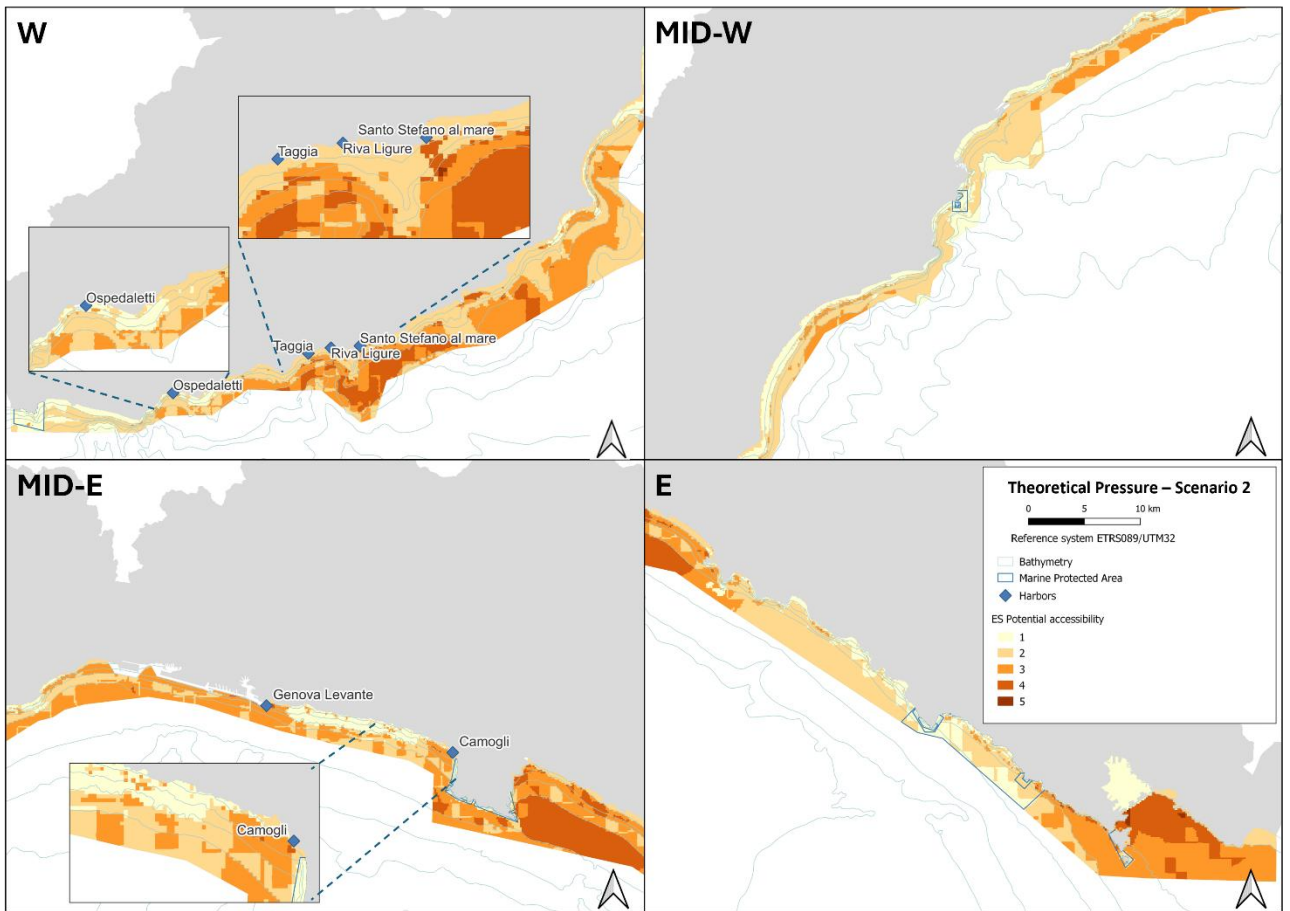


Figure 8. Spatial distribution of theoretical pressure values for the DBS scenario.

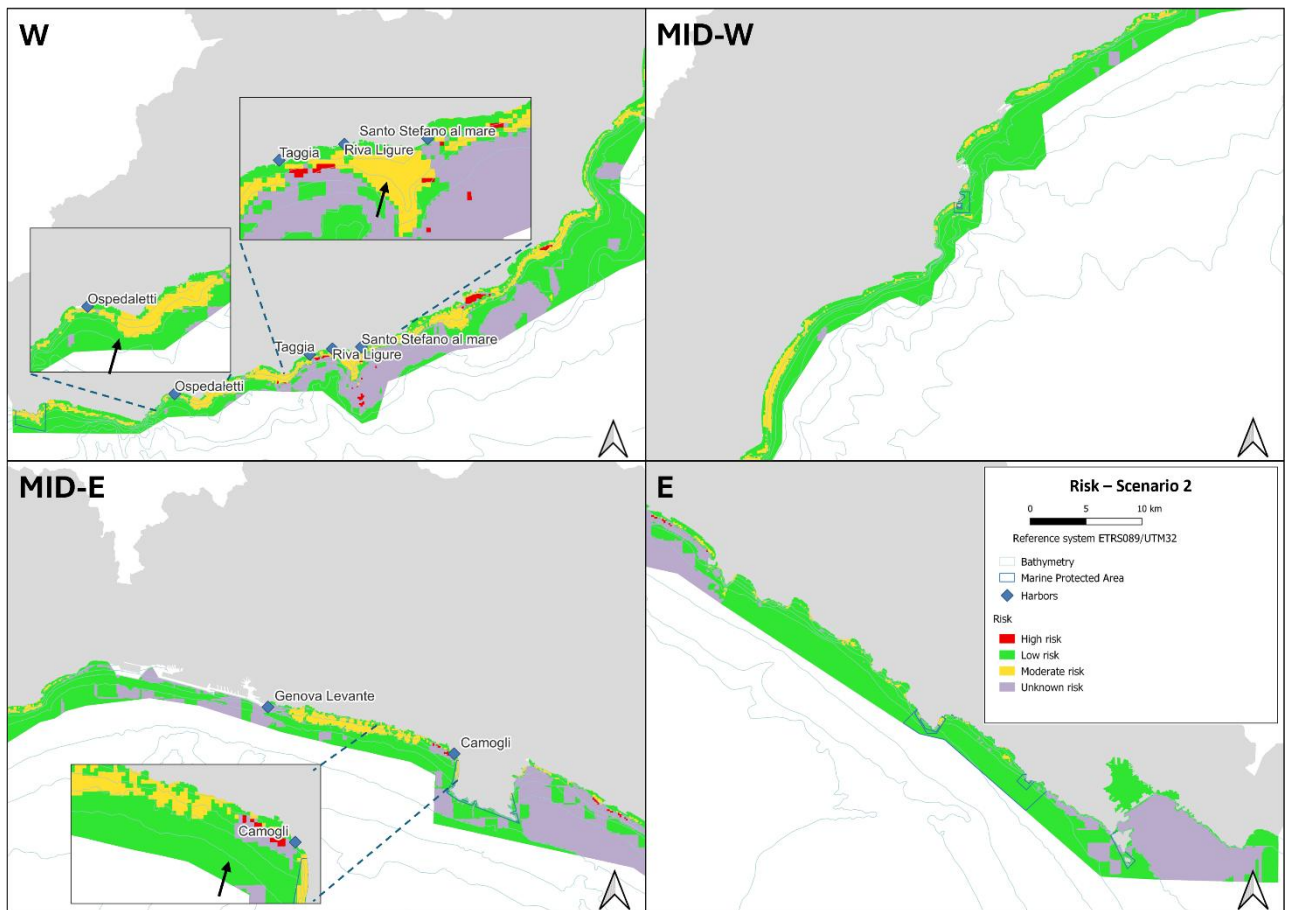


Figure 9. Spatial distribution of the risk classes in the study area for the DBS scenario

DISCUSSION

This study examines how changes in the area, such as coastal facilities, can affect potential pressures on ecosystem services and risks across a coastal study area. By examining two scenarios that differ from the baseline by varying the number of berths in some ports, the study demonstrates how changes in variables could be reflected in the study area.

The study focuses specifically on the number of berths because of their direct and strong influence on three key ecosystem services (RF, PF, and B), which together have the greatest influence on the overall value of a cell. RF is the largest contributor, accounting for 46% of the total theoretical pressure for an average cell, followed by PF and B, each contributing about 19%.

The assessment of risk associated with ecosystem services is structured according to a matrix that considers both the theoretical pressure on services and the supply of services provided by each habitat. This matrix categorizes risk into four classes: high risk (indicating potential overexploitation), unknown risk (indicating a possible lack of information or complex ecosystem dynamics), moderate risk (indicating a stable but valuable resource) and low risk

(reflecting limited ecosystem services and low pressure). Each scenario reflects shifts in these risk levels, providing insights into the spatial distribution of risk and potential management needs.

Under baseline conditions, 63.89% of cells are classified as low risk, indicating a balanced ecosystem where both ecosystem services supply and pressure are low. In contrast, a smaller subset of cells is in the high risk category, where both supply and pressure are elevated. In high-risk areas, elevated supply and pressure values indicate increased vulnerability and the need for urgent intervention to prevent overexploitation.

In IBS scenario, where berths are increased, the model shows an increase in high risk cells from 98 in the baseline to 253 cells. This shift suggests that an increase in berths, which increases pressure from professional fishing (PF), recreational fishing (RF) and boating (B), may push more areas into high risk classifications. Conversely, the DBS scenario, which reduces the number of berths, reduces the number of high-risk cells to 46 and expands the low-risk category, demonstrating that reducing pressure from berths can reduce risk.

Spatially, there are regional patterns across all scenarios. The western side of the study area, where habitats rich in ecosystem services supply (e.g. *Posidonia oceanica*) are located, shows a concentration of high and medium risk cells. This distribution corresponds to the high supply values in these areas, where habitats score up to 5 in ecosystem services contribution. In the high-risk cells, where both supply and theoretical pressure are elevated, there is an increased potential for overexploitation, reinforcing the need for region-specific management.

Cells in the eastern part of the study area tend to fall into the low risk or unknown risk categories. Unknown risk areas indicate a possible information gap or complex dynamics that warrant further investigation. The prevalence of unknown risk cells in the east highlights the need for additional data collection and monitoring to improve management accuracy.

This analysis highlights the adaptability of the model as a tool for visualizing potential management outcomes based on adjustments to features that could affect ecosystem services. The case of berths changes provides an illustrative example: increasing berths affect the pressure exerted by services such as RF, PF and B and increases risk, while reducing berths alleviates some of the high-risk classifications. However, other services can also affect risk patterns. For example, changes in SR, S or D could alter the supply/pressure balance of ecosystem services, particularly in localized areas, demonstrating the ability of the model to simulate both large-scale and site-specific scenarios.

The persistent concentration of high-risk cells in the west suggests that general adjustments (e.g. reducing the number of berths) may not fully mitigate risk in areas of inherently high

ecosystem services supply. Such areas may require tailored, high-priority management strategies that include protective measures, restricted activity zones or adaptive pressure regimes for RF, PF and B. Conversely, areas in the east with unknown risk classifications may benefit from targeted monitoring to clarify risk factors and improve management under conditions of limited information.

The scenario-based approach of the model provides a flexible framework for simulating changes in multiple ecosystem services variables, highlighting potential outcomes before real-world adjustments are implemented. Future research could do this by testing the model with different ecosystem services drivers, focusing on localized regions of high value habitat or on specific service adjustments (e.g. restricting RF in high-risk areas).

This work suggests that managers could benefit from scenario modelling to evaluate and refine policies, such as changes in the number of berths or spatial zoning, to balance ecosystem health with the demands of human activities. Improved data collection in high pressure and unknown risk areas could also improve model accuracy and support adaptive management in response to emerging environmental changes.

CONCLUSION

Understanding the trade-off between ecosystem service provision and human activities requires an integrated approach that considers both supply and demand pressures on coastal ecosystems. This study presents a methodology that maps the capacity of ecosystems to provide services against theoretical pressures from human activities. This approach provides a clearer understanding of spatial risk patterns, from areas at high risk of overexploitation to those where unclear dynamics suggest unknown risks. The case study approach, specifically the scenarios varying the number of berths in ports, demonstrates the adaptability and practical application of the model as a decision-making tool.

In conclusion, this study highlights the need for flexible, data-driven management strategies that respond to the dynamic pressures on coastal ecosystems. Integrating ecosystem service capacity and human demand into risk assessments provides a valuable tool for guiding sustainable management. Future research could explore additional variables, refine spatial resolutions, or expand the model's applications to other ecosystem services, further enhancing its utility in maintaining ecosystem health while considering human activities.

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4.6 SDSS

For the development of the SDSS, the following software has been utilized:

- PostgreSQL/PostGIS (version 11.1) as the database for managing alphanumeric and spatial data,
- DBeaver (version 24.3.0) as the DBMS for managing PostgreSQL/PostGIS,
- Quantum GIS (QGIS) (version 3.22.8) as GIS software for spatial data analysis,
- G3W-Suite (version 3.6.7) as WebGIS for publishing spatial data.

The dedicated website created for the WebGIS project can be accessed through the following link: <https://qgis.macisteweb.com/it/map/nbfc-restoration/>.

WebGIS systems are currently among the most advanced and widely used platforms for the visualization and distribution of geographic information. These systems are essential tools for environmental management, providing significant support in decision-making and analysis across sectors. By using WebGIS, users can easily view, explore, and download cartographic and alphanumeric data. The system is designed to be intuitive and user-friendly, allowing for quick updates and providing easy access to relevant data, all without requiring the installation of any software on the user's computer.

On this platform, users can interact with multiple layers of data, including base maps (such as geographic variables located in the study area—e.g., ports, river mouths, sewage systems, and population density, as shown in FIGURE 6). Additionally, thematic maps related to specific analysis results, such as the *P. oceanica* habitat suitability model from the research presented, are available for exploration (FIGURE 7).

The WebGIS interface allows for comprehensive navigation across the study area, providing tools to query maps, measure distances or areas, and download data in various formats, including reports or images. This capability ensures that stakeholders can easily interpret the data and make informed decisions based on up-to-date information.

In the future, as the SDSS evolves, the aim is to fully automate the processes behind these tools and expand accessibility so that external users, with minimal technical expertise, can freely explore and interact with the system. This will allow users to experiment with different input

scenarios, view the results in real time, and simulate a wide range of potential outcomes across the different models, without the need for administrative intervention.

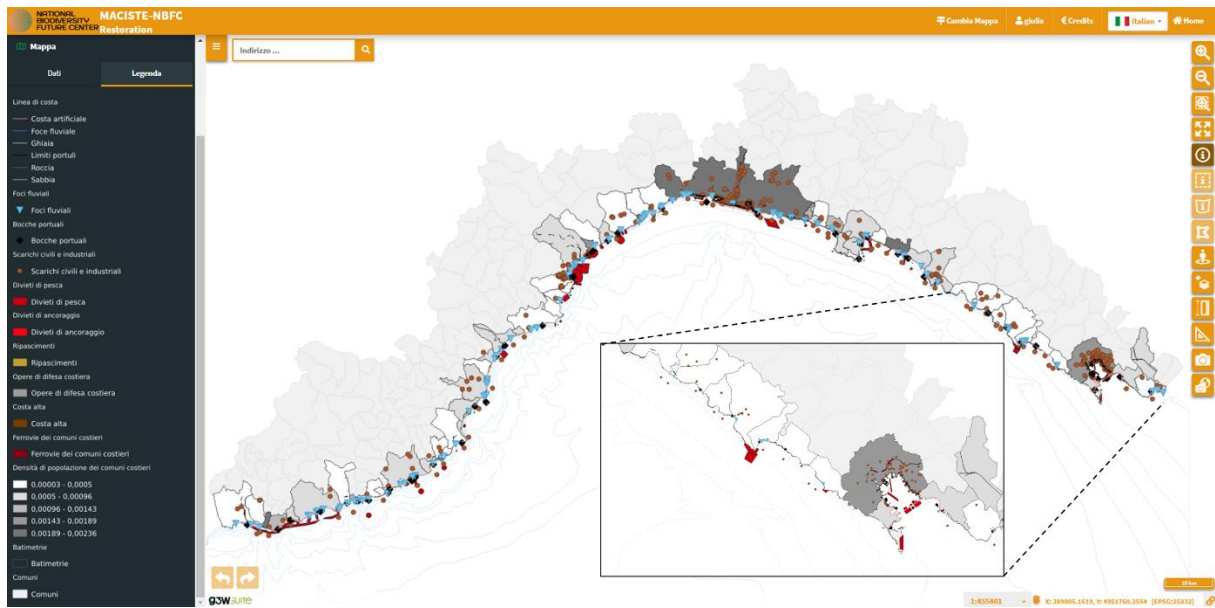


FIGURE 6. Geographic variables located in the study area

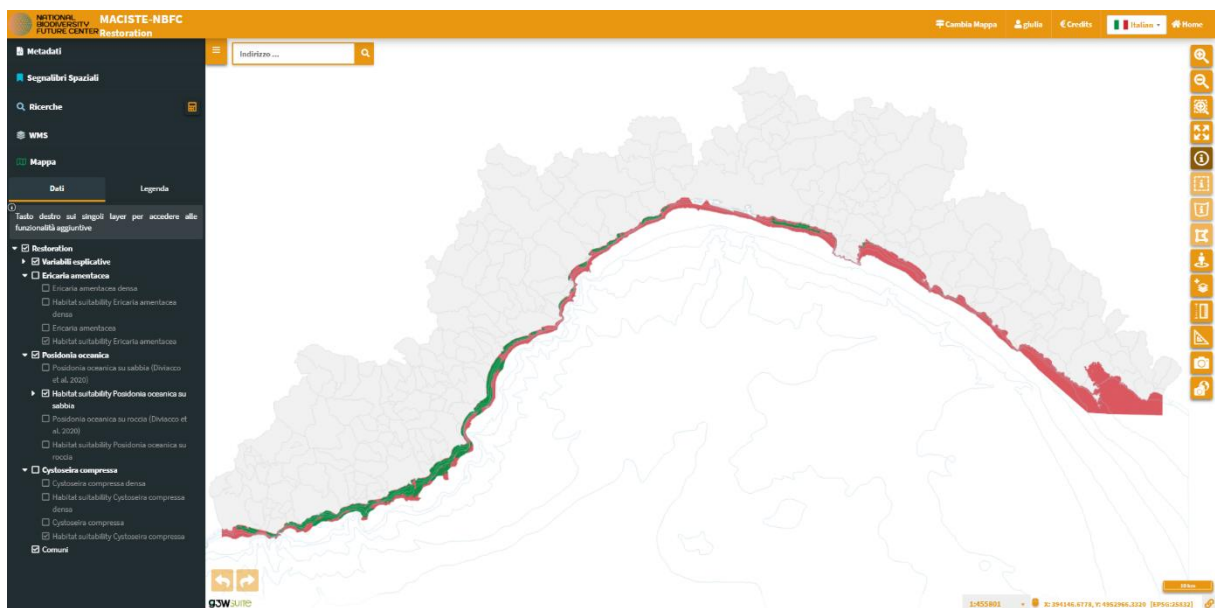


FIGURE 7. P. oceanica habitat suitability model

5. CONCLUDING REMARKS

Coastal ecosystems, as important interfaces between land and sea, are facing unprecedented challenges due to complex interactions between natural processes and increasing anthropogenic pressures. While these ecosystems are fundamental in providing services such as biodiversity, climate regulation, food supply, and tourism, they are increasingly under pressure from anthropogenic activities such as urbanization, infrastructure development, pollution, and climate change. As mentioned in the introductory chapter of this dissertation, the degradation of coastal ecosystems, due to both direct human activities and broader ecological changes, threatens the ability of these systems to continue to provide key services, thus compromising the future sustainability of coastal regions.

The objective of this dissertation was to develop a comprehensive SDSS capable of integrating environmental, economic and social components to enable sustainable management of coastal zones. This research aimed to provide key insights into the main elements of coastal ecosystem dynamics, from natural capital valuation to habitat suitability modeling and ecosystem service mapping, which will help to provide strategies for integrated management. This dissertation attempts to contribute to a better understanding of the balance between human development and environmental conservation in coastal areas using various technologies such as GIS, remote sensing, and empirical field data. Each study within this dissertation addresses a different aspect of coastal ecosystem assessment and management, thus enriching the overall understanding of the ecological integrity and resilience of the area.

PAPER I focused on the spatial analysis of natural capital and environmental flows along the Ligurian coast, demonstrating that protected areas, particularly those with more stringent conservation measures, play a fundamental role in enhancing ecosystem health and resilience. The results underscore the importance of ensuring that MPAs are well designed, taking into account the spatial distribution of key habitats and their potential to support self-sustaining ecosystems. PAPER II highlighted the high impact of human activities on coastal ecosystems, demonstrating that urbanization and coastal development significantly reduce natural resources and environmental processes. However, the negative impacts of human activities could be minimized by establishing appropriate conservation measures and by establishing restrictions on activities such as anchoring and fishing. These results underscore the importance of proactive, science-based policies to prevent ecosystem degradation and promote the recovery of degraded coastal ecosystems. The combination of quantitative modeling with expert-informed qualitative assessment proved useful in unpacking these dynamics and improving the

decision-making framework. In PAPER III, research on *P. oceanica* habitats, a very important seagrass species, demonstrated how historical human activities and contemporary environmental factors affect habitat distribution and health. The HSMs developed in this study provided important insights into the ecological preferences and vulnerabilities of these habitats, underscoring the need for targeted conservation efforts to protect and restore these critical ecosystems. The study demonstrated that HSMs can not only assess the current status of habitats, but also identify potential areas for ecological restoration, providing a coherent framework for coastal habitat management. Research on the distribution of the species *E. amentacea* (presented in RESEARCH I) further improved the understanding of the dynamics of coastal ecosystems.

The prediction of the distribution of this species along the Ligurian coast has shown the important role played by anthropogenic factors such as urbanization, pollution and habitat fragmentation in shaping its habitat suitability. These results highlight the importance of MPAs in conserving biodiversity, and thus habitat quality, in addition to proximity to urban areas, is one of the key drivers of species distribution. The importance of this finding lies in its implications for conservation practice, suggesting that more emphasis needs to be placed on intensive field surveys and habitat restoration efforts to better protect threatened species and their habitats. The final part of the study, presented under RESEARCH II, explores how the assessment of spatial patterns in ecosystem services, along with their relationship to anthropogenic pressures, can help to provide relevant information for prioritizing management interventions, especially in highly vulnerable regions. In addition, this study used a scenario-based approach to examine how changes in coastal infrastructure (e.g., berth expansion) affect the distribution of ecosystem services, thus increasing the risk of ecosystem overexploitation. This study demonstrates how integrated modeling can be used to guide future infrastructure development and help balance resource use with the conservation of ecosystem services.

Together, these studies provide a framework for comprehensive assessment and management of coastal ecosystems. The SDSS developed in this dissertation combines the findings from all these different research areas and provides tools to inform decision-making processes. The WebGIS platform created as part of the SDSS allows stakeholders, from policymakers to local communities, to access, explore, and visualize complex ecological and socio-economic data, facilitating more transparent, data-driven decisions.

The results of this dissertation have shown that an integrated approach that includes ecological, economic, and social dimensions is essential for effective coastal management.

Spatially explicit tools, such as the SDSS, allow for the examination of complex and difficult trade-offs between the conflicting interests of human development and environmental protection. The results also reinforce the need for policies that focus on ecosystem restoration, habitat protection, and sustainable use of coastal resources. An SDSS can therefore provide a decision-maker with an integrated, evidence-based tool for balancing the competing demands and ensuring the long-term sustainability of coastal ecosystems. This dissertation therefore contributes to ongoing efforts to address the serious challenges facing coastal ecosystems around the world.

The findings and tools presented in this study are meant to inspire further research and inform actionable, policy-driven steps to conserve and restore these critical ecosystems for the benefit of future generations. Protecting coastal areas is not only an environmental imperative, but also a social responsibility that requires collaboration at all levels of government and engagement with all stakeholders to ensure that these valuable ecosystems are resilient and healthy.

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