POLITECNICO DI TORINO

Master's Degree in Environmental and
Land Engineering

Master's Degree Thesis

Quantification of coastal ecosystem services in the Ligurian coast: application of *InVEST* software

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A Leo e Gabri
proteggendo il vostro futuro,
tutelando la nostra terra.

Abstract

In the coastal environment, the protection of ecosystems emphasises the interdependence of each part with the whole. Therefore, the importance and urgency of adopting effective strategies to deal with climate change and conserving biodiversity to protect fragile coastal ecosystems are evident. For the conservation of biodiversity, nature and coastal ecosystems in general, there are strands of economic studies that place the maintenance and replenishment of 'Natural Capital' at the basis of economic and social development. That quantifies the importance of natural resources and ecosystem services for coastal populations. This concept gave rise to the idea of assessing the coastal ecosystem services using a valuable quantification model for protecting the coast and its inhabitants. In an area of the western Ligurian coast from Finale Ligure (SV) to Vado Ligure (SV), the study uses two models developed by *Stanford University* in the open source software **InVEST** *(**In**tegrated **V**aluation of **E**cosystem **S**ervices and **T**radeoffs).* This thesis aims to demonstrate how the value of coastal ecosystem services and the damage caused to marine seagrasses *(Posidonia Oceanica and Cymodocea Nodosa)* can be quantified in terms of economics and coastal vulnerability.

The **Coastal Blue Carbon Model** is used to assess natural capital and quantifies climate-regulating ecosystem services by calculating the amount of carbon stored and sequestered in a coastal zone as a result of a change in land cover. As a final result, the model estimates the economic value of sequestration €$/(ha \cdot year)$ as a function of the amount of carbon sequestered $MtCO_2E/(ha \cdot year)$.

On the other hand, the **Coastal Vulnerability Model** produces a quantitative estimate of erosion exposure in terms of vulnerability index. It quantifies the ecosystem services of morpho-sedimentary regulation using geospatial information on marine habitat loss and local data such as DTM, bathymetry, lithology and wind and wave data (WaveWatch$_{III}$ format).

Quantification of ecosystem services in terms of economics and coastal vulnerability can be implemented in coastal spatial planning, in the hope that this will provide an incentive for better conservation and protection towards sustainability.

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Glossary

BC

Blue Carbon - the ability of marine ecosystems to store carbon dioxide over the long term, with positive consequences for the climate. (Languages, 2022)

Biocoenosis

Association of different organisms forming a closely integrated community. (Languages, 2022)

CN

Cymodocea Nodosa - An aquatic plant in the family *Cymodoceaceae* (Languages, 2022)

CBC

Coastal Blue Carbon - *InVEST* Coastal Blue Carbon model attempts to predict the amount of carbon stored and sequestered over a coastal zone at particular points in time due to changes in land cover. (Sharp et al., 2022)

CV

Coastal Vulnerability - *InVEST* Coastal Vulnerability model produces a qualitative estimate of such exposure in terms of a vulnerability index, which differentiates areas with relatively high or low exposure to erosion and inundation during storms.(Sharp et al., 2022)

DEM

Digital Elevation Model

DTM

Digital Terrain Model

ES

Ecosystem Services - Multiple benefits provided by ecosystems to mankind. (Mooney et al., 2005)

Epigean

Describing an organism's activity above the soil surface. (Languages, 2022)

Hypogeum

Describing an organism's activity below the soil surface. (Languages, 2022)

InVEST

Integrated Valuation of Ecosystem Services and Tradeoffs. (Sharp et al., 2022)

MPA

Marine Protected Area

PO

Posidonia Oceanica - An aquatic plant, endemic to the Mediterranean Sea, belonging to the *Posidoniaceae* family. (Languages, 2022

POM

Posidonia Oceanica Matte - Agglomeration of dead PO parts still anchored to the substrate. (Languages, 2022)

SCC

The social cost of carbon used by *InVEST* in the evaluation of net carbon sequestered. It represents a synthesis of several models, (Sharp et al., 2022)

SCIs

Site of Community Importance

SACs

Special Area of Conservation

SPAs

Special Protection Area

Chapter 1

Introduction

1.1 Ecosystem Services

The complex ecological processes regulating ecosystem balances have had little impact on space and resource management policies until now (Sanna, 2021). When anthropogenic activities cause the deterioration of natural systems but do not directly affect health, concern about the consequences of such actions usually focuses on environmental issues, often generating limited impact on public opinion and management policies. Instead when impacts on natural systems are translated into implications for human benefits, it creates a means of communication between science and management that satisfies both sides. For this reason, this study focuses on the ability of natural systems to provide ecosystem benefits in quantitatively terms.

The ecosystem presents itself as a complex unit because of the number of interactions within its different components. However, while it is not easy to assess and predict the behaviour of an ecosystem as a whole, it is possible to quantify the services rendered with economically compatible measurement systems, like the Ecosystem Services (ES): scientific research has defined ES as those direct or indirect contributions that ecosystems make to human well-being (EU, 2006).

Recently, the study *"The cost of policy inaction"* analysed the explicit and implicit costs that must be borne due to the loss of ES fostered by the inaction of environmental policies (Braat and Brink, 2008). It estimates a loss of biodiversity and related services quantified at 50 billion y. In another study, the authors (Costanza and Limburg, 2000), emphasises that the systematic underestimation of the ecological dimension in decision-making processes can be partly explained by the fact that the goods and services provided by Natural Capital are not well defined in quantitative terms like other services and other forms of Capital. The vast scientific literature identifies four different types of services (provisioning, regulating, cultural, supporting), which are vital for human well-being and health (Mooney et al., 2005; Costanza, 2008).

- *Provisioning* ESs are those functions related to the capacity of an ecosystem to provide real goods necessary for the survival of both the ecosystem itself and humankind.
- *Regulating* ESs are those deputed to the optimal maintenance and prevention of significant and negative alterations to ecosystems, in particular, those related to the upkeep of climatic balances, going against all those causes of extreme climatic events (e.g. floods) and the spread of diseases.
- *Cultural* ESs include aesthetic inspiration, cultural identity, sense of home and spiritual experience linked to the natural environment. Cultural services are deeply interconnected and often linked to supply and regulation services (FAO, 2020a).
- *Supporting* ESs are the services that underpin all ecosystems and their services. They are needed to provide living space for plants or animals and maintain their biodiversity (FAO, 2020b).

1.2 Coastal Ecosystem Services

Coastal ecosystems are threatened by human-induced pressures such as climate change and eutrophication. In the coastal zone, the fluxes and transformations of nutrients and carbon-supporting coastal ecosystem functions and services are strongly regulated by biological and chemical processes. Coastal systems also contribute to the regulation of climate and nutrient cycles by efficiently processing anthropogenic emissions from the land. The high value of these ESs is evident, considering that much of the world's population lives near the coast (Sanna, 2021). Currently, coastal areas are undergoing significant ecological changes driven by human-induced pressures such as climate change, anthropogenic nutrient inputs, over fishing and the spread of invasive species (Scanu et al., 2022). In many cases, the changes alter ecological functions in such a way as to shift the basal equilibrium of the ecosystems themselves significantly (Carli, 2015). In 2015, the UN set 17 Sustainable Development Goals (SDGs) to achieve specific targets by 2030 (UN, 2022). Their mission statement for their 14^{th} goal (Life Under Water) is *"to conserve and sustainably use the oceans, seas and marine resources for sustainable development"*. The goal shows the importance of coastal ESs in sustainable development.

Coastal marine ecosystems often differ from terrestrial ecosystems in the type and manner in which benefits are provided. An analysis of the main coastal ESs provided by phanerogams is given below. It is based on the concepts provided by Costanza, 2008 and interpreted by Carli, 2015.

- *Carbon sink*: is provided when the coastal species include organisms capable of fixing carbon dioxide in long-term resistant forms. This can occur by photosynthesis and storage of carbon in refractory forms, as in the case of *Posidonia Oceanica's Matte* (POM), or by carbon fixation in long-term resistant forms, such as the shell of many molluscs. The benefit to humanity from this function is linked to the need to reduce CO_2 emissions, which is demonstrated by the existence of an international emission market for CO_2 quotas. There is now widespread talk of *Blue Carbon* (BC), precisely about the ability of marine ecosystems to store carbon dioxide over the long term, with positive consequences for the climate.

- *Erosion protection*: refers to the ability of species in context to significantly reduce the erosive action that wave action has on the coastline. This can substantially influence the coastal vulnerability of the ecosystem and the nearshore populations. In the case of *Posidonia Oceanica* (PO), the prairie's leaf cover, which can even exceed one metre in height above the seabed, can absorb wave energy and dissipate some of it by reducing the height of the highest waves, which results in the most effective removal of sediment from the beach.

In addition to the ESs already discussed within the chapter, there are the following ESs: water cleaning, oxygen supply, bio remediation, food production, genetic resources, recreational potential and cultural/aesthetic potential. These ESs have not been addressed within the economic quantification of this study; therefore, a brief description is given in the following section.

- *Water cleaning*: when a biocoenosis produces biological structures that are epigean or otherwise capable of trapping suspended particles, such as fine sediment and organic matter, it leads to a reduction in suspended solids, resulting in increased light penetration and greater water transparency. The benefit for humanity derives from the possibility of enjoying a more valuable environment. Structures such as PO leaves can interact by their nature with the hydrodynamic flow, trapping significant amounts of suspended solid.

- O_2 *supply*: Biocoenoses based on photosynthetic organisms, in their metabolic community processes, often produce a surplus of oxygen, net of all respiration and oxidative processes. Should this benefit be lacking, coastal communities would be forced to make up for it by artificially oxygenating certain areas to allow the supply of most other uses, inhibit the proliferation of pathogens, and reduce the deterioration of numerous environmental parameters.

- *Bioremediation*: The ability of different organisms and biological communities to absorb and process potentially harmful substances plays a significant role in maintaining coastal ecological balances and, consequently, in the possibility for humans to enjoy and utilise their resources. For example, the ability of specific biological associations to absorb and process large quantities of nutrients allows them to exert physical control over the proliferation of invasive algal species, one of the leading causes of increased eutrophication and impoverishment of biodiversity. Another example, in a long possible series, is given by the ability of certain biological formations to immobilise heavy metals in resistant structures, reducing their bioaccumulation in the trophic network and, consequently, reducing the possibility of their contamination by humans.

- *Food production*: In the coastal marine environment, this benefit is linked to fishing, whether professional, artisanal or recreational. Not only does the biocenosis from which the resource is taken provide this benefit, but some biocenoses are also used by organisms as nursery, spawning or mating grounds. Biocenoses such as those in the coral reef, for example, provide safe havens for spawning, often also for pelagic or deep-sea organisms, and thus play a vital role in the possibility of human exploitation of the fish resource.

- *Genetic resources*: in the context of ESs, generally refer to the capacity of some ecosystems to conserve and protect part of the genetic heritage of different coastal biological populations. The biological and genetic diversity of coastal marine environments is rapidly becoming a natural resource, hand in hand with the advancement of biotechnological research.

- *Recreational potential*: There are numerous possibilities for exploiting biocoenosis for recreational purposes, from fishing to recreational diving to simple enjoyment benefits. This benefit is held in high regard in the literature, both for its intrinsic importance and for the substantial amounts of money spent on recreation. Among the various possible examples, well-preserved coralligenous biocoenoses are often important dive sites, as are PO meadows, which, among other things, also attract many recreational spearfishers.

- *Cultural/aesthetic potential*: the Millennium Ecosystem Assessment defines cultural services as intangible benefits that humans obtain from ecosystems, explicitly indicating *"cultural diversity, spiritual and religious values, knowledge systems, educational values, inspiration, aesthetic value, social relations, sense of peace, cultural heritage"* (Mooney et al., 2005). It is a benefit more associated with terrestrial rather than aquatic environments, but it is also increasingly recognised in coastal marine areas.

1.3 Ecosystem Services provided by phanerogams

The current study aims to highlight the potential of the essential ESs provided by PO and *Cymodocea Nodosa* (CN) along the western Ligurian coast. Marine phanerogams provide ESs of great economic and cultural value in the Ligurian area. A detailed explanation of marine phanerogams and their significance in the context studied will be provided in section 3.2.2. The ESs of seagrasses are not limited to facing coastal erosion but also concern the proper supply of sediment and nutrients to the marine-coastal ecosystem. Seagrass beds also play an effective action in the permanent sequestration of CO_2 from the atmosphere. PO also plays a role in the ESs of recreational tourism. A good example is diving, which, like many other activities, relies on the optimal state of conservation of natural resources.

The following section illustrates the ESs that seagrasses provide to coastal populations. As already highlighted in the previous section 1.2, among the seagrass-related ES of interest for this study are the ESs of morphosedimentary regulation and climate change mitigation.

1.3.1 Morphosedimentary regulation services

Regarding morphosedimentary regulation services, several studies reveal that phanerogams meadow influence coastal sedimentary dynamics (Fonseca et al., 2007; Fonseca and Fisher, 1986; Jeudy De Grissac, 1984; Fornós et al., 2007). This ability would be due to the conformation of the plant (Fornós et al., 2007). The rhizomes and their type of growth can hold and fix sediments, creating resilient natural barriers that dampen the force of wave motion by forcing it to break in an area further away from the coastline (Duarte, 2002). Leaves and other phanerogam fragments also dampen waves' impact by increasing the water's viscosity (Tigny et al., 2007). In addition, the frequent presence of floating pieces of dead PO increases water viscosity, reducing wave energy and thus protecting the beach from erosion. This mitigates erosive processes by absorbing up to 50 % of the power of the sea (Boudouresque, 2000). Furthermore, the POM represents, at the same time, an elastic and rigid structure that can absorb some of the wave energy (Fonseca et al., 2007). The erosion rate in this way can be four to six times lower than usual. This dampening effect of wave action is considered to be more effective than artificial submerged protection devices that are installed to protect coastlines (Fonseca and Fisher, 1986; Jeudy De Grissac, 1984; Basterretxea, 2004).

1.3.2 Climate regulation services

Concerning the function of facing climate change, the investigation of ESs also revealed the ability of the phanerogams matte to sequester CO_2 from the atmosphere permanently. The capacity of seagrass beds (*matte*) to sequester large quantities of carbon is also known as Blue Carbon (BC) (Mcleod et al., 2011). When seagrasses beds are degraded or destroyed, these ecosystems emit the carbon they have stored for centuries into the atmosphere, and the oceans become sources of greenhouse gas emissions. Therefore, it is crucial to work towards their conservation and restoration (Boudouresque, 2000). Marine seagrasses are being lost rapidly and it affects the ability of forests to mitigate the damage caused by climate change. For this reason, public and private funds have been allocated internationally to support sustainable marine forest management projects (Commission, 2008). In addition to carbon, other regulatory ESs include water and air purification and soil protection. The overall objective of the EU SEAFOREST LIFE project is to increase the carbon storage capacity of Posidonia beds through actions to reduce their degradation (Bonamano and Simeone, 2020). In this context, the EU pays particular attention, as mentioned earlier, to the restoration of carbon-rich habitats and the protection and restoration of wetlands and coastal ecosystems (Commission, 2008; EU, 2006). In this case, anthropogenic disturbance factors causing regression can be managed by implementing preventive actions, including the economic quantification of ESs for climate regulation. Preventive actions are preferred because restoring degraded areas often involves complex, time-consuming and costly operations, which are not always as desired. Disturbing factors include intensive coastal development, pollution, invasive exotic species, unsustainable fishing practices and poorly planned tourism, all of which need to be addressed (Diviacco and Coppo, 2006). In this context, the two seagrasses' specific stressors are studied in section 3.2.2.

1.4 Quantification of ES in the Mediterranean area, peer review analysis

In the following section, an excerpt from the research of scientific publications on the quantification of coastal ESs in the Mediterranean area is reported. The purpose of this research is to question state of the art, that is, what has already been analysed in the same areas of interest and in the same way. Anthropogenic pressure, pollution and loss of biodiversity are having a significant impact on the health of coastal ecosystems. To minimise their impact, Marcelli et al., 2018, suggest that coastal management plans must include conserving the ecological processes. Their conservation affects its ESs, both in qualitative and quantitative terms (Scanu et al., 2022). For this reason, an attempt was made in this paper to quantitatively assess the role of ESs in the area under consideration. As reviewed by O'Brien, 1998, the approach to socio-economic concepts for the quantification of ES helps to highlight the *"Societal Dependence on Natural Ecosystems"* and to favour more concrete conservation objectives. The economic value of ES allows for a better management of the coast that enables more concrete resource allocation management choices (Scanu et al., 2022). Although the assessment of Natural Capital on a Mediterranean scale is still inadequate to provide the correct environmental accounting (Franschetti et al., 2011), surveys aimed at understanding habitat distributions along the Italian coast have increased considerably in recent years (ISPRA, 2022; Bianchi and Peirano, 1995; Diviacco and Coppo, 2006;Liguria, 2020). Focusing on seagrasses, and in particular on PO, an extensive regression of seagrass beds has been recorded throughout the Mediterranean due to climate change and human activities (Scanu et al., 2022). ESs estimates of seagrasses beds can provide crucial information for sustainable coastal management (Sanna, 2021). Among the published scientific literature, there are several examples of Natural Capital assessment and ES estimation for PO seagrass beds (Scanu et al., 2022; Vassallo et al., 2013; Bonamano and Simeone, 2020), but fewer examples concerning seagrasses in general or other less protected coastal habitats (González-García et al., 2022).

In addition to these publications, there are technical reports from the European Union that are working to define a starting point for assessing ESs of PO in particular (Weatherdon et al., 2017; Bonamano and Simeone, 2020; Cozzolino et al., 2021; Commission, 2008). Among these projects is the work of Sea Forest Life *"Posidonia meadows as carbon sinks of the Mediterranean"* (Bonamano and Simeone, 2020), which highlights the role of ESs as a tool for mitigate climate change, and the work of the S.E.POS.S.O.EU Life Project, which represent a technical guide on the economic evaluation of environmental impacts on PO meadows (Cozzolino et al., 2021).

In particular, the papers published by different authors (Vassallo et al., 2013, Campagne et al., 2015 and Marcelli et al., 2018) are an important reference point for the assessment of PO's ESs. They describe different methodological approaches and are particularly useful for comparative analysis in terms of economic estimation of the services considered. As pointed out by Scanu et al., 2022, the papers provided different approaches to the economic evaluation of the benefits brought by ES, some on the international territory (Campagne et al., 2015), others on the Italian territory (Vassallo et al., 2013). In the latter study, Vassallo et al., 2013 uses an approach called the *"Emergy Money Ratio"*, in which the flow of matter and energy from various inputs into the ecosystem is estimated and regulated by the solar energy required to maintain this process. This study in particular refers to the Marine Protected Area (MPA) *Isola di Bergeggi* (Ligurian Sea, NW Mediterranean), to quantify the economic loss associated with PO regression. In addition to this, there is the work of Scanu et al., 2022, already cited several times within this literature review. The author uses the approach applied by the *InVEST* software to quantify the *"Economic Evaluation of Posidonia Oceanica Ecosystem Services along the Italian Coast"*.

This study therefore aims to fill the gaps highlighted by the papers listed above by analysing and quantifying the economic value of the ESs of the seagrass beds most commonly found in the Ligurian Sea (PO and CN). It is carried out using the *InVEST* software by means of synoptic representations. To obtain a good result in the application of the *InVEST* software, it is necessary to use specific data; in the absence of these, data from similar ecosystem zones obtained from the studies analysed in this section will be used.

In appendix B will be listed the methods and applications in which the literature data previously analysed were used.

Chapter 2

Natural Capital Project & InVEST

2.1 Natural Capital Project

As highlighted in previous sections, ESs can be linked to the concept of Natural Capital. Compared to other forms of Capital, Natural Capital is little known and is undergoing rapid degradation, with the risk of losing the flow of many benefits to people. In this context, the Stanford University Natural Capital Project was born (Stanford, 2022). It aims to change this current situation by fully understanding the intertwined concepts of ESs and Natural Capital. As such, the project seeks to develop mapping and analysis of ESs that can lead directly to real-world applications and inform decisions in crucial areas such as water and food security and promoting resilience in the face of climate change.

Reducing or avoiding emissions from soil, for example, can be a cost-effective way to tackle climate change. The carbon market offers many coastal offset options, including reforestation of seagrass beds, marine protection and reduction of marine deforestation. An ESs approach can help support coastal-based carbon offset projects by identifying how and where these 'co-benefits' from carbon investments can be maximised. This information can guide the selection of projects for investment, improve the efficiency of the chosen projects and estimate the likely level of co-benefits.

2.1.1 The NatCap Approach

Within Stanford University's NatCap project, a new approach was developed to help people translate their goals into plans to best achieve goals to help people and nature. In complex nature dynamics with multiple goals to be evaluated, it is good to follow a process with appropriate tools and helpful questions to illustrate the key inputs and outputs of the plan.

The NatCap approach divides the project into scientifically designed phases to achieve the best objectives with limited budgets. The NatCap approach uses the open source *InVEST* platform, which will be explained extensively in the next section 2.2. The first phases aim to identify the context through collaboration with local stakeholders and the search for data sources necessary to produce valuable results. The NatCap approach at this early stage recommends liaising with a broader network of local experts, including those with helpful knowledge of relevant data sets.

Beyond this initial phase, it is necessary to ask questions and explore scenarios where natural investments could significantly impact the best use of allocated resources. In this phase of asking questions and exploring options, NatCap's *InVEST* software platform acts as a *"What if?"* machine, allowing users to explore changes in the provision of critical ESs under different management choices and a changing climate. These scenario maps are used as inputs in *InVEST*. The results allow stakeholders to understand better how ESs flow to their community and how their future choices (i.e. policies) protect, enhance or harm these services. Strong interactions between policy choices and Natural Capital investments are highlighted through software such as InVEST, which serves as a visual and quantitative means of communication between scientists and local governments. In the next phase, models run, data are analysed, and maps, graphs and other results are produced for stakeholders. Modelling tools quantify and map potential outcomes associated with ESs. Modelling results and supporting information are used to understand how policies, management choices, investments or climate change affect the provision of ESs to people.

Behind the creation of open-source software like *InVEST* is the Natural Capital Project's mission to highlight the connections between people and nature. Thanks to the *InVEST* software, nature's contribution to society is more evident. This way, leaders and decision-makers can make better decisions for both nature and people. There is a need to restore natural capital, directing investments in people and places and the kinds of new economic systems that will pave this path for green and inclusive growth. Right now, the way governments, investors and businesses make decisions are not capturing the connection between nature and people. NatCap's work could reveal to decision-makers what was previously invisible in new ways.

2.2 *InVEST* software

The NatCap project has created the *InVEST* (Integrated Valuation of ESs and Tradeoffs) suite to map and value the ESs that sustain and satisfy human life

(Sharp et al., 2022). The suite contains free and open-source software models that can be used by anyone with basic knowledge of GIS (Geographic Information System) platforms.

The approach used by *InVEST* outlines three concepts, namely the supply, service and value of ESs.

- *Supply* encapsulates what the ecosystem structure and function can offer: in other words, it represents what is potentially available from the ecosystem.
- *Service* helps to clarify the project demand, such as coastal erosion and flood reduction.
- *Value* represents the economic quantification of ESs, e.g. calculating the damage avoided by erosion and flooding.

The user, with the application of *InVEST*, can guide decision-makers between trade-offs and alternative management choices through the described approach without overshadowing nature. The main products of InVEST's models are maps, reports and summary tables to identify areas where investments in Natural Capital can improve environmental protection and ensure sustainable development.

InVEST developers define their models as spatially explicit because they *"use maps as sources of information and produce maps as outputs"* (Sharp et al., 2022. The spatial resolution of the maps is flexible and allows the user to work on a local, regional or global scale. *InVEST* can also provide results in biophysical or economic terms: speaking of blue carbon, for example, the models can return the tonnes of carbon sequestered by phanerogams' meadows or its respective net economic value calculated through the current reference price.

In addition, like the NatCap project approach, *InVEST* can produce scenario models that consider the possible influences of flows and values that ESs may experience.

The *InVEST* suite is modular, it contains several models that can also be used and downloaded individually, giving the user only the option of selecting those of interest. The *InVEST* suite includes additional tools to facilitate the assessment of ESs. Within the version used for this study, *InVEST* 3.12.0.*post*7, the models in tables 2.1-2.2 are available. It is possible to subdivide the suite of models by the ESs they characterise, such as terrestrial, coastal and marine ESs. Some models fall explicitly within these sets; others can be used in more than one context. Of the models described above in section 2.3, this study uses only two tools that fall within the assessment of coastal ESs: Coastal Blue Carbon and Coastal Vulnerability models, described in section 2.3.1 and 2.3.2.

Table 2.1: List and description of models in the *InVEST* 3.12.0.*post*7 suite.

Models	Description
Carbon Storage and Sequestration	Estimates the current amount of carbon stored in a landscape and values the amount of sequestered carbon over time.
Forest Carbon Edge Effect	Estimates the amount of carbon stored in a tropical landscape, taking into account degradation due to the creation of forest edges.
Coastal Blue Carbon	Estimates the amount of carbon stored and sequestered in coastal habitat and quantifies the marginal value of sequestration over time.
Annual Water Yield	Quantifies the annual average amount of water produced in a watershed and values freshwater yield for reservoir hydropower production.
Seasonal Water Yield	Quantifies the contribution of a watershed to monthly freshwater quick flow and provides relative indices for its contribution to annual base flow.
Nutrient Delivery Ratio	Estimates the amount of nutrient (nitrogen and phosphorus) runoff that enters freshwater streams in a watershed.
Sediment Delivery Ratio	Maps the location and quantity of erosion produced in a watershed and the amount of sediment that enters freshwater streams.
Unobstructed Views: Scenic Quality Provision	Uses a viewshed analysis to estimate the visibility of features or objects such as coastal development, clear-cuts, or aquaculture facilities.
Visitation: Recreation and Tourism	Uses social media data to understand where people recreate and relates this information to the location of natural habitats and other features that influence visitation.
Wave Energy Production	Measures and values the electricity generation potential of ocean waves.

Continued on next page

Table 2.1 – *Continued from previous page*

Service and Supporting Models	**Description**
Offshore Wind Energy Production	Measures the electricity generation potential of wind over the ocean and large lake surfaces.
Marine Finfish Aquacultural Production	Estimates the weight and economic value of Atlantic salmon grown in netpen aquaculture facilities.
Fisheries	Estimates harvest volume and economic value of single-species fisheries.
Habitat Quality	Uses habitat quality as a proxy to represent the biodiversity of a landscape; estimates degradation of habitat and vegetation types from different threats.
Habitat Risk Assessment	Evaluates risks posed to multiple habitats in terms of exposure to human activities and the habitat-specific consequence of that exposure for delivery of ESs.
Pollinator Abundance: Crop Pollination	Focuses on wild bees as a key animal pollinator and estimates bee abundance across a landscape as well as the contribution of those bees to crop pollination.
Crop Production	Estimates crop yield and nutrient value for a fixed set of crops.
Urban Cooling	Estimates the heat reduction provided by vegetation in cities.
Urban Flood Risk Mitigation	Calculates the reduction in stormwater runoff related to natural infrastructure in cities.

Table 2.2: List and description of the additional models in the *InVEST* suite.

Models	**Description**
Coastal Vulnerability	Uses geophysical and natural habitat characteristics of coastal landscapes to compare their exposure to erosion and flooding in severe weather.
GLOBIO	Provides an index of biodiversity according to species abundance and response to different stressors.
RouteDEM	Creates maps of flow direction, flow accumulation, slope and stream networks from a digital elevation model.
DelineateIt	Delineates watersheds for points of interest along a stream network.
Scenario Generator: Proximity Based	Generates spatial scenarios based on user-defined principles of where land changes could occur and the possible extent of these changes.

2.3 *InVEST* and its valuable tools for the analysis of coastal ESs

The explanation of the *InVEST* models used is largely based on the guide by Sharp et al., 2022 available in the *InVEST* User Guide web page. This paragraph is intended as a helpful transcript to understand the application of the models to the case study; it is not a part of the work that might otherwise be understood as plagiarism to the *InVEST* documentation. The two model-specific guides used are available at the specific web page in the *InVEST* User Guide web page, Coastal Blue Carbon (NatCap, 2022a) and Coastal Vulnerability Model (NatCap, 2022b).

2.3.1 Coastal Blue Carbon

Blue Carbon represents a large amount of carbon stored by coastal vegetation, particularly coastal marshes, mangroves and seagrasses. By storing carbon through their sediments, leaves and other forms of biomass, they create large reservoirs of sequestered carbon long-term, diminishing the effect that CO_2 has on climate change.

The *InVEST* Coastal Blue Carbon model makes it possible to quantify the ES of climate regulation by calculating the amount of carbon stored and sequestered in a coastal zone due to a change in land cover. Furthermore, *"using an estimate of the social, monetary value or, if available, a market price for stored and sequestered carbon, the Coastal Blue Carbon model also quantifies the marginal value of storage and sequestration"* (Sharp et al., 2022; NatCap, 2022a).

The results of the *InVEST* Coastal Blue Carbon model can be used *"to compare current, and future scenarios of carbon stock and net sequestration as well as to identify locations within the landscape where degradation of coastal ecosystems should be avoided, and restoration of coastal ecosystems should be prioritised to preserve and enhance this carbon storage and sequestration services"* (Sharp et al., 2022). This model uses various information, including:

- the spatial distribution of coastal vegetation and its abundance;
- site-specific information on the carbon stocks of the studied habitat;
- knowledge and characteristics of the impact of various land cover disturbances on biomass, carbon stocks, and carbon emissions;
- carbon stocking rates help estimate a coastal zone's net sequestration and value;
- estimates of the social, monetary value or market price of carbon.

InVEST Coastal Blue Carbon models the carbon cycle through an accounting approach (Houghton, 2003; NatCap, 2022a). This method simplifies the study of the carbon cycle by accounting for storage in three leading sinks: biomass, sediment carbon (i.e. soil), and dead standing carbon (i.e. litter), see *Figure* 2.1. Pendleton et al., 2012 states that sediments are the most significant carbon storage in coastal habitats. The model quantifies carbon storage across the entire land or seascape by summing the carbon stored in these three carbon pools.

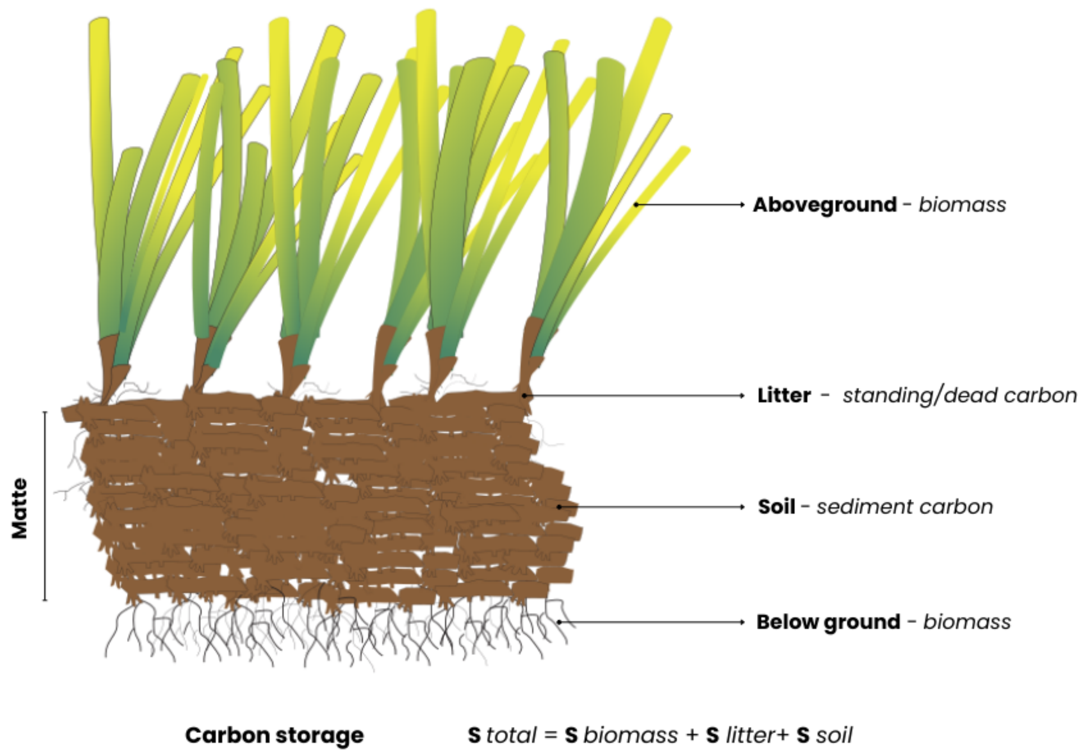

Figure 2.1: Carbon storage model used by *InVEST* within the Coastal Blue Carbon model. Example based on Houghton, 2003 approach and adapted on marine seagrasses. Storage is accounted for in three main sinks: biomass, sediment carbon (i.e. soil) and dead standing carbon (i.e. litter).

For the assessment of net carbon storage for a given year t, each coastal blue carbon habitat is assumed to be in storage equilibrium at any given time (NatCap, 2022a). The carbon stocks S for a given year t and basin p are calculated by adding the net carbon sequestration of the year to the stores available in the previous year *t-1*. Alternatively, using the initial stock values from the biophysical table, $S_{t,p_{baseline}}$. The model also calculates the total stocks for each year of the timestep, simply the sum of all carbon stocks in all three pools, as shown below

$$S_{t,total} = S_{t,p_{soil}} + S_{t,p_{biomass}} + S_{t,p_{litter}} \tag{2.1}$$

The valuation option of the blue carbon model estimates the economic value of sequestration as a function of the amount of carbon sequestered, the monetary value of each tonne of carbon sequestered, a discount rate and the change in the value of carbon sequestration over time (NatCap, 2022a). The value of carbon sequestering depends on who decides to change carbon emissions and falls into two categories: social and private. Considering a public approach to the case study, decision-makers must weigh the benefits of development against the social losses from carbon emissions. Since local carbon emissions affect the atmosphere globally, the social cost of carbon (SCC) is commonly calculated globally (USIWGSCC, 2016).

Hence, net present value V is calculated for each snapshot year s after the baseline year, extending to the final analysis year

$$V = \sum_{t=O}^{T} \frac{p_t(S_t - S_{t-1})}{(1+d)^t} \tag{2.2}$$

where

- V is the net present value of carbon sequestration.
- T is the number of years between the $t_{baseline}$ and the snapshot years. If an analysis year is provided beyond the final snapshot year, this will be used in addition to the snapshot years.
- p_t is the price per ton of carbon at timestep t.
- S_t represents the total carbon stock at timestep t, summed across the soil and biomass pools.
- d is the discount rate.

For further information on the specifications used by the Coastal Blue Carbon model, the reader is referred to the section in A.1.

2.3.2 Coastal Vulnerability Model

The *InVEST* coastal vulnerability model produces a quantitative estimate of the exposure to erosion and inundation coastal communities will face as climate change intensifies. In the model, exposure is expressed in terms of a Exposure Index (EI), which differentiates areas with relatively high or low exposure to erosion and inundation during storm surges. By highlighting the relative role of natural habitat in reducing exposure and showing areas where coastal populations are threatened, the model can be used to study how management actions or land-use changes can influence the exposure of human populations to erosion and flooding. Model inputs include

- a polyline with attributes on the local coastal geomorphology along the coastline;
- polygons representing the position of natural habitats (e.g. seagrass meadows);
- net rates of change of the coastal erosion and flooding in the area;
- a digital elevation model (DEM) representing the topography of the coastal area;
- a point shapefile containing observed storm wind speed and wave power values;
- a raster representing the population distribution.

The CV model is used to qualitatively assess how coastal vulnerability has changed as a function of changes in marine habitats, in this case, PO and CN meadows. As highlighted in the previous chapter 1.2, seagrasses play a substantial role within the ESs of morphosedimentary regulation. Few models map the relative vulnerability of coastal areas to erosion and flooding based on a region's geophysical and natural habitat characteristics. The CV model helps to fill this gap.

The *InVEST* coastal vulnerability model produces an exposure index for each point along a coastline at a user-specified interval. The EI represents the relative exposure of different coastal segments to erosion and inundation caused by storms in the region of interest. The index is constructed using up to seven biogeophysical variables, just six of them will be included in the study. These variables represent variations in the region's natural biological and geo-morphological characteristics, the rate or magnitude of sea-level rise, local bathymetry and topography, and the relative strength of wind and waves associated with storms.

The model is suitable for large, exposed, uniform, and complex, heterogeneous, protected coastlines.

The EI is calculated using a spatial representation of the following i^{th} biogeophysical variables:

- Geomorphology.
- Relief.
- Habitats (biotic and abiotic).
- Wind exposure.
- Wave exposure
- Surge potential depth contour.

The main output of the model is a geospatial dataset (points) plotted at user-defined intervals along the coastline of the coastal region of interest. The results of the model are potentially relevant at different scales and extents, depending on the resolution of the input data. This set of points includes a table with a set of indices and rankings of the input variables and can be used to create customised maps according to the user's needs. The grades range from very low exposure (grade=1) to very high exposure (grade=5), based on a combination of user- and model-defined criteria, see *Table* 2.3. This ranking system is based on methods proposed by Gornitz, 1990 and Hammar and Thieler, 2001.

Table 2.3: Classification table used by the Coastal Vulnerability Model.

The ranking values (1 to 5) are defined for each variable using a combination of user- and model-defined criteria.

Rank	**1**	**2**	**3**	**4**	**5**
GeoM	Rocky; high cliffs; seawalls	Medium cliff; small seawalls	Low cliff; alluvial plain;	Cobble beach; estuary;	Barrier and sand beach;
Natural Habitats	Coral	Mangroves	Coastal forest	Seagrass	No habitat
Relief[1] **i.e. DEM**	81 to 100	61 to 80	41 to 60	21 to 40	0 to 20
Wind Exposure[1]	0 to 20	21 to 40	41 to 60	61 to 80	81 to 100
Wave Exposure[1]	0 to 20	21 to 40	41 to 60	61 to 80	81 to 100
Surge Potential[1]	0 to 20	21 to 40	41 to 60	61 to 80	81 to 100

[1] The quantities refer to the percentiles of the values corresponding to each variable

The model calculates the exposure index EI for each shoreline point as the geometric mean of all the variable ranks

$$EI = (R_{Geomorphology} \cdot R_{Relief} \cdot R_{Habitats} \cdot R_{WindExposure} \cdot R_{WaveExposure} \cdot R_{Surge})^{1/6} \quad (2.3)$$

or more generally:

$$EI = (\sum_{i=1}^{n} R_i)^{1/n} \quad (2.4)$$

where R_i represents the ranking of the i^{th} bio-geophysical variable to calculate EI (listened above). For further information on the specifications used by the Coastal Vulnerability model, the reader is referred to the section in A.2.

Chapter 3

Case Study - Background and Assessment

Mapping and modelling changes in carbon storage and sequestration for coastal and marine habitats can present challenges. The types of spatial inputs and information available on the carbon cycle vary by location. Some study areas have high-quality data for detailed analysis, while other sites lack the information needed to model changes in the context and function of coastal vegetation. For this reason, the chosen area has a large amount of data that can be used as input in the two models applied.

3.1 The selected coastal area

The area chosen in this study comprises a stretch of coastline of approximately 15 km between the municipalities of Finale Ligure (SV) and Vado Ligure (SV), both within the jurisdiction of the Province of Savona (SV), Italy. Savona is the second largest Province in the Region of Liguria, located in the NW part of Italy and bordered along its entire coast by the Ligurian Sea, see *Figure* 3.1.

Like the other Provinces in the region, the Province of Savona is characterised by significant exploitation of the coastal area, both for seasonal tourism and maritime trade. Over the years, this has led to substantial degradation of seagrass beds, which, due to anthropic pressure, have decreased in quantity and quality (Diviacco and Coppo, 2006). In this context, this study helps quantify the decrease in seagrass meadows in the area. It could highlight the areas most damaged and of the most negligible economic value in carbon sequestration. The chosen location presented numerous peculiarities and was selected for its spatial heterogeneity and the presence of sufficient data.

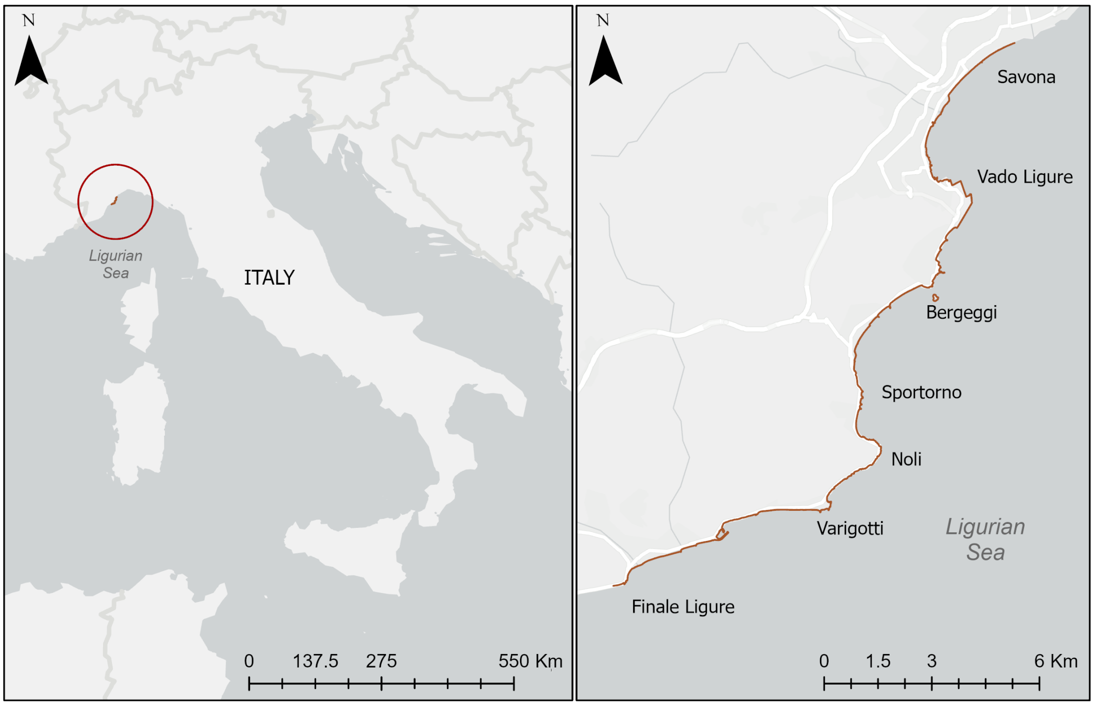

Figure 3.1: Coastal area of approximately 15 km between the municipalities of Finale Ligure (SV) and Vado Ligure (SV), both within the jurisdiction of the Province of Savona (SV), Italy.

3.1.1 The commercial port of Vado Ligure

The commercial port of Vado Ligure start from the municipality of Vado Ligure and proceeds towards the "Ponente" (western) area. The port of Vado Ligure is an essential European port, one of the largest national-level ferries to Corsica, Sardinia and North Africa. The port, managed by the Port System Authority of the Western Ligurian Sea, has recently been expanded. In December 2019, the container platform Vado Gateway (i.e. Porta di Vado) was inaugurated. It represents one of the maritime terminals for connecting the markets of Northern Italy, Switzerland, Germany and north-eastern France with the rest of the world. The commercial importance of the port of Vado Ligure is evident, but the impact these ports of call have on the coastal ecosystem balance is overshadowed. For example, the presence of an international trading hub has favoured the spread of an invasive alien species, the (i.e. *Caulerpa Cylindracea*) in the area (Diviacco and Coppo, 2006). As explained in the paragraphs of sub-section 3.2.1, the presence of the *Caulerpa Cylindracea* is negative for the seagrasses of the Ligurian Sea, as it can supplant native species by reducing their habitat range. Moreover, the problems caused by the port are also morpho sedimentary, interfering with the hydrodynamic regime and sediment transport (Jeudy De Grissac, 1984, Basterretxea, 2004).

3.1.2 Marine Protected Area of Bergeggi (SV)

Beyond the commercial port of Vado Ligure is the Protected Marine Area of Bergeggi, part of the municipality of Bergeggi (SV). Marine Protected Areas (MPAs) were introduced in Italy by the Law for the Defence of the Sea No. 979 of 1982 *D.L. n. 979* 1982, where they are defined as those *"marine environments made up of waters, seabeds and stretches of coastline that are of significant interest due to their natural, geomorphological, physical and biochemical characteristics (Art. 25)"*. The following Framework Law No. 349 of 1991 on protected natural areas enriched the regulatory framework *D.L. n. 394 - Legge quadro aree protette* 1991, also establishing the purposes of MPAs:

- conservation of animal or plant species, plant or forest associations, geological singularities, palaeontological formations, biological communities, biotypes, scenic or panoramic values, natural processes, hydraulic, hydrogeological and ecological balances;

- application of management or environmental restoration methods suitable for achieving integration between man and the natural environment, including safeguarding anthropogenic, archaeological, historical and architectural and traditional values;

- promotion of education, training and scientific research activities, also interdisciplinary, as well as compatible recreational activities;

- defence and reconstruction of hydraulic and hydrogeological balances.

The MPAs are divided into three zones, the *Figure* 3.2 shows the division into the three buffer zones for the Bergeggi MPA:

- Zone A (Integral Reserve), with strict constraints, intact area considered of absolute conservation.

- Zone B (General Reserve), with intermediate constraints, is the area on the borders of Zone A, where the conditions, although restrictive, seek to guarantee partial use of the marine environment.

- Zone C (Partial Reserve), with milder constraints, all sea use activities with a modest environmental impact are possible.

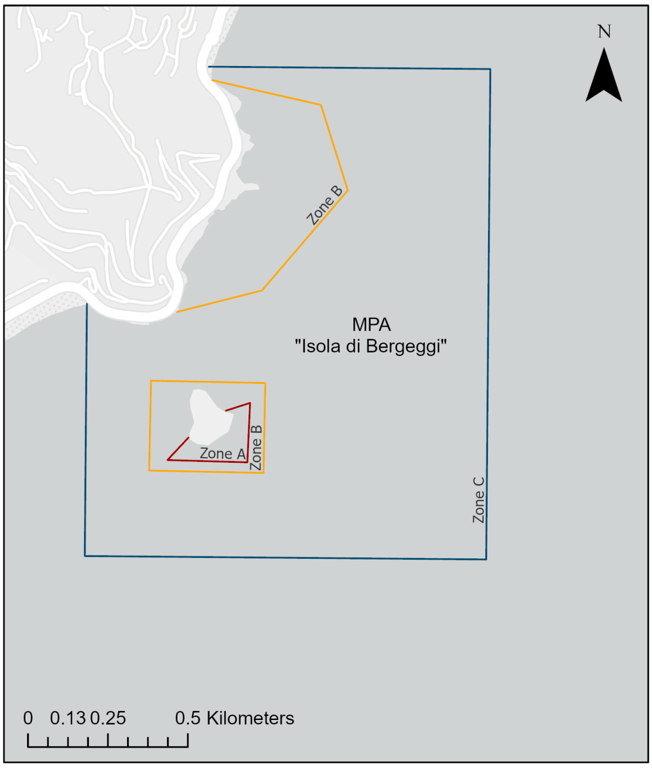

Figure 3.2: Division of the protection zones in the MPA of Bergeggi (SV)

In 1997 and 1998, the first two MPAs were established in Liguria, Cinque Terre and Portofino. Subsequently, on 5^{th} September 2007, the marine protected area called *'Isola di Bergeggi'* was established through the Official Gazette of the Italian Republic no. 206 (Repubblica Italiana, 2007). Furthermore, the Site of Community Importance covers the coastal marine environment between Noli and Bergeggi IT 1323271, established to protect the PO prairie that stretches for about 83 hectares from Noli to the Island of Bergeggi, with bathymetries between 10 and 20 m deep.

SCIs (Sites of Community Importance) or SPAs (Special Areas of Conservation) are areas of high environmental value identified on the territory according to the criteria proposed by the European Union's Habitats Directive (EC Directive 92/43, EU, 2010). Together with SPAs (Special Protection Areas), SACs make up the Natura 2000 Network, the main instrument of European Union policy for biodiversity conservation. In Italy, SCIs, SACs and SPAs cover approximately 19% of the national land territory and almost 4% of the marine territory (EU, 2000). In Liguria, the Natura 2000 Network includes 126 SCIs, 27 of which are marine, and 7 SPAs referring to three biogeographical regions (Alpine, Continental and Mediterranean), for a total of 165,000 hectares. The Habitat Directive identifies

PO meadows and submerged and semi-submerged caves among the marine and coastal habitats of particular interest.

3.1.3 Area of geological interest

A stretch of coastline is particularly important from a geomorphological point of view beyond the municipalities of Noli and Bergeggi, see *Figure* 3.3. This stretch of coast from the area of Capo Noli to Finale Ligure, passing through Varigotti, is distinguished by important geological features. Due to its geology, geomorphology and geography, the Varigotti area belongs to the Finale region between Bergeggi to the east and Borghetto Santo Spirito to the west. The examined area of the Varigotti district include Capo Noli and the area of Manie. During the Quaternary geological period, many limestone formations, including dolomite limestone and Pietra di Finale, ultimately emerged and were subject to karstic erosion. In addition to these formations, along the coast, there are particular forms of sedimentation in submerged and parts that emerged from the sea, referred to by the scientific term 'beach rock'. The most accredited thesis on the origin of these formations is the presence of submarine springs near the coast whose calcium carbonate-rich waters (after passing through calcareous rocks) in contact with the sea give rise to the precipitation of calcium carbonate, which acts as the cement of the loose sand or gravel. Beach rocks are a microhabitat of the coastal zone where typical, fragile fauna and flora develop.

CHANGE IT!!!

To better understand the geological map and to be able to recognise and distinguish the various predominant rock types in the terrain, a brief description of the rocks outcropping in the examined area is given, listed from the oldest to the most recent formations (Brancucci, 2020).

- Gorra schist (325-280 Myr): quartz-rich metamorphic schist rocks derived from fine arenaceous-clayey sediments deposited in a continental environment during the disintegration of the crystalline basement.

- Ponte Nava Quartzites (225 Myr): again, these are metamorphic rocks originating from the transformation of quartz-rich sands.

- San Pietro dei Monti Dolomites (220-205 Myr): grey limestone rock present in large banks. They characterise most of the territory examined. It originates from the accumulation of carbonate sediments in a shallow marine environment. The dolomitisation process of the limestone muds subsequently intervenes due to the replacement of calcium ions with magnesium ions in seawater.

- Val Tanarello limestones (162-136 Myr) well stratified light marble limestones deposited in the deep sea.

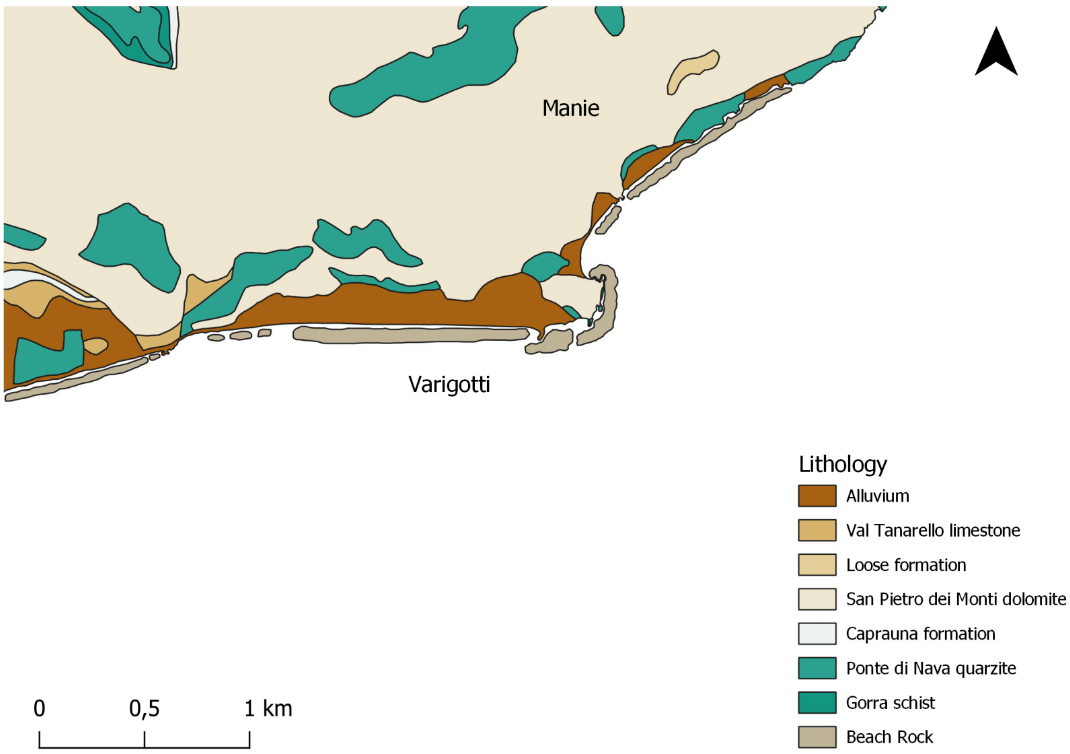

Figure 3.3: Geolithological map of the Varigotti - Manie area

3.2 Focus on PO and CN in Ligurian Sea

In the following paragraphs, more information on the structure and biology of marine phanerogams will be given to understand better their importance and their areal distribution in the site of interest.

3.2.1 Introduction to marine phanerogams

Marine phanerogams are aquatic *Angiosperms* confined to the marine environment. The main characteristics, which distinguish marine phanerogams, are:

- plants adapted to live in a saline environment;
- plants able to live submerged entirely;
- plants that present a secure anchoring system;
- plants whose leaves are devoid of stomata and have a thin cuticle that promotes the exchange of gases and nutrients.

There are five species of marine phanerogams in the Mediterranean Sea (EU, 2000):

1. *Cymodocea Nodosa (Zosteraceae)* found mainly on fine surface sediments and in waters of variable salinity, can in some cases exceed 20 m depth.

2. *Nanozostera noltii (Zosteraceae)* has a similar ecology to CN, like it can colonise shallow (maximum 5 m) and variable salinity sheltered areas such as estuaries and mouths.

3. *Zostera marina (Zosteraceae)* is mainly distributed along the coasts of the Atlantic Ocean and is quite rare in the Mediterranean; it is present in areas characterised by salinity and low temperatures.

4. *Halophyla stipulacea (Hydrocaritaceae)* is a widely distributed species in tropical seas that colonised some areas of the eastern and southern Mediterranean following the opening of the Suez Canal. It has been reported in the Aeolian Islands, Sicily and Calabria.

5. *Posidonia Oceanica (Posidoniaceae)* is exclusive to the Mediterranean basin and is the only species, in terms of breadth of prairies and leaf density, that forms stands of significant ecological importance; its lower limit can be as deep as 40 m.

PO and CN are the two most widespread marine phanerogams in the coastal habitats of the Mediterranean Sea; their most important biological and ecological characteristics are described below (Scanu, 2017).

Cymodocea Nodosa

CN is a marine phanerogama that forms vast submerged meadows at depths varying between 5 and 20 m. It generally grows on sandy (both fine and coarse sand) and muddy bottoms; it is often found on dead mats of PO and at river mouths. CN is not endemic to the Mediterranean, like PO, and is also present in the north-east Atlantic, between the Bay of Biscay and Senegal. It is a perennial plant, with a robust, cylindrical, reddish-white rhizome, growing horizontally, with internodes with a branched root and a short erect stem, supporting 2 to 5 ribbon-shaped leaves. Each leaf consists of a cylindrical, light red leaf sheath, 3 to 7 cm long; the leaf blade is 10-30 cm long and 2-5 mm wide. The CN meadow is very important as a precursor to PO in establishing itself on a substratum; however, in some cases the expansion of this plant is linked to the regression of PO meadows, compared to which it is more resistant to environmental stress (Bianchi and Peirano, 1995). The regression phenomena of CN may be due to mainly anthropic:

- the increase in turbidity, with the consequent decrease in photosynthetic rate;

- organic pollution, and therefore the increase in algal felt covering the plant's photosynthesis;
- the construction of coastal works, interfering with the hydrodynamic regime and sediment transport, can cause silting up or undermining of rhizomes;
- the introduction of allochthonous species (e.g. *Caulerpa taxifolia and Caulerpa Cylindracea*), which supplant the substrate occupied by native species (Diviacco and Coppo, 2006).

Posidonia Oceanica

PO is a marine phanerogamous plant (or *Magnoliophyte*) endemic to the Mediterranean basin belonging to the *Posidoniaceae* family *(Angiosperms, Monocotyledons).* This phanerogama is represented by extensive submerged prairies between the surface and 40 metres depth. It grows mainly on sandy bottoms but is also found on rocky bottoms.

Den Hartog, 1970 estimated that seagrass occupied an area corresponding to about 38,000 km^2 (about 3 %) of the entire Mediterranean basin. Even though this area seems to have shrunk considerably, PO represents one of the most important and productive coastal marine ecosystem key species in the Mediterranean (Boudouresque, 2000). It thrives in areas where salinity is almost constant and temperatures range between 10 and 28°C (Scanu, 2017). PO is morphologically structured into leaves, rhizome and roots, see *Figure* 3.4. The leaves regulate the plant's water and ion exchange with its environment and are able to absorb nutrients directly from the water. They have a ribbon-like appearance and are organised in bundles that originate from a basal meristem at the base; they can reach a maximum length of about 1.5 m and are 10 mm wide (Bianchi and Peirano, 1995).

The base of the leaves persists on the rhizome for many years after the leaf blade falls off, forming the so-called scale that contributes to the formation of the rhizome. The rhizome is a modified stem, and together with the roots, produces structures called stolons that can grow horizontally *(plagiotrope rhizome)* or vertically *(orthotropic rhizome).* The latter (*orthotropic*) allows the plant to grow upwards, also counteracting possible siltation. This growth mode is the basis for the formation of the *matte*, a terrace structure that retains sediment. This can extend vertically for several metres. The growth of the *matte* is very slow, about 1 m per century (Boudouresque, 2000). This structure typical of PO is an important formation that stabilises the seabed,thus protecting the coasts from erosion. The leaves and rhizomes host a rich community of epiphytic organisms (animal and plant) that contribute to biomass production (Bianchi, 2012).

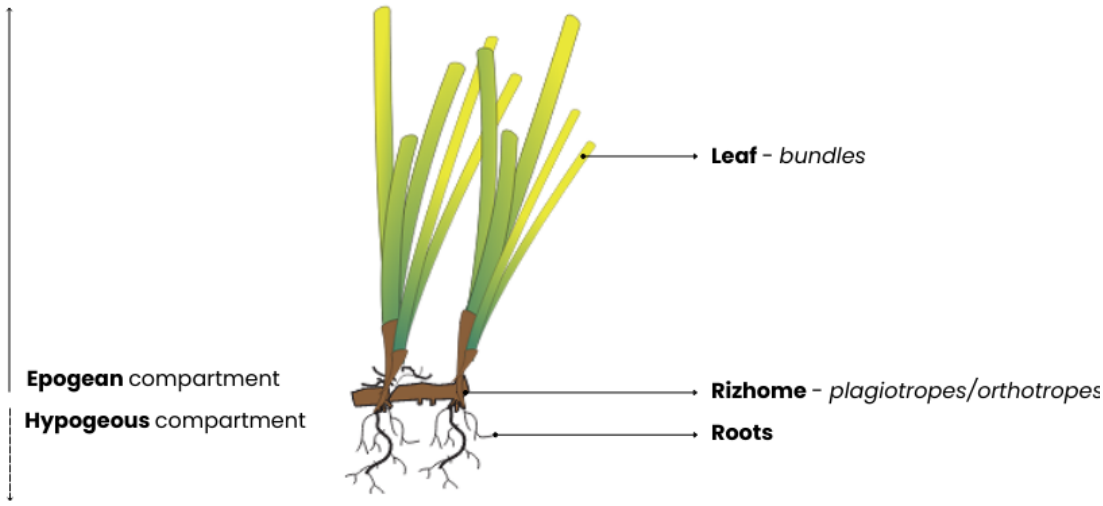

Figure 3.4: PO is morphologically structured into leaves, rhizome and roots. This structure makes it important as a morphosedimentary ESs in both its hypogean and epigeal parts.

In general, the morphological characteristics and size of a PO meadow depend on the conformation of the coast and seabed, the transparency of the water, lighting, hydrodynamics and sedimentation of solid materials. If these parameters change, the prairie loses its dynamic equilibrium and tends to become progressively depleted (Bianchi and Peirano, 1995). Each PO prairie is characterised by an upper and a lower limit. The former is the most superficial limit, close to the coast, with high densities of leaf bundles and the presence of matte; while the latter limit is the one that delimits the prairie in depth. The lower boundary is described by four classes: progressive, net, erosion and regressive boundary.

The PO meadow forms a very important community, a complex and well-structured biocenosis, characterised by high biological variability, productivity and water oxygenation activity. As already explained in section 1.3, in the context of coastal dynamics, PO plays multiple and peculiar roles that justify its importance:

- it stabilises the seabed by compacting soft substrates;
- it shapes the seabed and protects sandy coasts from erosion by reducing the hydrodynamics caused by the foliar layer and dampening the wave motion on the shore due to the presence of dead beached leaves (*banquettes*);
- it constitutes a shelter and a source of direct and indirect nutrition for numerous coastal and pelagic organisms.

- it contributes significantly to the oxygenation of waters and, thanks to its leaf development, releases up to a summer maximum of 14 litres of oxygen per day per m^2 of grassland and a minimum of 3 litres per day of oxygen in winter (Sanna, 2021);
- it has some of the highest primary production values among coastal marine systems, representing one of the most important carbon stores (Mcleod et al., 2011);
- it has characteristics that make it a good biological indicator.

In the Mediterranean we are witnessing a generalised phenomenon of regression of PO meadows. Its rarefaction and disappearance is due to multiple causes, both anthropic and natural. The causes of regression include (Bianchi and Peirano, 1995):

- mechanical matte erosion due to trawling and other types of destructive gear;
- damage caused by recreational boat anchors;
- construction of coastal works (harbours, embankments) can cause the total disappearance of the prairies due to both the direct action of excavation and covering, and turbidity that prevents light penetration and suffocates the prairies with the deposition of clayey material. In this way, the construction of coastal works modifies the current geometry and hydrodynamics, thus interfering with sediment transport. Pollution acts in various ways on the seagrass beds close to the discharges, altering them with the presence of chemicals or the high turbidity of the water in eutrophic areas;
- presence of alien species in the Mediterranean, such as the allochthonous algae *Caulerpa Cylindracea and Taxifolia*, whose rapid growth has damaged PO meadows at some sites.

3.2.2 Phanerogams in the Ligurian context

The distribution of PO and CN extensions were studied for the first time along the entire Ligurian coast by Bianchi and Peirano, 1995. The extension of PO meadows was very diversified: in total, they bordered about 140 km of coastline (equal to 42 % of Liguria's coastal development), occupying less than 4800 hectares (equal to 10-15 % of the Ligurian seabed between the surface and 35 m depth). The extension of these prairies in front of the Riviera di Ponente is almost three times as large (3500 ha) as that in front of the Riviera di Levante (1300 ha); furthermore, the Riviera di Ponente has vast meadows, unlike those of the Riviera di Levante, which are medium and small in size. In particular, the subdivision, in percentage, of Ligurian phanerogams within the Provinces is as follows (Ferrario, 2012):

- Province of Imperia: 51 %
- Province of Savona: 22 %
- Province of Genoa: 25 %
- Province of La Spezia: 2 %

These different percentages of PO meadows may derive from natural and anthropic causes. The Province of Genoa, for example, is the most anthropized; instead, the low percentages found in the Province of La Spezia may be due to the different coastal morphotypes of the Levante area. The average depth of the lower boundary is around 23 m, but in the more anthropised coastal areas (Genoa and Savona Provinces) go up to about 20 m. The meadows of CN border 114 km of coastline (equal to slightly more than 34 % of the coastal development of Liguria) and extend for about 2300 ha (equal to 4-7 % of the Ligurian seabed between the surface and 35 m); they often settle on dead *matte* of PO.

The abundance of CN in Liguria could be due to an increase in anthropic environmental degradation, which leads to a reduction in PO meadows, with a consequent occupation of free space by CN, which is more tolerant to environmental stress. This can be confirmed by the ratio between the extension in hectares of CN meadows and that of PO meadows, which is higher in front of more industrialised and urbanised areas (Bianchi and Peirano, 1995). Data from the Marine Habitat Atlases financed by the Liguria Region show a progressive negative loss ranging between 42 - 48 % of the previously mentioned areas (Bianchi and Peirano, 1995; Diviacco and Coppo, 2006; Liguria, 2020). This aspect will be addressed in more detail in the following chapters.

Chapter 4

Methods

4.1 *InVEST* modelling input data

The following section details the input data that the *InVEST* software requires to use the models chosen for analysis. Like section 2.3, the following section is also primarily based on the *InVEST* user guide; the reader is referred to this guide for further details (Sharp et al., 2022). The analysis of the input data will be broken down into the two models used: Coastal Blue Carbon and Coastal Vulnerability Model. The first model will be treated in two different steps.

4.1.1 Coastal Blue Carbon

The model is based on land cover transitions between two different LULC rasters (Land Use and Land Cover raster data), referring to two different temporal moments. For this reason, to facilitate the analysis process, the *InVEST* software makes available a preprocessor to identify land cover transitions occurring on the landscape and the nature of these transitions. The results of the preprocessor are used and edited by the user before being fed into the main model.

1^{st} Step

The first phase of CBC model (also known as *Pre-processor*) requires the input of two or more LULC rasters to identify the set of all occurring LULC transitions. In this specific case, the two rasters, covering the years 2000 and 2020, contain information on the variation of marine seagrasses, PO and CN, see *Figure* 4.1. The two rasters considered were obtained from vector or digital data (then vectorised) obtained from atlases of marine habitats of the Ligurian region (Bianchi and Peirano, 1995; Diviacco and Coppo, 2006; Liguria, 2022). More information on the data used can be found in the section 4.2 and in Appendix B.

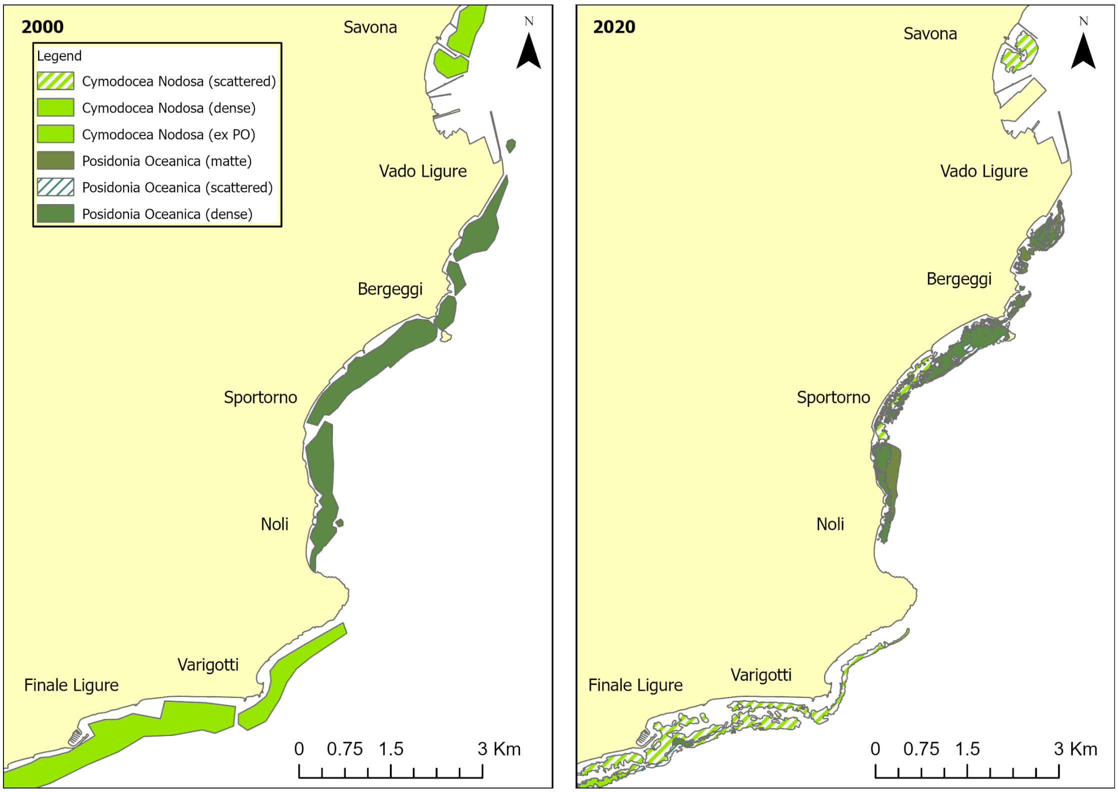

Figure 4.1: Overall view of the Seagrass Atlas in the year 2000 (left) and 2020 (right). Year 2000 data from the publications of Bianchi and Peirano, 1995 and Diviacco and Coppo, 2006 work. The data for the year 2020 were downloaded from the Liguria Region geoportal.

The two LULC rasters are indicated within the LULC snapshot table (csv format) with their reference period, see *Table* 4.1. It represents the mapping table of snapshot years to the corresponding LULC maps for each year.

Table 4.1: Example of a LULC snapshot table to be inserted into the CBC model preprocessor.

snapshot_year	*raster_path*
2000	Raster_AHM2000_012.tif
2020	Raster_AHM2020_012.tif

In addition to this table, a LULC look-up table (csv format) is required, which maps the LULC codes from the snapshot rasters to the corresponding LULC class names and whether or not the class is a coastal blue carbon habitat, see *Table* 4.2.

Table 4.2: Example of a LULC look-up table to be inserted into the CBC model preprocessor.

lulc-class	*code*	*is_coastal_blue_carbon_habitat*
cym	1	TRUE
pos	2	TRUE
NODATA	0	FALSE

From the information obtained from the LULC snapshot table and the LULC look-up table, the pre-processor finds the LULC rasters. It compares them, generating a transition table as output. This resulting matrix contains a biophysical table template the user can fill in with information quantifying the carbon change due to LULC transitions. The user must further modify this table, and the modified table is a necessary input for the next step. An example of an edited biophysics table (transposed) is available in Appendix B.1, see *Table* B2. Informations from González-García et al., 2022, were used to complete the biophysical table.

2^{nd} Step

The second phase of the CBC model (also known as *Main Model*) calculates carbon stock and sequestration over time, based on the transition and carbon pool informations generated by the pre-processor and modified by the user, i.e. the biophysical table. The table is organised into 16 columns that must be completed for each class defined in the LULC look-up table that refers to rasters. The first two columns identify the codes and related classes used in the rasters, while the remaining 14 refer to the storage data in the biomass, soil and litter pools, see *Table* B2. As defined in section 2.3.1, the CBC models the carbon cycle through an accounting approach (Sharp et al., 2022; Houghton, 2003). This method simplifies the study of the carbon cycle by accounting for storage in three leading sinks: biomass, sediment carbon (i.e. soil), and dead standing carbon (i.e. litter) see *Figure* 2.1.

The input information for the three sinks is calculated concerning the initial (Mt/ha), the half-life accumulation parameters of the habitat considered and the annual CO_2E accumulation rate in the biomass sink $(MtCO_2E)/(ha \cdot y)$. The latter parameter is often zero when referring to the annual accumulation rate per litter pool (litter-yearly-accumulation). In addition, it is necessary to include, for biomass and soil only, information on the percentage of the carbon stock that is disturbed when a cell moves away from this LULC class in a low or high-impact disturbance. As highlighted before, the information included in the biophysical table was obtained from the analysis of scientific literature, using particular studies on the application of the CBC model to areas with similar habitats and morphology (Scanu et al., 2022; González-García et al., 2022).

In addition to the LULC snapshot table and the biophysical table, the model also requires a land cover transition table (csv format). The transition table maps the type of carbon action suffered when one type of LULC transitions to another. The preprocessor creates the table and is edited by the user before being inserted into the main model. An example of the transition table is available in Appendix B, see *Table* B3.

Finally, if the user desires it, the model can calculate the value of carbon sequestration by marine habitats. This is done by entering a table containing the annual price of carbon. For this study, three different price tables were formulated considering a discount rate of 2.5 %, 3 % and 5 % relative to the Social Cost of Carbon (SCC). The SCC suggested by *InVEST* represents a synthesis of some models such as Tol and Richard, 2010, Hope, 2002, DICE and RICE (Kumar, 2010). This synthesis was carried out by the US Interagency Working Group on the Social Cost of Carbon which guided the appropriate SCC over time for the three different discount rates (USIWGSCC, 2016).

The use of discount rate tables uses the concept that damage from carbon emissions occurs beyond the date of their initial release into the atmosphere. Therefore, damages from emissions in any period are the sum of future damages, discounted up to that time. Since the tables presented by the US Interagency Working Group on SCC estimate costs from 2010 to 2050, they had to be modified to look back to 2000. For this purpose, the data were interpolated and the SCC from 2000 to 2009 was generated based on the trend from 2010 to 2050. This made it possible to evaluate the analysis by considering the development of three different discount rate tables over the time span analysed in the case study (2000 - 2020). The data provided by the US Interagency Working Group were in US currency, valued from US_{2007}, so they had to be modified to match the current value in European currency (€$_{2020}$), the study area of the analysis. First, the inflation rate from $US\$_{2007}$ to $US\$_{2020}$ was considered, as 2020 corresponds to the upper limit year of the analysis. Hence, the data were multiplied by a correction factor

$$US\$_{2020} = 1.43 \cdot US\$_{2007} \tag{4.1}$$

All the values obtained were corrected to the European currency €$_{2020}$ taking into account a currency exchange factor

$$€_{2020} = 1.01181 \cdot US\$_{2020} \tag{4.2}$$

For an example of the interpolation, correction and conversion of the SCC tables see *Table* B4 in Appendix B.1. Values within the *Table* B4 refer to the 3 % discount rate. The *Table* B5, in Appendix B.1, shows the $€_{2020}$ values of the SCC used in the CBC model for each discount rates.

4.1.2 Coastal Vulnerability

The Coastal Vulnerability model requires a lot of geospatial information; such information are often easy to find. This includes digital elevation model data (dtm, raster), bathymetry adjacent to the considered coastal zone (raster) and land mass (vector, polygon). These data were obtained from the Liguria Region geoportal (Liguria, 2022), and modified for use in the *InVEST* model. In addition, other specific informations are available as sample data from *InVEST* (Sharp et al., 2022), such as the continental shelf contour (vector, linestring/multiline string format) and the wave and wind data.

Wind and wave data can be represented as point data with a format typical of the WaveWatch_{III} model (vector, point). This format consists of a map of gridded wind and wave data that represent storm conditions. *InVEST* releases global WaveWatch_{III} data format but it does not cover the Mediterranean basin. For this reason, the data used in the model were derived from the 360-degree wind and wave information provided by the model developed by the MeteOcean group of DICCA, 2022. The MeteOcean group carried out a reanalysis of weather and wave conditions, producing a hindcast database running from January 1979 to the end of December 2020 on the domain used for weather and wave simulations (De Leo et al., 2020a; De Leo et al., 2020b; De Leo et al., 2021; De Leo et al., 2022; Mentaschi et al., 2015; Lira Loarca et al., 2022). In the next section 4.2, the data processing steps of the MeteOcean group for creating the wind and wave data required by *InVEST* for the CV model will be shown.

In addition, the CV model requires the provision of spatial information of marine habitats and a relative natural marine habitat table, which indicates the relative amount of coastline protection this habitat provides (1: *very low exposure* to 5: *very high exposure*). As with the CBC, data for the CV were taken from the atlases of marine habitats in Ligurian Region (Bianchi and Peirano, 1995; Diviacco and Coppo, 2006; Liguria, 2022). The information concerning shoreline protection provided by the habitats was assessed using the user guide of *InVEST* and its community, which generally corresponds to a value of 3 for coastal forests in good condition and a value of 4.05 for degraded and fragmented seagrasses (Sharp et al., 2022). For this reason, a value of 3 (coastal forest) was assigned to the most consistent seagrass habitats, while a value of 4.05 was assigned when the habitats were more scattered or with 'matte' type structures. As a result, the 2000 data are predominantly associated with a higher coastal protection value, whereas, the 2020 data protect less land because they are largely associated with the 4.05 ranking value. In addition to the required data, optional geomorphological information was added to provide a relative risk of shoreline exposure based on the lithology of the area. Starting from the geological data derived from the geoportal of the Region of Liguria, a linestring/multilinestring vector was defined to which a classification corresponds to a relative exposure of the shoreline segment, see *Figure* **??**Lithology). This classification incorporates the modality already used by the CV model, where a ranking value is assigned according to the relative protection that the coastline segment has concerning its lithology (1: *very low exposure* to 5: *very high exposure*).

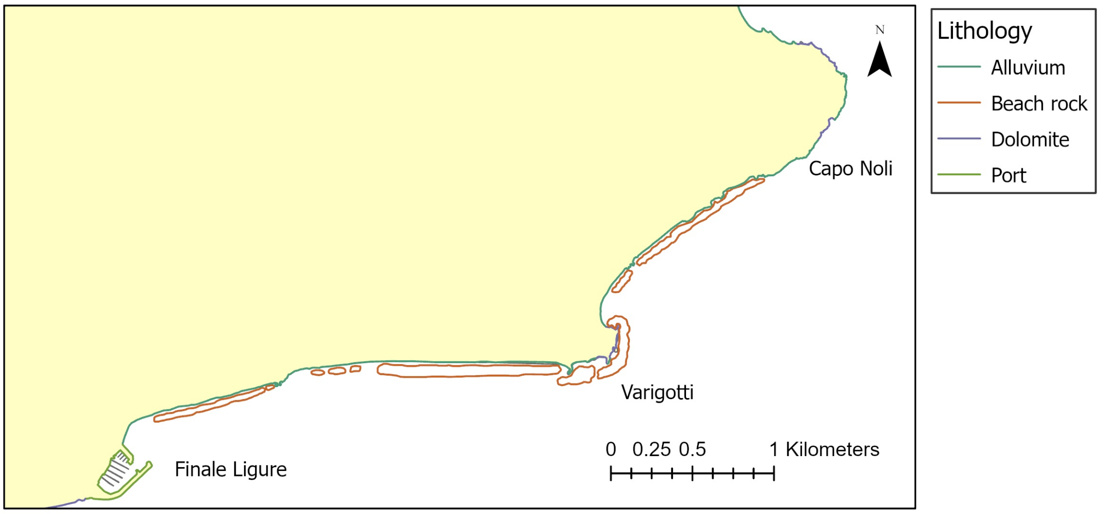

Figure 4.2: Representation of the geomorphological input data in the area of Capo Noli, see section 3.1.3 for more information about the geological background.

Finally, input values relating to the resolution of the final results and the distances of the impact of the values on the final result are requested, also chosen based on the *InVEST* reference values.

The output result consists of a geospatial point vector file with the considered point's complete exposure information. This value, as mentioned in section 2.3.2 is calculated for each shoreline point as the geometric mean of all the variable ranks.

4.2 Data Processing

The following section analyses the main data processing steps to structure the data required by *InVEST* in the application of the Coastal Blue Carbon and Coastal Vulnerability models. In particular, we will focus on the creation of the LULC rasters for the CBC model and the processing of the wind and wave data required by the CV model.

4.2.1 Coastal Blue Carbon

The search for data for the CBC model began with the creation of the two LULC rasters referring to the years 2000 and 2020. Both files were elaborated from the knowledge provided by studies on marine habitats in collaboration with the Liguria Region. The more recent data were easily obtained from vector format files downloadable from the Liguria Region geoportal (Liguria, 2022). On the other hand, the less recent data are the result of processing from analogue, georeferenced and vector format data using GIS (Geographical Information System) platforms. Data from the 2000s are derived from Bianchi and Peirano, 1995 and Diviacco and Coppo, 2006 work. These studies were fundamental to research on Ligurian marine habitats occupied by seagrasses.

As can be seen from $Figure$ 4.1, the 2020 data are more precise in terms of shape and habitat description (e.g. dense, scattered). This is mainly due to a different type of data acquisition that has significantly evolved over the past few years (e.g. data from small-scale photo-interpretation). These considerations will be taken up and addressed in the following chapters to assess the data's quality and the resulting outcomes. Additionally, the habitats studied in this paper are those occupied by the seagrasses present in the area; it was decided to exclude the other coastal marine habitats (e.g. common seagrasses and corals) from the analysis, as they are very different in terms of ESs to the seagrasses studied. Furthermore, as will be noted in the 5.1, the loss of typical seagrass habitats is often caused by partial or complete replacement by alien species, such as *Caulerpa Cylindracea*; therefore, the inclusion of such species within the study in the quantification of the ESs of seagrasses would not be consistent. Further considerations regarding the compilation of the tables to be included in the CBC model have already been made in the section 4.1.1 and will be elaborated in more detail in the Appendix B.

4.2.2 Coastal Vulnerability

The wind and wave data required by the model were generated from data provided by the MeteOcean group of DICCA, 2022. Unlike other studies using the CV model, in this case it was necessary to develop the wind and wave data for two reasons: firstly, no data in the WaveWatch$_{III}$ format in the Mediterranean area were available among the sample data released by InVEST; secondly, the use of more accurate (down-scale) data would have improved the CV model results. Below are the main steps that led to the creation of this dataset.

To estimate the importance of wind exposure and wind-generated waves, wind statistics measured in the vicinity of the AOI (Sharp et al., 2022). For this reason, data from three reference points of the hindcast database (000257,000287, 000288) were requested from the MeteOcean group, see $Figure$ 4.3.

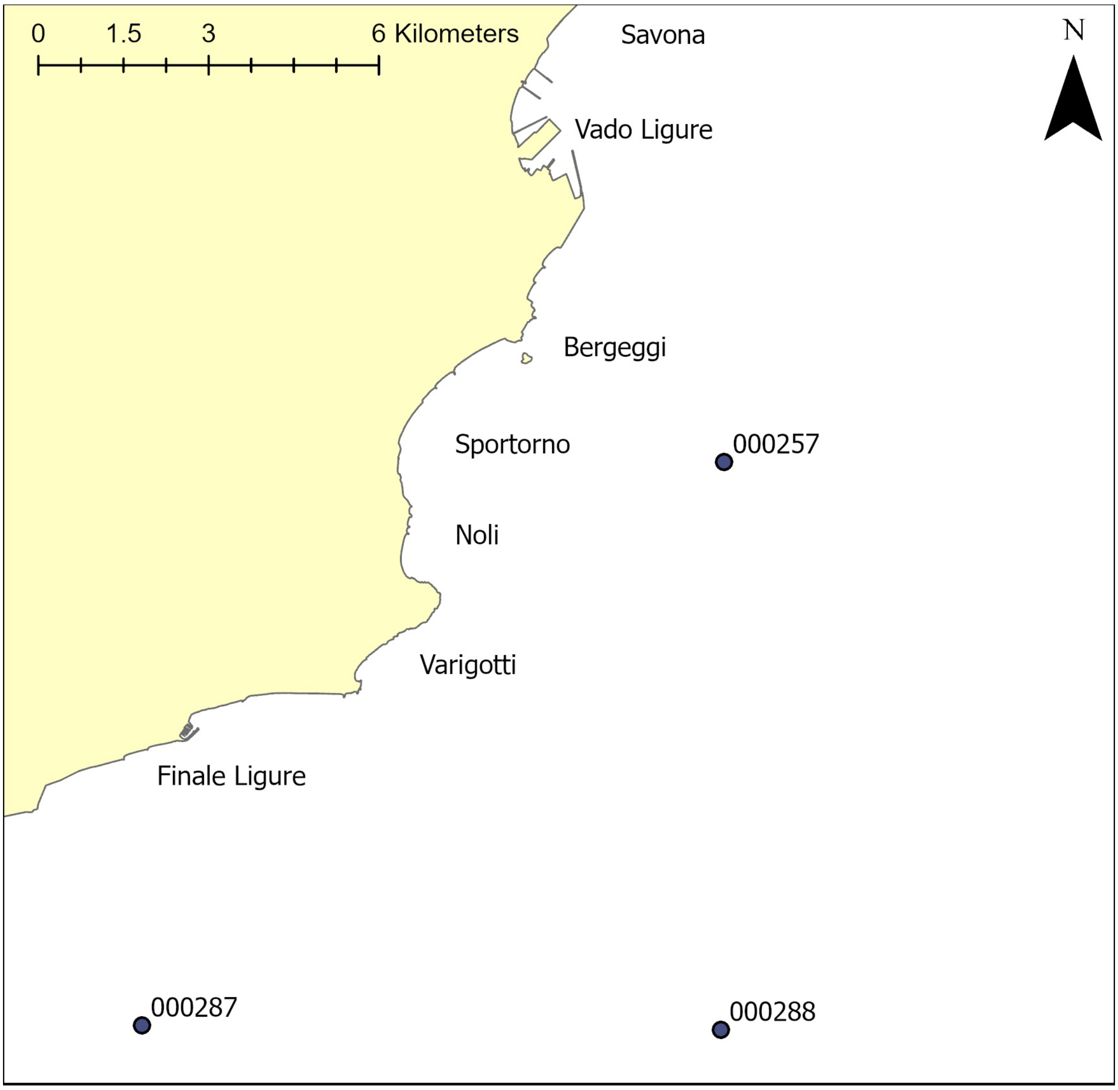

Figure 4.3: Representation of points provided by the MeteOcean group to evaluate wind and wave data.

The model requires the average of at least 5 years of data in each of 16 equiangular sectors of wind speeds observed in the vicinity of the segment of interest to calculate the relative exposure index REI, see *Equation* (A.7) (Keddy, 1982). Consequently, the analysed data correspond to the time span from January 1995 to December 2000 for the year 2000 analysis and the time span from January 2015 to December 2020 for the year 2020 analysis. An X-value corresponds to the 16 equiangular sectors, where the X-value varies between [0,22,45,67,90,112,135,157,180,202,225,247,270,292,315,337], see *Figure* 4.4.

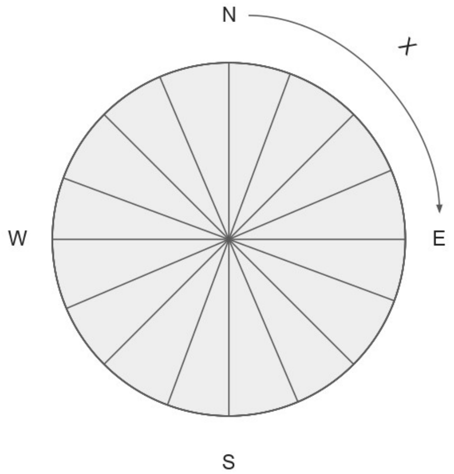

Figure 4.4: Representation of the division into 16 equiangular sectors to evaluate wind and wave data

All wind velocities that have a direction centred on each of the 16 equiangular sectors are assigned to that sector, i.e. $\pm$ 11.25 $degN$ with respect to the considered X value. The *Equation* (4.3) was considered to evaluate the wind speed w and the parameters derived from it to evaluate the modulus of the scalar wind speed $\vec{u}$ with respect to its components u_w (West-East Wind Velocity $[m/s]$) and v_w (South-North Wind Velocity $[m/s]$).

$$w = |\vec{u}| = \sqrt[2]{u_w^2 + v_w^2} \tag{4.3}$$

After assessing the wind speed for each element, the average of the wind speeds was calculated, the percentage of wind in each sector and the average of the highest 10 % of the wind speeds centred on the main direction of sector X. These values will correspond to three vectors with 16 columns named REI_VX, REI_PCTX, and V10PCT_X, where the X value varies between [0,22,45,67,90,112,135,157,180,202,225,247,270,292,315,337],

Similarly, to calculate the wave data, reference is made to:

- time span between January 1995 to December 2000 for the analysis on the year 2000;
- time span from January 2015 to December 2020 for the analysis on the year 2020;
- values calculated with respect to the 16 equiangular sectors to which an X value corresponds.

For all waves in each angular sector, wave power P $[\frac{kW}{m}]$ is computed in *Equation* (4.4) as, Sharp et al., 2022:

$$P = 0.5 \cdot H_s \cdot T_m \tag{4.4}$$

where P is the wave power of an observed wave with a height H_s and a period T_m. Finally, the average wave power and the percentage of the wind centred on the main direction of the X sector are calculated. These values will correspond to two vectors with 16 columns named WavP_X, and WavPPCT_X.

Data summary that compare the years 2000 and 2020 is provided in Appendix B.2, it contains the REI_VX, REI_PCTX, V10PCT_X, WavP_X, and WavPPCT_X vectors of the three different points considered, see *Tables* B6, B7, B8, B9, B10 and B11.

Chapter 5

Discussion

5.1 Results

Anthropogenic pressures, rising sea temperatures and the invasion of alien species have led to a considerable change in marine habitats and their areal size. The change is evident also in the area considered in the case study, where the estimated decrease was assessed according to the areal data provided by the Liguria Region geoportal and its atlases of marine habitats, as elaborated in section 4.2.

Figure 4.1 shows how the seagrass beds have changed in terms of range size and shape from 2000 to 2020, the meadows in 2020 show more jagged and scattered form. The decreasing trend of seagrass meadows is evident for both PO and CN. The decrease assessed in areal terms shows a 48 % decrease in CN and a 42 % decrease in PO compared to 2000 values, see *Figure* 5.1. This decrease leads mainly to the replacement of PO seagrass with:

- CN meadows, that are more resistant to higher temperatures (Diviacco and Coppo, 2006);

- other alien invasive species, such as *Caulerpa Cylindracea*.

It is interesting to note that the decrease in seagrasses and their replacement could be correlated with the seagrasses' position concerning specific locations. The replacement of PO prairies with alien species occurs mainly near the harbour area of Vado Ligure, where a progressive enlargement of *Caulerpa Cylindracea* can be seen in a south-westerly direction, see *Figure* 5.2.

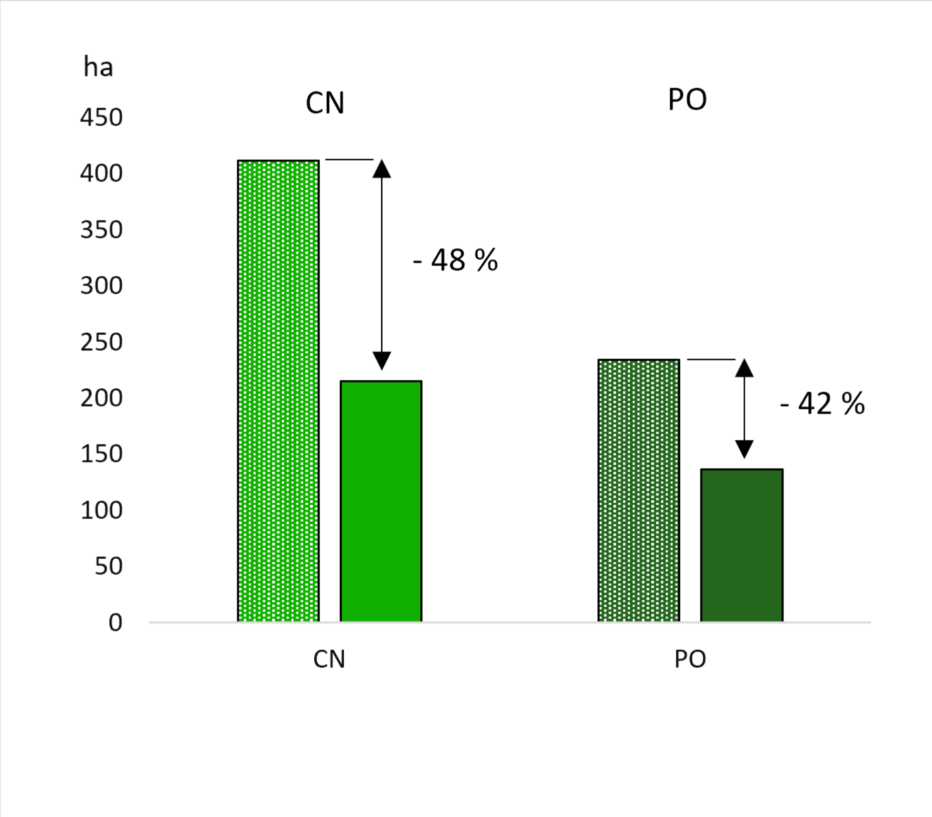

Figure 5.1: The decrease assessed in areal terms in 2020 shows a 48 % decrease in CN and a 42 % decrease in PO compared to 2000 values.

5.1.1 Coastal Blue Carbon

The InVEST Coastal Blue Carbon model was used to assess changes in carbon sequestration associated with changes in habitat type between 2000 and 2020 in the study area considered. For this, the application of the two CBC steps, described in the 4.1.1 section, resulted in six raster files for each of the three different discount rates considered, i.e. for each associated scenario. Sharp et al., 2022 defines the output files as:

1. **Carbon accumulation between 2000 and 2020**
   carbon-accumulation-between-[year]-and-[year][Suffix].tif
   Amount of carbon accumulated between the two specified years.
   Units: Megatonnes of CO2 per hectare.

2. **Carbon Emissions between 2000 and 2020**
   carbon-emissions-between-[year]-and-[year][Suffix].tif

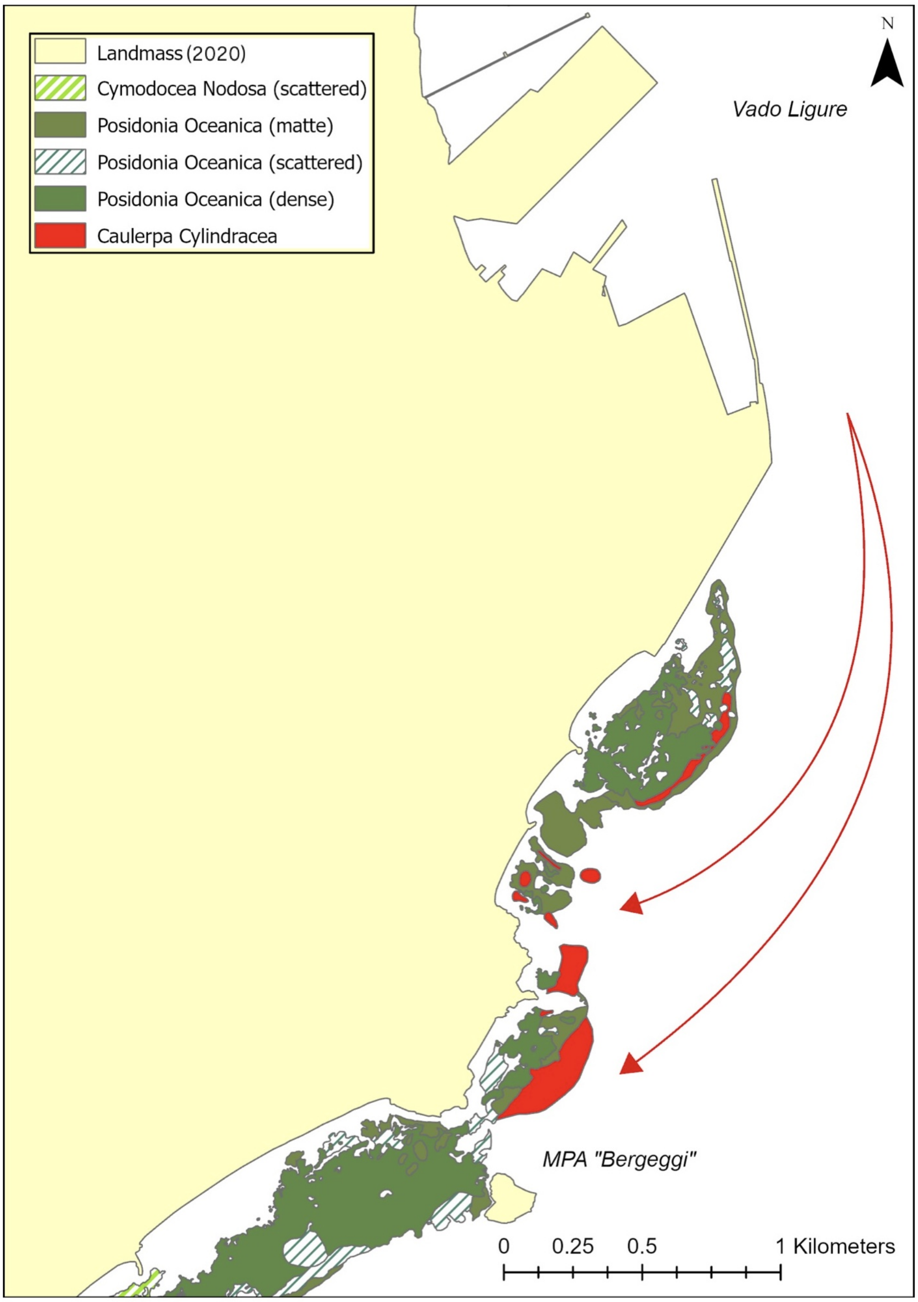

Figure 5.2: Replacement of PO prairies with alien species near the harbour area of Vado Ligure, here a progressive enlargement of the range of the *Caulerpa Cylindracea* can be seen in a south-westerly direction

Amount of carbon lost due to disturbance between the two specified years.
Units: Megatonnes of CO2 per hectare.

3. **Carbon stock at 2000**
carbon-stock-at-[year][Suffix].tif
Sum of the 3 carbon pools for each LULC for the reference year.
Units: Megatonnes of CO2 per hectare.

4. **Carbon stock at 2020**
carbon-stock-at-[year][Suffix].tif
Sum of the 3 carbon pools for each LULC for the specified year.
Units: Megatonnes of CO2 per hectare.

5. **Total net carbon sequestration between 2000 and 2020**
total-net-carbon-sequestration[Suffix].tif
Total carbon sequestration over the entire time period between the reference scenario and the last reference or analysis year, based on accumulation minus emissions.
Units: Megatonnes of CO2 per hectare.

6. **Net present value**
net present value[Suffix].tif
Monetary value of carbon sequestration.
Units: €$_{2020}$ per hectare.

The overall results for the first five raster files are summarised in the $Table$ 5.1. Since one of the primary objectives of the study is to quantitatively assess the ESs of marine seagrasses, the results of the last two listed rasters were mainly processed. The first, which provides the total carbon sequestration over the entire time period between the reference scenario (2000) and the last reference year (2020), calculated the Megatonnes of CO_2 per hectare for each species. This result, common to all three scenarios, showed a total carbon sequestration of 9.6 $(MtCO_2E)/ha$ for CN and 36.2 $(MtCO_2E)/ha$. The net present values for each of the scenarios (2.5, 3, 5 %) were calculated using these net sequestration values of CO_2E and the price tables, already described in the 4.1.1 section and elaborated in more detail in the appendix B.1.

Each discount rate, with an associated price table, has generated an economic quantification of marine phanerogams, or in more specific terms, it generated a monetary value of carbon sequestration. The results obtained for both species analysed are summarised in the $Table$ 5.2 in terms of €$_{2020}$ per hectare. In addition, the overall result is shown in $Figure$ C6 in the appendix section C.1,

As analysed in the section 1.4, many studies have focused on the economic quantification of seagrass ecosystem services. Among these, a vast scientific literature is

Table 5.1: Overall results related to the application of the CBC model (excluding net present value - see *Table* 5.2). The values units are $(MtCO_2E)/ha$

	CN	PO
Carbon accumulation between 2000 and 2020	9.57	36.19
Carbon Emissions between 2000 and 2020	0.03	0.01
Carbon stock at 2000	470.93	1813.91
Carbon stock at 2020	480.50	1850.10
Total net carbon sequestration	9.60	36.20

Table 5.2: Results of net present value related to the application of the CBC model. The values units are $€_{2020}$ per hectare.

	CN	PO
2.5%	10 907.6	41 130.76
3.0%	6 317.06	23 820.59
5.0%	5 276.99	19 898.67

available that attempts to economically quantify the carbon sequestration of marine seagrasses, particularly PO. The work by Scanu et al., 2022, *"Economic evaluation of the ecosystem services of Posidonia oceanica along the Italian coast"*, states that *"The average ES value obtained on the Italian national scale is 21 660.5* $€/(ha \cdot y)$*, which is comparable with the values reported in the international literature for the ES of PO"*. Considering that, the results obtained with the *InVEST* software were calculated with respect to the year 2020, the value reported by Scanu et al., 2022 for PO is between the values obtained for the 3 % and 5 % discount rate scenario.

5.1.2 Coastal Vulnerability

The Coastal Vulnerability model produces a qualitative index of coastal exposure to erosion and flooding; it does not directly assess ESs, but classifies sites as having a relatively low, moderate or high risk of erosion and flooding. As specified on the *InVEST* User Guide, the CV model produces an exposure index for each point along a coastline at a user-specified interval. The exposure index represents the relative exposure of different coastline segments to erosion and storm surge inundation in the region of interest.

In the case study, the CV model was used to assess changes due to loss of seagrass habitat between 2000 and 2020. In addition to the latter, changes between the input data in 2000 and 2020 are related with wind and wave data and landmass changes (e.g. expansion of the port of Vado Ligure).

Sharp et al., 2022 defines the output files of the CV model as:

1. **coastal_exposure.gpkg**
   This point vector file contains the final outputs of the model. The points are created according to the resolution of the input model, spatial mass and AOI. The columns in this table are as follows:

   - *Exposure* is the final exposure index (EI in Exposure Index).
     Units: Ranked versions (1 - 5), dimensionless.
   - *R_* all other exposure index variables are columns in this table with the prefix R_.
     Units: Ranked versions (1 - 5), dimensionless.

2. **coastal_exposure.csv**
   This is an identical copy of the coastal_exposure.gpkg attribute table, provided in csv format.

The exposure index data were visualised using GIS software, see *Figure* C7 in appendix C.2 and below.

In addition, the data were processed to assess a possible relationship between changes due to loss of seagrass habitat, wind wave data and the exposure index (EI) between 2000 and 2020.

In *Table* 5.3 it is possible to see how the EI data reflect a change over the time span considered. In particular, one can see how the minimum, maximum and mean EI values increased between 2000 and 2020, increasing EI values. By evaluating the EI values for each of the 331 points along a coastline through a combined histogram divided into 17 intervals, a shift towards higher EI values for 2020 can be seen, see *Figure* 5.4.

Table 5.3: Minimum, maximum and mean EI values are increased between 2000 and 2020. This is graphically represented by the combined histogram, *Figure* 5.4.

	EI 2000	**EI 2020**
min	1.37	1.42
MAX	4.50	4.52
mean	2.75	2.87

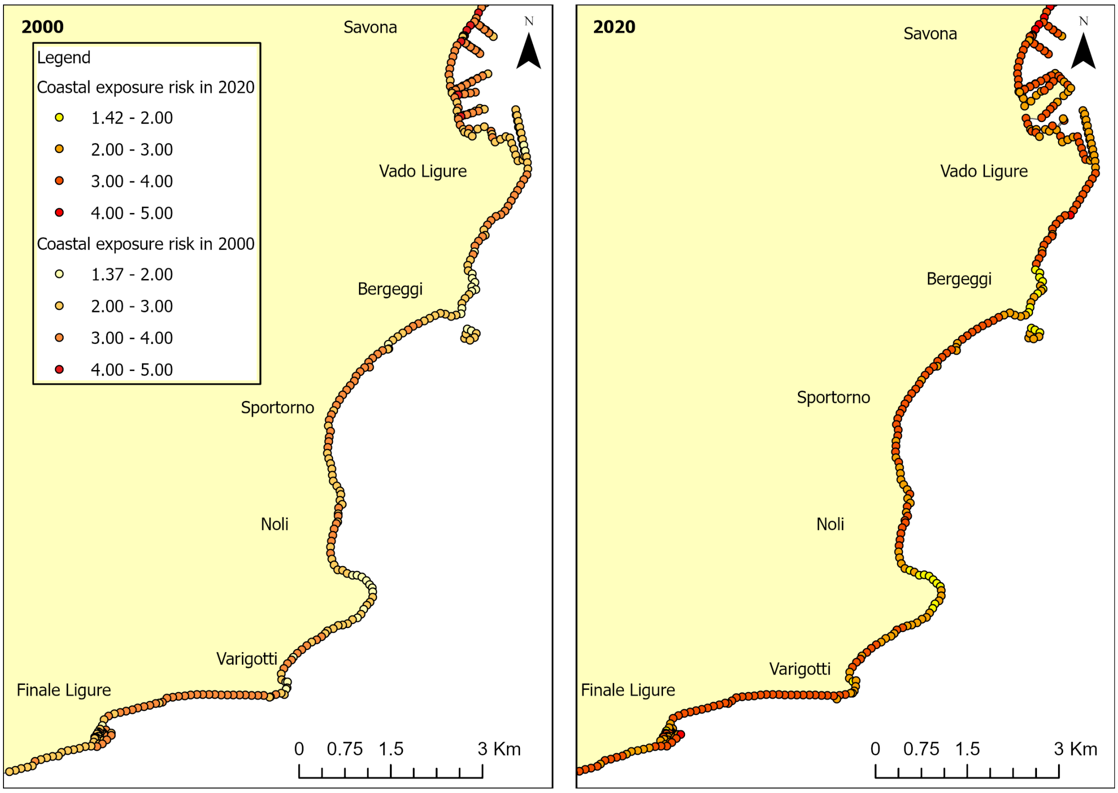

Figure 5.3: Overall result of CV application expressed in EI values, GIS overview

5.2 Limitations and possible improvements

5.2.1 Limitations

The models used, CBC and CV, are subject to limitations given by their computational methodology or the theoretical assumptions chosen in the design of the models. These considerations are described in the *InVEST* User Guide, and along with them are case study situations where the application of the models may be inconsistent. After considering the design limitations related to the two models, the remainder fall into the methodology used: that is, mainly in the quality of the data used and their spatial and temporal resolution.

For example, the data used to derive marine seagrass habitats have been derived very differently: marine habitat identification techniques have evolved considerably in recent decades, leading to improved spatial precision in defining areal limits. Data for 2000 and 2020 may differ not only because of the consistent decrease in seagrasses, but also because of the different technical identification capacity between 2000 and 2020. In fact, the 2020 data are much more precise both spatially and

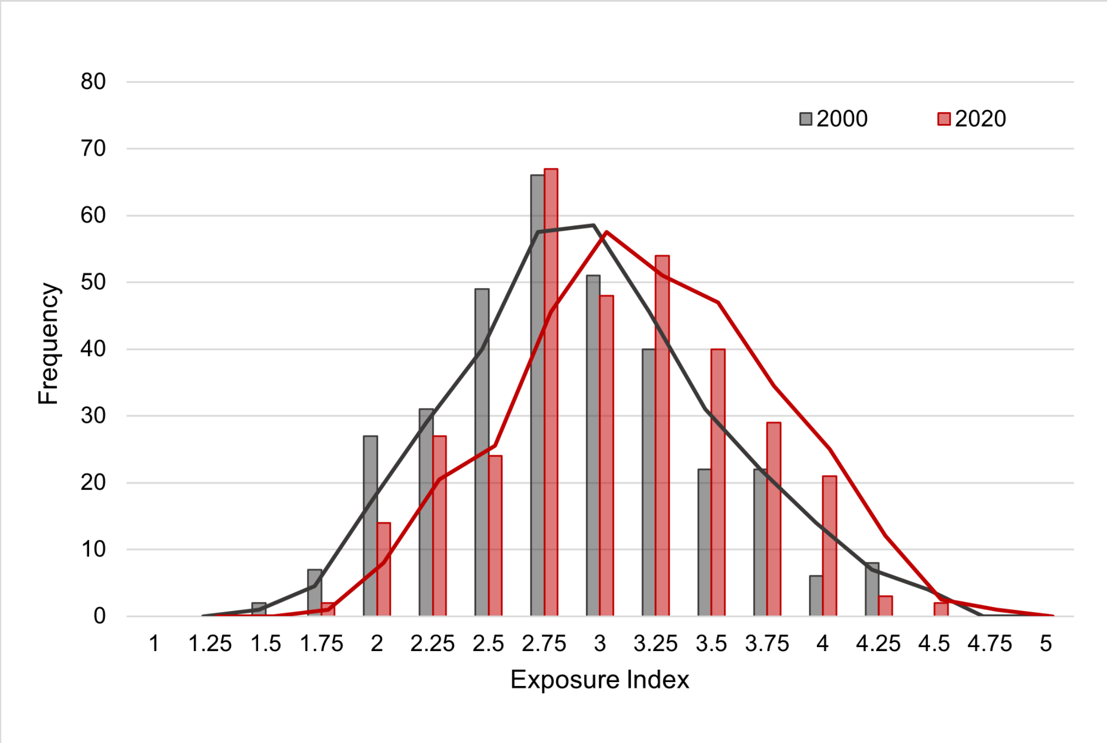

Figure 5.4: The combined histogram shows the general result obtained of CV model application between 2000 and 2020. In gray color there are the frequency communalities of the 2000 EI values with respect to 17 frequency classes, see *Table* 5.4. In red color are the same with respect to 2020 EI data. Also available are the trend lines of the two histograms, in gray and red color, respectively: these lines help to understand how the EI values have shifted to the right (frequency classes with higher EIs) and thus are increased from 2000 to 2020.

in specific habitat identification (consistent, scattered, matte seagrasses). These considerations are relevant when the user wants to accurately calculate the increased risk given by habitat loss or, even more so, estimate the CO_2 E sequestered from coastal marine habitats.

Other types of limitations fall into the effectiveness of the results of the models considered: for example, one of the final results of the CBC is the economic evaluation of the CO_2 E sequestered over 20 years. The values for the three different scenarios were compared with the results available in the literature. In this regard, there are two aspects to take into consideration:

- The amount of studies referring to the economic quantification of seagrass ESs is limited (PO) or almost nonexistent (CN). So it is difficult to assess whether the results obtained are consistent with the results provided by other studies.

Table 5.4: Frequency classes and relative frequencies used to represent the combined histogram, represented in *Figure* 5.4.

Frequency classes	**2000**	**2020**
0 - 1	0	0
1 - 1.25	0	0
1.25 - 1.5	2	0
1.5 - 1.75	7	2
1.75 - 2	27	14
2 - 2.25	31	27
2.25 - 2.5	49	24
2.5 - 2.75	66	67
2.75 - 3	51	48
3 - 3.25	40	54
3.25 - 3.5	22	40
3.5 - 3.75	22	29
3.75 - 4	6	21
4 - 4.25	8	3
4.25 - 4.5	0	2
4.5 - 4.75	0	0

- Studies that evaluate ESs economically often use different methodologies and values to take into account. The study proposed by Scanu et al., 2022, economically evaluates the role of seagrass and its ESs in general, without referring exclusively to Blue Carbon (CO_2Esequestered). The lack of guidelines for assessing BC has been filled by European projects such as Life project SEPOSSO (Cozzolino et al., 2021), which, however, are still at an early stage and are not used as a reference model in an unique way.

Further limitations of the study are more technical in nature, they could be bridged by a downscale analysis and are considered in the section 5.2.2.

5.2.2 Possible improvements

In order to evaluate the study performed and the impact of its results might have, it is good to consider what improvements could be made in the future. As pointed out in the previous paragraph (section 5.2.1), the major limitations to the project are technical. The analysis should be able to use data that have been derived in the same way, or if that is not possible, increase the number of observations over the time frame considered to assess the actual change in the analysis. Marine habitat change would need an assessment based on multiple years within the time frame:

knowing how seagrasses have declined between 2000 and 2010, and from 2010 to 2020 could be useful in assessing their scale of decline and the relative results of the CBC and CV models. These data should come through a photo interpretation analysis of the years between 2000 and 2020 that are not available in the Liguria Region website.

Another aspect would be enrich the study by using not only the information of marine seagrasses in the area (PO and CN) but expanding the assessment on all marine habitats in the area (e.g. corals, common seagrasses). In addition, it could be useful enlarge the analysis over the entire Ligurian coastal area, still maintaining a good resolution of the input data.

Downscale analysis however remains a good approach for the model when considering the conformation of the Ligurian coast. As such, the evaluation of the role of seagrasses in decreasing coastal erosion could be explored. This would help to assess whether seagrasses actually contribute to decreasing the impact of coastal erosion in the hydrodynamic domain also in the Ligurian territory, where there is a considerable depth increase already a few meters from the coast.

Therefore, it is necessary to decrease the approximations made and deepen the choice of some parameters to make them site specific. Such collaborations are to be considered both in the biological-chemical fields (for modelling the CBC biophysical table) and in the hydrodynamic field (wind and wave modelling, CV assessment).

Therefore, once again, the sharing of data and results obtained in the scientific field turns out to be the key to the improvement of studies developed by scholars even in different fields.

Chapter 6

Conclusions

In this thesis work, two models of the $InVEST$ software were applied to assess whether the quantification of ES is applicable in coastal areas. Based on several studies reviewed in the literature, the idea was to evaluate ESs of seagrasses for climate and morphosedimentary regulation using the Coastal Blue Carbon and the Coastal Vulnerability Model. During the development phase, several issues were addressed, such as data acquisition, data processing and identification of suitable sources to fill gaps. Once the necessary input data were obtained, the results for both models were obtained.

The results showed that the proposed approach is a viable solution to quantitatively estimate some of the ES provided by marine seagrasses in the Ligurian Sea.

Indeed, the case study confirmed that the economic assessment of CO_2E sequestration is in line with the values found in the literature. In particular, the results obtained with the CBC model for the discount rates of 2.5, 3 and 5 % include the value obtained by Scanu et al., 2022 regarding Posidonia Oceanica. In addition, an increase in the risk exposure (EI) between 2000 and 2020 was confirmed; which, thanks to the CV model, can be attributed to the loss of marine habitat and to the variation of wind and wave data.

Further steps are needed to improve the project's results. Firstly, in order to successfully ascertain the results of CO_2E sequestration by seagrasses, it is necessary to use site-specific data that can be obtained through collaboration with experts in the biological sciences. Furthermore, since the influence of seagrasses in combating coastal erosion is currently being evaluated in the Ligurian territory, further down-scale simulations need to be carried out to assess their actual influence.

Finally, it is necessary to assess how the quantification of ESs can be implemented in coastal spatial planning, in order to develop a transition towards sustainable protection.

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Appendix A

InVEST Models

In addition to what has already been specified in sections 2.3.1 and 2.3.2, the reader will find below some specifications with respect to the mathematical statements used by *InVEST* within the CBC Model (section A.1) and the CV Model (section A.2).

A.1 Coastal Blue Carbon Model

InVEST Coastal Blue Carbon models the carbon cycle through an accounting approach (NatCap, 2022a; Houghton, 2003). This method simplifies the study of the carbon cycle by accounting for storage in three leading sinks: biomass, sediment carbon (i.e. soil), and dead standing carbon (i.e. litter), see *Figure* 2.1. Pendleton et al., 2012 states that sediments are the most significant carbon storage in coastal habitats. The model quantifies carbon storage across the entire land or seascape by summing the carbon stored in these three carbon pools.

For the assessment of net carbon storage for a given year t, each coastal blue carbon habitat is assumed to be in storage equilibrium at any given time (Sharp et al., 2022). As shown in *Equation* (A.1), the carbon stocks S for a given year t and basin p are calculated by adding the net carbon sequestration of the year to the stores available in the previous year $t-1$. Alternatively, using the initial stock values from the biophysical table, $S_p,t_{baseline}$.

$$S_{p,t} = \left\{ \begin{array}{lll} S_{p,t-1} + N_{p,t} & if & t > t_{p,t} \\ S_{p,t_{baseline}} & if & t = t_{baseline} \end{array} \right\}. \tag{A.1}$$

where

- The carbon stocks of year t represent the carbon stocks at the beginning of year t.

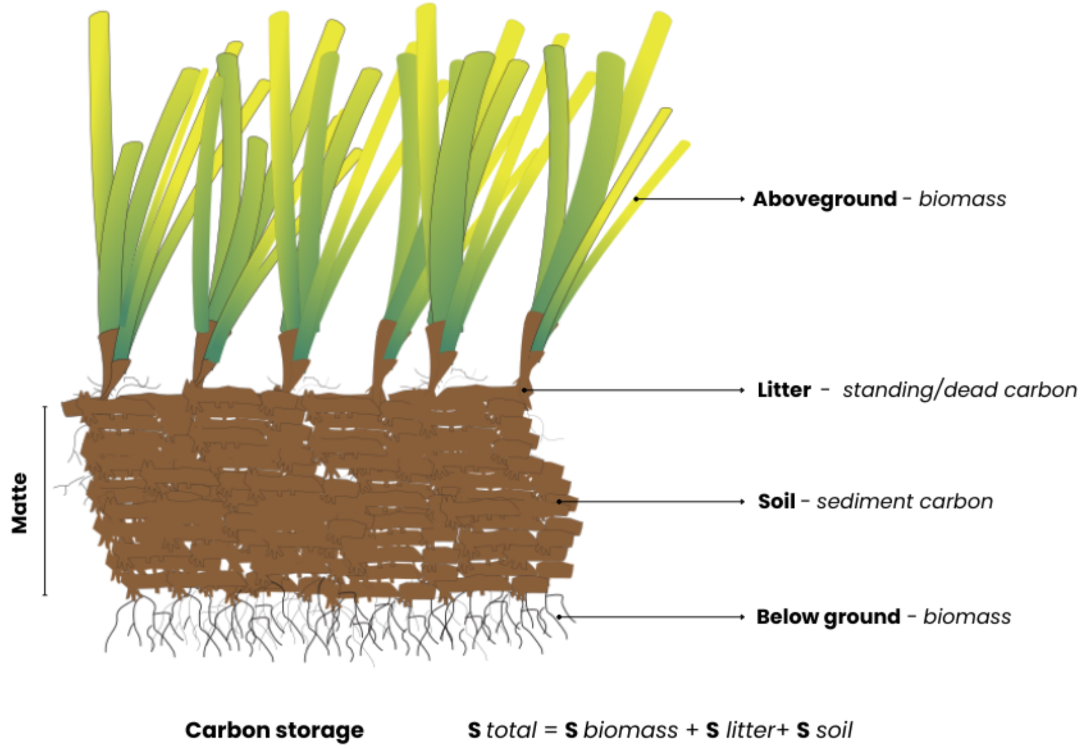

Figure A1: Carbon storage model used by *InVEST* within the Coastal Blue Carbon model. Example based on Houghton's (2003) approach and adapted on marine seagrasses (Houghton, 2003). Storage is accounted for in three main sinks: biomass, sediment carbon (i.e. soil) and dead standing carbon (i.e. litter).

- Net sequestration $N_{p,t}$ refers to the amount of carbon gained or lost in year t.

The status of the most recent transition determines whether carbon accumulates (positive net sequestration) or emits (negative net sequestration). A single cell can get or emit carbon. Therefore, $N_{p,t}$, will be equal to one of these equations, depending on the state of the most recent transition, see *Equation* (A.2):

$$N_{p,t} = \left\{ \begin{array}{lll} -1 \cdot N_{p,t} & if & carbon\ is\ emitting \\ A_{p,t} & if & carbon\ is\ accumulating \end{array} \right\}. \tag{A.2}$$

where

- $A_{p,t}$ represent the accumulation rate, defined by the user in the biophysical table for each land cover classification.

- $E_{p,t}$ represent the emissions rate, calculated as a positive value because the value -1 is needed to reflect a loss of carbon from the pool.

Note that (A.2) only applies to biomass and soil pools. Litter stocks are not subject to emissions and, therefore, can only accumulate linearly according to the rate defined by the user in the biophysical table, see *Equation* (A.3):

$$S_{p_{litter}} = S_{p_{litter}}, t_{baseline} + (A_{p_{litter}} \cdot (t - t_{baseline}) \tag{A.3}$$

Therefore, the net sequestration for the litter pool, $N_{p_{litter,t}}$ is equivalent to $A_{p_{litter}}$, which the user defines in the biophysics table. The model also calculates the total stocks for each year of the timestep, simply the sum of all carbon stocks in all three pools, see *Equation* (A.4):

$$S_{t_{total}} = S_{t,p_{soil}} + S_{t,p_{biomass}} + S_{t,p_{litter}} \tag{A.4}$$

More in-depth explanations of how carbon is accumulated, emitted and evaluated in economic terms by the CBC model can be found below.

A.1.1 Carbon Accumulation

Accumulation is calculated as the rate of carbon retained in the soil in organic form after the first year of decomposition. This accumulation contributes to the development of carbon 'sinks' that are considered virtually permanent unless disturbed. Therefore, even without a change in land use or cover, carbon continues to be sequestered naturally. The impacts of coastal development on carbon storage vary, as some actions may involve soil paving, which often keeps a large percentage of the stored carbon intact. Alternatively, dredging may remove seagrass and disturb the underlying sediments, releasing carbon into the atmosphere.

A.1.2 Carbon Emission

When human activities degrade coastal ecosystems, carbon stored in living plant material and soil may be emitted to the atmosphere. The type of disturbance will determine the amount of biomass loss at the surface and the depth of alteration of the soil profile. The deeper the effects of the disturbance, the more soil carbon will be exposed to oxygen, oxidised and consequently emitted as CO_2. Some disturbances disturb only the upper layers of the soil, while the deeper layers remain inundated and their carbon intact. To estimate the extent of the impact of various disturbances, the model classify them into three impact categories: high, medium and low. Carbon emissions begin in an instantaneous year when the land cover classification below grid cell x changes to a low, medium or high impact disturbance state. In subsequent years, emissions continue until one of the grid cells x undergoes another transition or until the year of analysis is reached. The model uses an exponential decay function H_p based on the user-defined half-life of the carbon pool in question and the volume of carbon disturbed. In *Equation* (A.5), s represents the year of the transition and $E_{p,t}$ represent the volume of carbon emitted from pool p in year t.

$$E_{p,t} = D_{p,s} \cdot (0.5^{\frac{t-(s+1)}{H_{p,s}}} - 0.5^{\frac{t-s}{H_{p,s}}}) \tag{A.5}$$

The volume of disturbed carbon $D_{p,s}$ represents the total volume of carbon that will be released over time from the transition in grid cell x in the transition year as time $t \to \infty$. This quantity is determined by the magnitude of the disturbance $M_{p,s}$ (low, medium or high impact), the stocks S present at the beginning of year s and the land cover transition undergone in year s:

$$D_{p,s} = S_{p,s} \cdot M_{p,s} \tag{A.6}$$

The amount of disturbance is determined by the transition matrix (low, medium or high impact) and specified as the percentage of carbon disturbed in the biophysical table. When a land cover classification transitions to an emission state, the magnitude of disturbance will be taken from the land cover class of origin.

A.1.3 Valuation of Net Sequestered Carbon

The valuation option of the blue carbon model estimates the economic value of sequestration as a function of the amount of carbon sequestered, the monetary value of each tonne of carbon sequestered, a discount rate and the change in the value of carbon sequestration over time (NatCap, 2022a). The value of carbon sequestering depends on who decides to change carbon emissions and falls into two categories: social and private. Considering a public approach to the case study, decision-makers must weigh the benefits of development against the social losses from carbon emissions. Since local carbon emissions affect the atmosphere globally, the social cost of carbon (SCC) is commonly calculated globally (USIWGSCC, 2016).

The social cost of carbon (SCC) used by *InVEST* represents a synthesis of several models such as FUND Tol and Richard, 2010, PAGE Hope, 2002, DICE and RICE Kumar, 2010 (Sharp et al., 2022). The synthesis of this work, carried out by the US Interagency Working Group on the Social Cost of Carbon, drove defined an appropriate SCC over time for three different discount rates USIWGSCC, 2016). This synthesis is used in the CBC model through the use of three tables that evaluate the SCC from 2010 to 2050 with respect to different discount rates (2.5 %, 3 %, 5 %).

For more information on the mathematical specifications used by the CBC Model, the reader is invited to use the Coastal Blue Carbon *InVEST* User Guide available at the specific web page NatCap, 2022a).

A.2 Coastal Vulnerability Model

In addition to what has already been specified in chapter 2.3.2, the reader will find below some specifications with respect to the mathematical specifications used by *InVEST* within the CV Model.

A.2.1 Shore Points and Area of Interest

The model requires a vector of polygons representing the landmass in the area of interest. From this landmass, the model plots points along the coastline at a user-specified distance interval as the model resolution. The model assigns a value for each coastline point for all variables described in the following sections.

A.2.2 Relief

Sites that are, on average, at a higher elevation than mean sea level (MSL) have a lower risk of being inundated than areas at a lower elevation. Relief is defined in the model as the average elevation of the coastal area that lies within a user-defined average elevation radius around each coastal point. For this variable, the model requires a digital elevation model (DEM) that covers the area of interest and extends beyond the AOI for at least the distance of the mean elevation radius.

A.2.3 Natural habitats

Natural habitats (marshes, seagrass beds, mangroves, coastal dunes or other) play a key role in reducing the impact of coastal hazards that can erode coastlines and damage coastal communities. For example, large waves break over coral reefs before reaching the coastline, mangroves and coastal forests drastically reduce wave heights in shallow waters and decrease the force of wave and wind-generated currents, seagrass beds and marshes stabilise sediments and promote near-shore accretion, and dissipate wave energy. On the other hand, beaches with little or no biological habitat or sand dunes offer little protection against erosion and flooding.

To calculate the degree of natural habitat exposure for a given shoreline point, the model determines whether a certain class of natural habitat is located within a user-defined search radius from the point. Once all habitats in the vicinity of that point have been identified, the model creates an R-array containing all the ranks associated with these habitats, as defined in the example classification table.

A.2.4 Wind exposure

Strong winds can generate strong swells and/or powerful waves if they blow over an area for a sufficiently long period of time. The wind exposure variable is a result that classifies coastal segments according to their relative exposure to strong winds. This variable is calculated as the relative exposure index (REI) defined by Keddy, 1982. This index is calculated by taking the highest 10 per cent wind speed from a long record of measured wind speeds, dividing the wind rose (or 360 degree compass) into 16 equiangular sectors and combining the wind and fetch characteristics in these sectors as follows in (A.7):

$$REI = \sum_{n=1}^{16} U_n P_n F_n \tag{A.7}$$

where:

- U_n is the average wind speed, expressed in metres per second, of the highest 10% wind speed in the equiangular sector;
- P_n is the percentage of all wind speeds in the record of interest blowing in the direction of the sector;
- F_n is the fetch distance (distance where the wind blows across the water), in metres, in the sector.

To estimate the fetch distance for a given shoreline point, the model casts rays outwards in 16 directions and measures the maximum length of a ray before it intersects with a land mass. The maxiumum fetch distance parameter is used to avoid launching rays across an entire ocean.

A.2.5 Wave Exposure

The relative exposure of a stretch of coastline to storm waves is a qualitative indicator of the potential for shoreline erosion. A given stretch of coastline is generally exposed to ocean waves or waves generated locally by wind. Moreover, waves with a longer period have greater power than shorter waves for a given wave height. Coasts exposed to the open ocean are generally more exposed to waves than sheltered regions, because winds blowing over a very wide distance, or fetch, generate larger waves. In addition, exposed regions suffer the effects of long-duration waves, or swells, generated by distant storms. Similarly, for each of the 16 equiangular wind sectors, the average of the highest 10% of wind speed, wave height and wave power was calculated.

For more information on the mathematical specifications used by the CV Model, the reader is invited to use the Coastal Vulnerability *InVEST* User Guide available at the specific web page (NatCap, 2022b).

Appendix B

InVEST Input Data

The search for valuable and detailed data is crucial to the success of the analysis conducted by *InVEST* using the two models considered. The search for data was preceded by a detailed analysis of what has been done in the Mediterranean Sea area to quantify coastal ESs, see section 1.4). As mentioned in section 4.2, this study uses considerations and data taken from papers and scientific publications analysing the coasts of Liguria, Italy and, more generally, Mediterranean Europe, especially Spain. Below the reader can consult a summary table of all the reference sources used to obtain the data, see *Table* B1).

Table B1: List of reference sources used to get the data.

Reference	Title	Area	Model	Use
Liguria, 2022	**Geoportal of the Liguria Region**	Italy	**CBC, CV**	Geospatial information (dtm, landmass, bathymetry)
NatCap, 2022a	**Sample data provided in the user guide of Coastal Blue Carbon.**	Global	**CB**	Price tables of SCC (2,5%, 3%, 5% discount ratio)
NatCap, 2022b	**Sample data provided in the user guide of Coastal Vulnerability Model**	Global	**CV**	Continental Shelf Contour, Parameters
DICCA, 2022	**MeteOcean**	Italy	**CV**	Wind and wave data
Bianchi and Peirano, 1995	**Atlas of Marine Phanerogams of Liguria: PO and CN**	Liguria	**CBC, CV**	Geospatial information on marine habitats in Liguria, 1995 data
Diviacco and Coppo, 2006	**Atlas of Marine Habitats of Liguria Region**	Liguria	**CBC, CV**	Geospatial information on marine habitats in Liguria, update 1995 data
Liguria, 2020	**Atlas of Marine Habitats of Liguria Region**	Liguria	**CBC, CV**	Geospatial information on marine habitats in Liguria, 2020 data
González-García et al., 2022	**National blue carbon assessment in Spain using InVEST: Current state and future perspectives**	Spain	**CBC**	Specific carbon sequestration data for biophysical table, CBC *InVEST* application

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Table B1 – continued from previous page

Reference	Title	Area	Model	Use
Monnier et al., 2022	**Quantification of blue carbon stocks associated with PO seagrass meadows in Corsica (NW Mediterranean)**	Corsica	**CBC**	Specific carbon sequestration data for biophysical table
Rigo et al., 2021	**The Natural Capital Value of the Seagrass PO in the North-Western Mediterranean**	Liguria, Corsica	**CBC**	Comparison of results obtained in economic quantification
Scanu et al., 2022	**Economic Evaluation of PO ESs along the Italian Coast**	Italy	**CBC**	Comparison of results obtained in economic quantification, CBC *InVEST* application (theoretical)
Vassallo et al., 2013	**The value of the seagrass PO: A natural capital assessment**	Bergeggi MPA	**CBC**	Comparison of results obtained in economic quantification
USIWGSCC, 2016	**Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis**	Global	**CBC**	Price table with different discount rates

B.1 Coastal Blue Carbon Model

Table B2: Example of a Biophysical transposed table to be inserted into the CBC Main Model. Accumulation units are (Megatonnes of $CO_2E/(ha \cdot y)$), half-life is in integer years, and disturbance is in integer percent. The edited table is used as input to the main Coastal Blue Carbon model as the Biophysical Table.

code	**0**	**1**	**2**
lulc-class	**nodata**	**cym**	**pos**
biomass-initial	0	1.63	8.06
soil-initial	0	469.3	1805.85
litter-initial	0	0	0
biomass-half-life	0	0.3	0.3
biomass-low-impact-disturb	0	0.3	0.3
biomass-med-impact-disturb	0	0.5	0.5
biomass-high-impact-disturb	0	1	1
biomass-yearly-accumulation	0	0	0
soil-half-life	0	1	1
soil-low-impact-disturb	0	0.5	0.5
soil-med-impact-disturb	0	0.7	0.7
soil-high-impact-disturb	0	1	1
soil-yearly-accumulation	0	0.48	1.81
litter-yearly-accumulation	0	0	0

Table B3: Example of a land cover transition table to be inserted into the CBC Main Model. The transition table maps the type of carbon action suffered when one type of LULC transitions to another. The preprocessor creates the table and is edited by the user before being inserted into the main model.

lulc-class	nodata	cym	pos
nodata	NCC	accum	accum
cym	med-impact-disturb	accum	accum
pos	high-impact-disturb	accum	accum

Legend	
empty	cells indicate that no transitions occur of that type
disturb	(disturbance) change to low- med- or high-impact-disturb
accum	(accumulation)
NCC	(no-carbon-change)

The corrected and converted values were used in the CBC model, see *Table* B4 for an example of the interpolation, correction and conversion of the SCC tables. Values within the *Table* B4 refer to the 3% discount rate. The *Table* B5 shows the €$_{2020}$ values of the SCC used in the CBC model for each discount rates.

Table B4: Example of SCC conversion table from $US\$_{2007}$ to €$_{2020}$.

Year	**US\$$_{2007}$**	**US\$$_{2020}$**	**€$_{2020}$**
2000	21	30.03	30.38
2001	22	31.46	31.83
2002	23	32.89	33.28
2003	24	34.32	34.73
2004	25	35.75	36.17
2005	26	37.18	37.62
2006	27	38.61	39.07
2007	28	40.04	40.51
2008	29	41.47	41.96
2009	30	42.90	43.41
2010	31	44.33	44.85

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Table B4 – continued from previous page

Year	**US$**$_{2007}$	**US$**$_{2020}$	**€**$_{2020}$
2011	32	45.76	46.30
2012	33	47.19	47.75
2013	34	48.62	49.19
2014	35	50.05	50.64
2015	36	51.48	52.09
2016	38	54.34	54.98
2017	39	55.77	56.43
2018	40	57.20	57.88
2019	41	58.63	59.32
2020	42	60.06	60.77
2021	42	60.06	60.77
2022	43	61.49	62.22
2023	44	62.92	63.66
2024	45	64.35	65.11
2025	46	65.78	66.56
2026	47	67.21	68.00
2027	48	68.64	69.45
2028	49	70.07	70.90
2029	49	70.07	70.90
2030	50	71.50	72.34
2031	51	72.93	73.79
2032	52	74.36	75.24
2033	53	75.79	76.69
2034	54	77.22	78.13
2035	55	78.65	79.58
2036	56	80.08	81.03
2037	57	81.51	82.47
2038	58	82.94	83.92
2039	59	84.37	85.37
2040	60	85.80	86.81
2041	61	87.23	88.26
2042	61	87.23	88.26
2043	62	88.66	89.71
2044	63	90.09	91.15
2045	64	91.52	92.60
2046	65	92.95	94.05
2047	66	94.38	95.49
2048	67	95.81	96.94
2049	68	97.24	98.39
2050	69	98.67	99.84

Table B5: Example of SCC table in €$_{2020}$.

Year	**2,5%** [1]	**3%** [1]	**5%** [1]
2000	57.35	32.59	6.56
2001	58.95	33.93	7.14
2002	60.55	35.28	7.73
2003	62.15	36.62	8.31
2004	63.75	37.96	8.90
2005	65.36	39.30	9.48
2006	66.96	40.65	10.07
2007	68.56	41.99	10.65
2008	70.16	43.33	11.24
2009	71.77	44.68	11.82
2010	72.34	44.85	14.47
2011	73.79	46.30	15.92
2012	76.69	47.75	15.92
2013	78.13	49.19	15.92
2014	79.58	50.64	15.92
2015	81.03	52.09	15.92
2016	82.47	54.98	15.92
2017	85.37	56.43	15.92
2018	86.81	57.88	17.36
2019	88.26	59.32	17.36
2020	89.71	60.77	17.36
2021	91.15	60.77	17.36
2022	92.60	62.22	18.81
2023	94.05	63.66	18.81
2024	95.49	65.11	18.81
2025	98.39	66.56	20.26
2026	99.84	68.00	20.26
2027	101.28	69.45	21.70
2028	102.73	70.90	21.70
2029	104.18	70.90	21.70
2030	105.62	72.34	23.15
2031	107.07	73.79	23.15
2032	108.52	75.24	24.60
2033	109.96	76.69	24.60
2034	111.41	78.13	26.04
2035	112.86	79.58	26.04
2036	114.30	81.03	27.49
2037	117.20	82.47	27.49
2038	118.64	83.92	28.94
2039	120.09	85.37	28.94

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Table B5 – continued from previous page

Year	**2,5%** [1]	**3%** [1]	**5%** [1]
2040	121.54	86.81	30.38
2041	122.99	88.26	30.38
2042	124.43	88.26	31.83
2043	125.88	89.71	31.83
2044	127.33	91.15	33.28
2045	128.77	92.60	33.28
2046	130.22	94.05	34.73
2047	133.11	95.49	34.73
2048	134.56	96.94	36.17
2049	136.01	98.39	36.17
2050	137.45	99.84	37.62

[1]

[1]The size of the data in the table corresponds to the price (€$_{2020}$) of CO2E in that year.

Table B6: Wind and wave data for point 000257 for the year 2000, the data analysed correspond to the time span from January 1995 to December 2000.

X	REI_VX	REI_PCTX	V10PCT_X	WavP_X	WavPPCT_X
0	3.07	11.78	4.45	1.64	15.86
22.5	2.95	5.13	16.68	1.95	16.68
45	2.52	2.62	4.16	1.14	15.41
67.5	2.13	2.02	4.02	0.52	15.25
90	2.28	2.22	11.37	0.90	11.37
112.5	1.91	6.78	4.00	0.62	16.59
135	1.80	13.59	3.77	0.77	18.55
157.5	1.78	11.50	3.85	0.77	19.41
180	1.83	21.90	4.22	1.29	75.02
202.5	2.10	12.05	4.32	2.73	51.12
225	2.18	0.72	4.30	2.18	29.06
247.5	2.87	0.46	23.97	1.95	23.97
270	2.88	0.37	3.88	1.51	6.45
292.5	2.89	0.46	3.93	1.23	6.66
315	3.03	0.91	4.33	1.50	9.96
337.5	3.19	7.50	4.35	1.56	12.14

B.2 Coastal Vulnerability Model

The data summary comparing the years 2000 and 2020 is provided below, see see *Tables* B6,B7,B8,B9,B10 and B11). Each table contains the vectors REI_VX, REI_PCTX, V10PCT_X, WavP_X and of the three different points considered, whose raw data were provided by the MeteOcean group of the University of Genoa (DICCA, 2022). The quantities for each vector are as follows:

- $[m/s]$ for the REI_VX and V10PCT_X vectors;
- [%] for the REI_PCTX vector;
- $[kW/m]$ for the vectors WavP_X and WavPPCT_X.

Table B7: Wind and wave data for point 000257 for the year 2020, the data analysed correspond to the time span from January 2015 to December 2020.

X	REI_VX	REI_PCTX	V10PCT_X	WavP_X	WavPPCT_X
0	3.05	9.81	4.63	1.58	22.57
22.5	2.97	5.02	15.23	1.78	15.23
45	2.58	2.73	4.16	1.13	18.53
67.5	2.17	2.10	4.20	0.74	22.13
90	2.28	2.22	23.32	1.21	23.32
112.5	1.91	5.88	4.13	0.94	35.61
135	1.82	11.24	4.47	1.36	107.07
157.5	1.80	10.15	4.27	0.98	102.48
180	1.79	27.14	4.44	1.17	92.19
202.5	2.05	13.56	4.60	2.50	123.46
225	1.93	0.69	3.95	1.93	11.74
247.5	2.88	0.42	8.73	1.93	8.73
270	2.95	0.43	4.04	1.93	9.44
292.5	2.93	0.47	4.11	1.53	8.57
315	3.06	0.95	4.43	1.53	9.49
337.5	3.09	7.18	4.38	1.32	15.24

Table B8: Wind and wave data for point 000287 for the year 2000, the data analysed correspond to the time span from January 1995 to December 2000.

X	REI_VX	REI_PCTX	V10PCT_X	WavP_X	WavPPCT_X
0	3.16	10.87	4.59	1.98	17.48
22.5	3.04	6.77	18.85	1.88	18.85
45	2.55	3.92	4.30	1.00	17.55
67.5	2.19	3.09	3.99	0.48	13.64
90	2.17	3.90	16.37	0.66	16.37
112.5	1.83	9.99	3.84	0.60	16.08
135	1.77	11.87	3.84	0.71	19.10
157.5	1.75	10.98	3.82	0.69	17.60
180	1.82	20.82	4.24	1.11	63.27
202.5	2.17	10.81	4.55	2.49	46.30
225	1.40	0.50	4.00	1.40	11.03
247.5	2.69	0.28	11.65	1.47	11.65
270	2.85	0.26	4.15	1.57	7.71
292.5	2.86	0.32	4.01	1.49	7.44
315	3.06	0.83	4.58	1.83	16.19
337.5	3.27	4.79	4.41	2.30	15.09

Table B9: Wind and wave data for point 000287 for the year 2020, the data analysed correspond to the time span from January 2015 to December 2020.

X	REI_VX	REI_PCTX	V10PCT_X	WavP_X	WavPPCT_X
0	3.15	8.99	4.66	1.89	23.56
22.5	3.05	7.51	20.04	1.87	20.04
45	2.51	4.22	4.41	0.75	24.48
67.5	2.13	3.37	4.28	0.62	27.06
90	2.18	3.88	27.95	0.96	27.95
112.5	1.83	8.61	4.01	0.72	40.37
135	1.79	10.58	4.28	1.29	98.49
157.5	1.78	10.76	4.47	0.81	88.36
180	1.77	26.07	4.41	1.00	82.55
202.5	2.14	11.78	4.45	2.33	95.63
225	1.79	0.41	4.05	1.79	22.65
247.5	2.79	0.21	6.60	1.77	6.60
270	2.82	0.20	3.91	1.60	5.87
292.5	3.08	0.24	4.31	2.12	9.75
315	3.18	0.62	4.45	2.26	11.13
337.5	3.18	2.55	4.36	1.83	13.54

Table B10: Wind and wave data for point 000288 for the year 2000, the data analysed correspond to the time span from January 1995 to December 2000.

X	REI_VX	REI_PCTX	V10PCT_X	WavP_X	WavPPCT_X
0	3.17	13.30	4.54	2.99	30.00
22.5	2.94	9.45	30.23	2.45	30.23
45	2.58	3.75	4.26	1.89	23.09
67.5	2.37	2.15	3.97	1.46	21.67
90	2.23	2.29	12.02	1.16	12.02
112.5	1.86	6.14	3.73	0.75	21.23
135	1.79	8.99	3.73	0.91	23.55
157.5	1.80	7.07	3.84	0.98	25.64
180	1.79	14.66	4.54	1.50	107.86
202.5	2.00	23.55	4.40	3.71	97.57
225	3.05	3.53	4.37	3.05	67.96
247.5	2.74	0.76	16.22	3.21	16.22
270	2.75	0.43	4.16	2.79	14.94
292.5	2.88	0.44	4.08	2.67	14.53
315	3.00	0.69	4.44	3.01	20.71
337.5	3.19	2.80	4.41	3.23	18.55

Table B11: Wind and wave data for point 000288 for the year 2020, the data analysed correspond to the time span from January 2015 to December 2020.

X	REI_VX	REI_PCTX	V10PCT_X	WavP_X	WavPPCT_X
0	3.12	12.22	4.76	2.64	43.38
22.5	2.98	8.46	26.58	2.62	26.58
45	2.64	3.81	4.36	2.06	31.76
67.5	2.46	2.19	4.19	2.39	33.65
90	2.23	2.18	32.38	1.59	32.38
112.5	1.83	4.97	4.02	0.99	45.38
135	1.85	7.44	4.44	1.68	91.93
157.5	1.81	6.07	4.31	1.48	110.31
180	1.81	15.01	4.53	1.58	97.58
202.5	1.95	29.74	4.72	3.08	194.38
225	3.43	3.14	4.39	3.43	75.69
247.5	2.79	0.67	20.68	3.60	20.68
270	2.88	0.48	4.02	3.40	15.41
292.5	2.98	0.43	4.29	3.41	12.69
315	2.95	0.73	4.32	2.69	16.77
337.5	3.12	2.45	4.44	2.56	17.33

Appendix C

InVEST Results

In addition to what has already been specified in sections 5.1.1 and 5.1.2, the reader will find below some additional tables or graphical representations of the results within the CBC Model (section C.1) and the CV Model (section C.2).

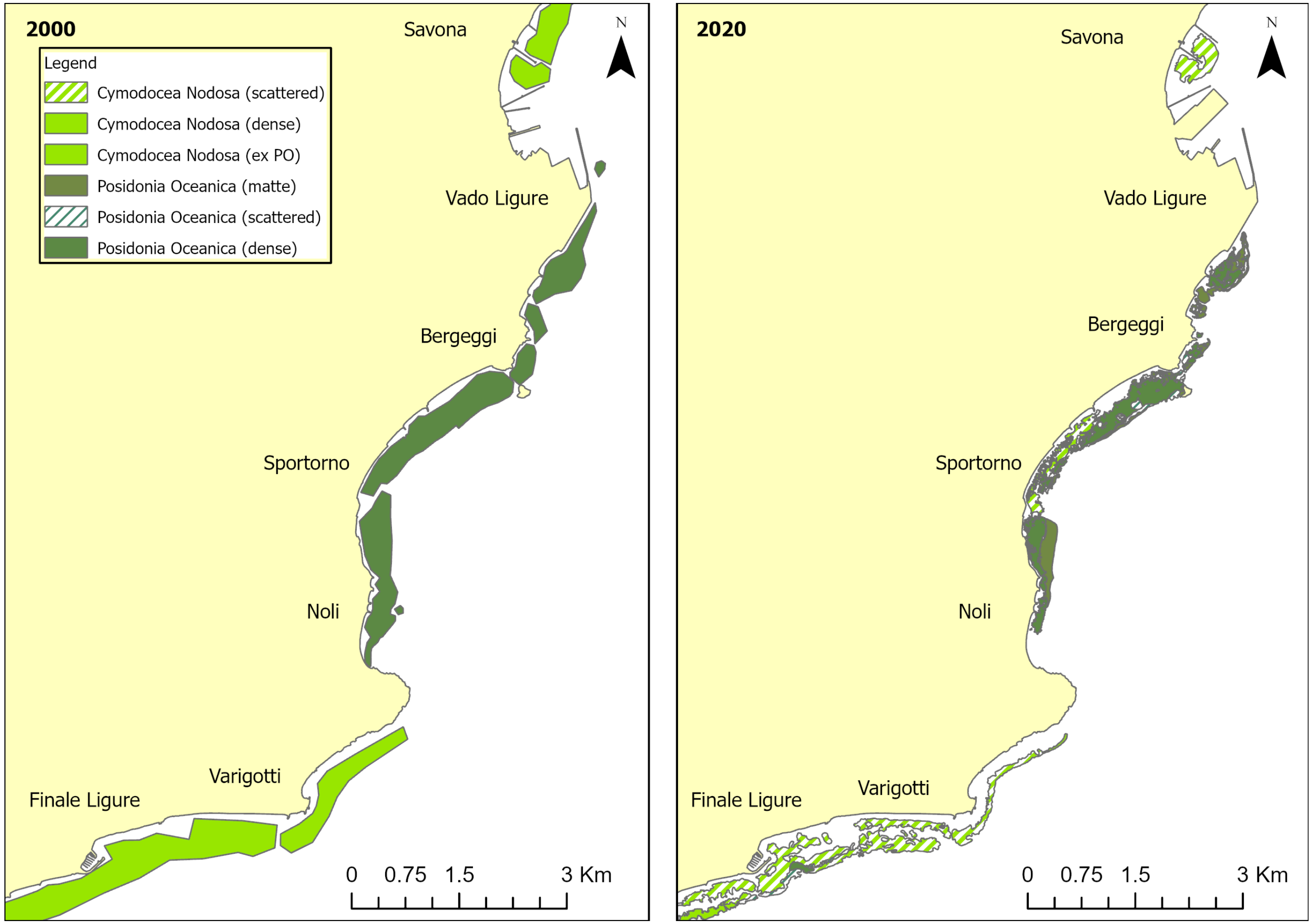

Figure C1: Overall view of the Seagrass Atlas in the year 2000 (left) and 2020 (right). Year 2000 data from the publications of Bianchi and Peirano, 1995 and Diviacco and Coppo, 2006 work. The data for the year 2020 were downloaded from the Liguria Region geoportal.

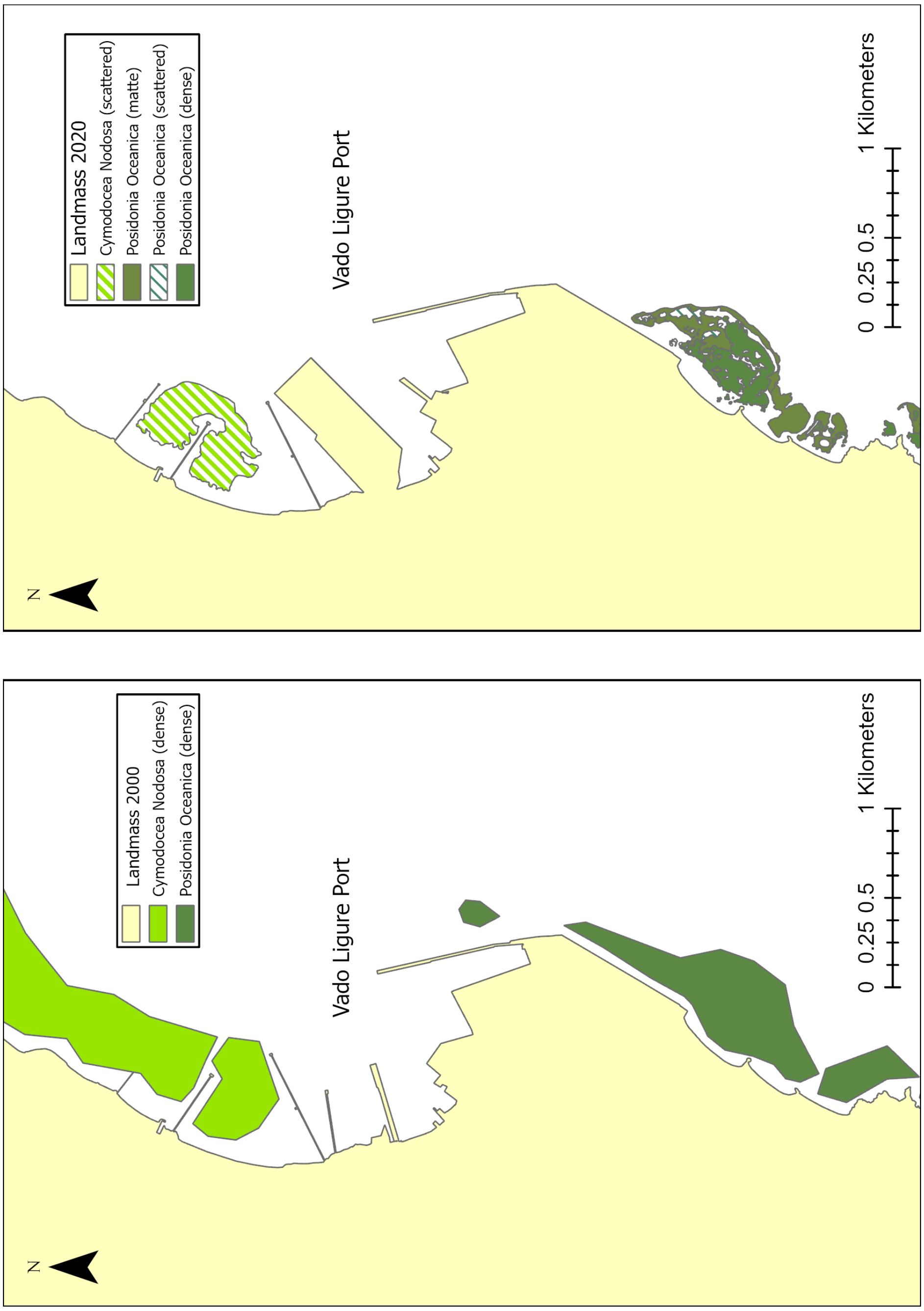

Figure C2: The decreasing of seagrass meadows for PO and CN in the area of Vado Ligure.

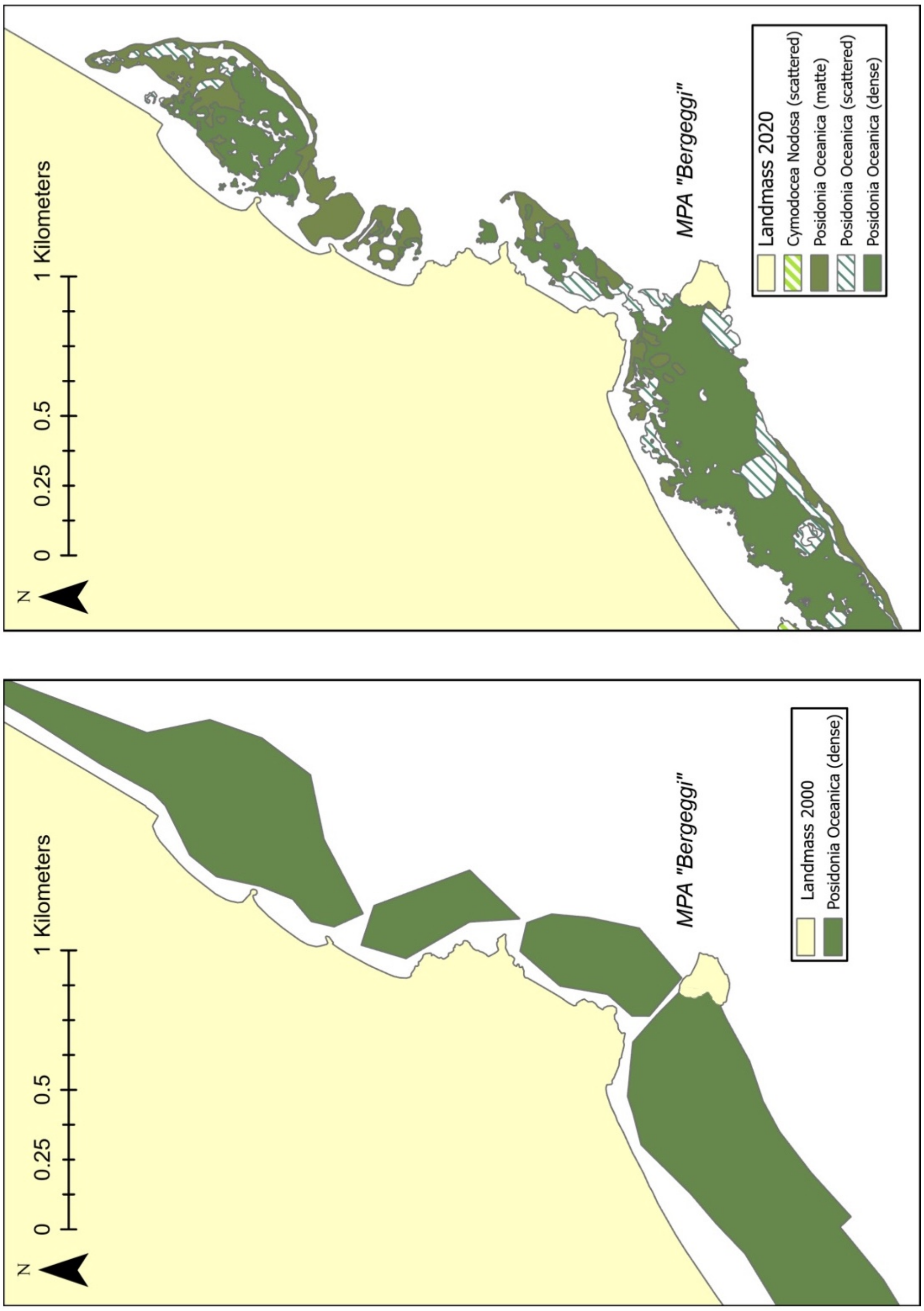

Figure C3: Prevention policies in the MPA of Bergeggi helped to have a slight decrease of meadows in the area compered to the all case study area.

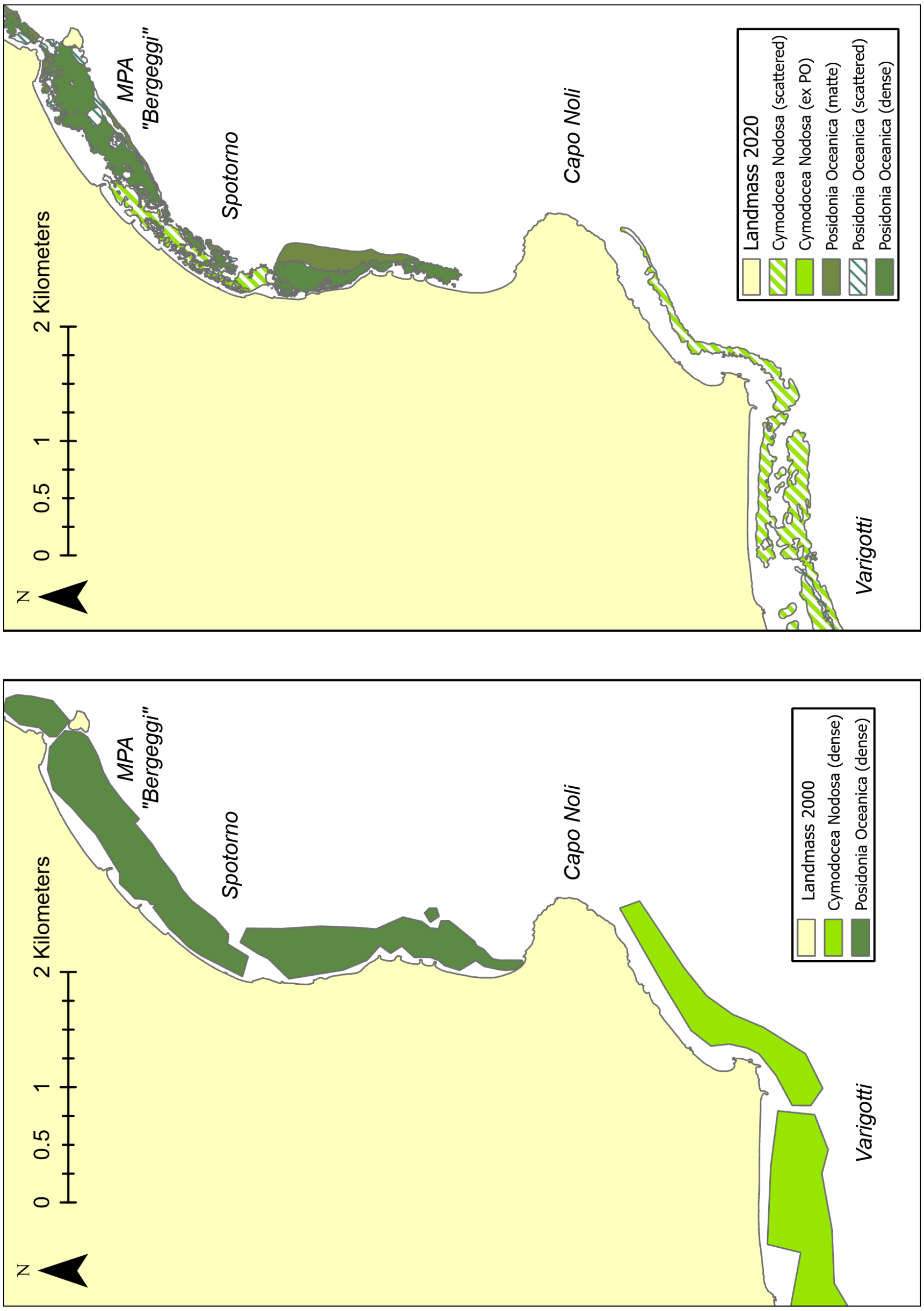

Figure C4: The decreasing of seagrass meadows for PO and CN in the area from Spotorno to Capo Noli.

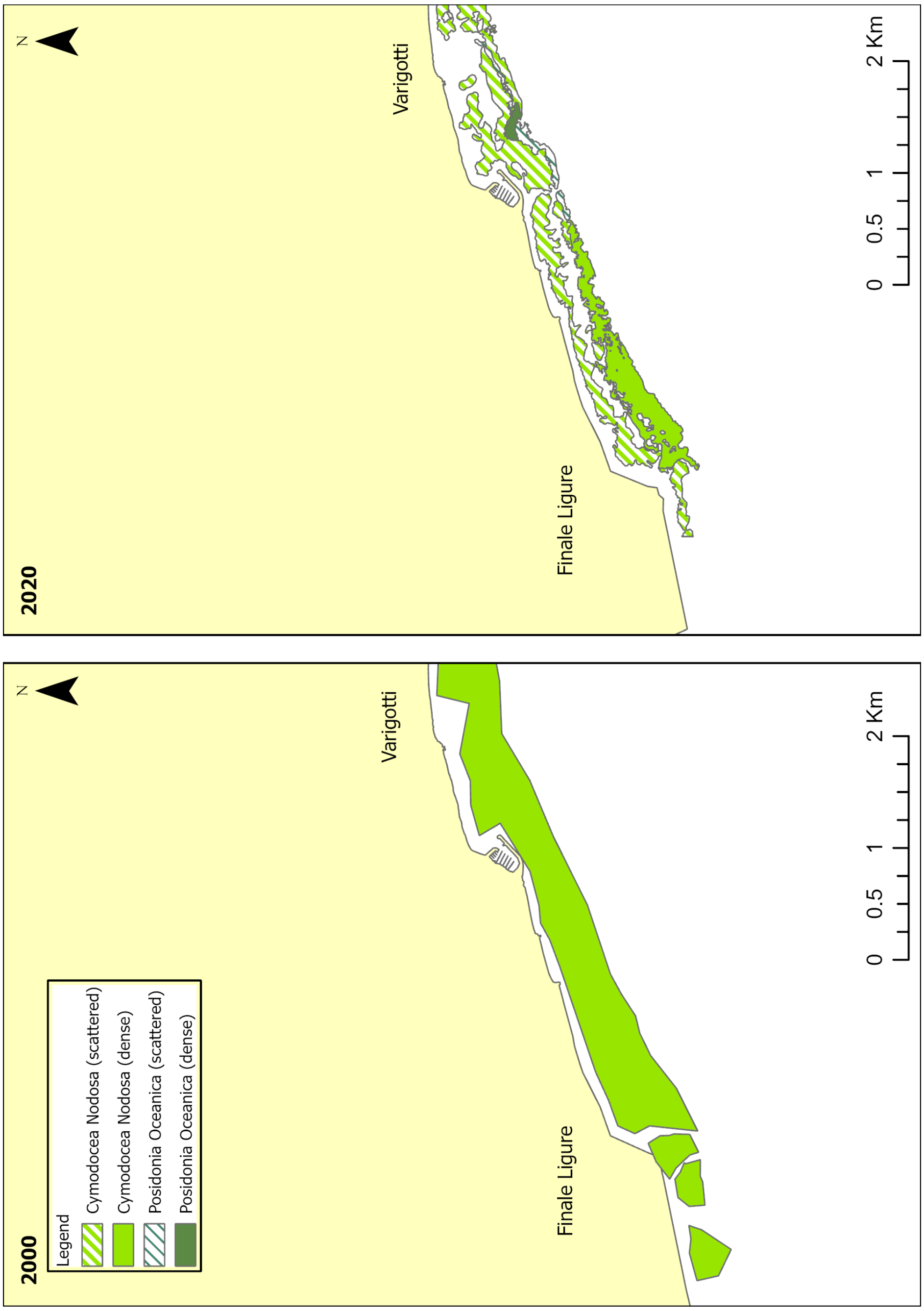

Figure C5: The decreasing of seagrass meadows for PO and CN in the area of Finale Ligure.

C.1 Coastal Blue Carbon Model

In addition to what has already been specified in section 5.1.1, the reader will find below some additional tables or graphical representations of the results within the CBC Model.

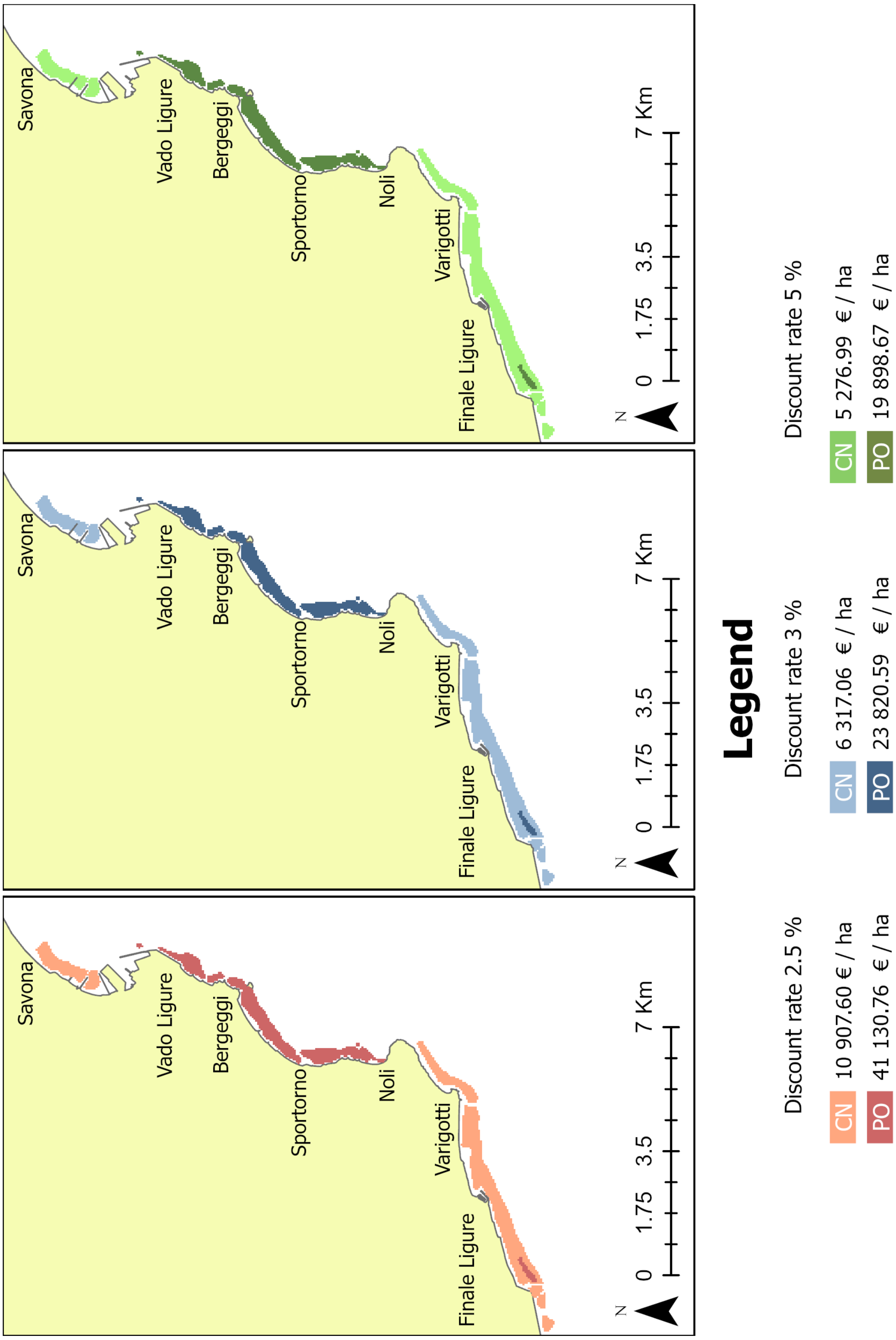

Figure C6: Results of net present value related to the application of the CBC model for the different discount rates.

C.2 Coastal Vulnerability Model

In addition to what has already been specified in section 5.1.2, the reader will find below some additional tables or graphical representations of the results within the CV Model.

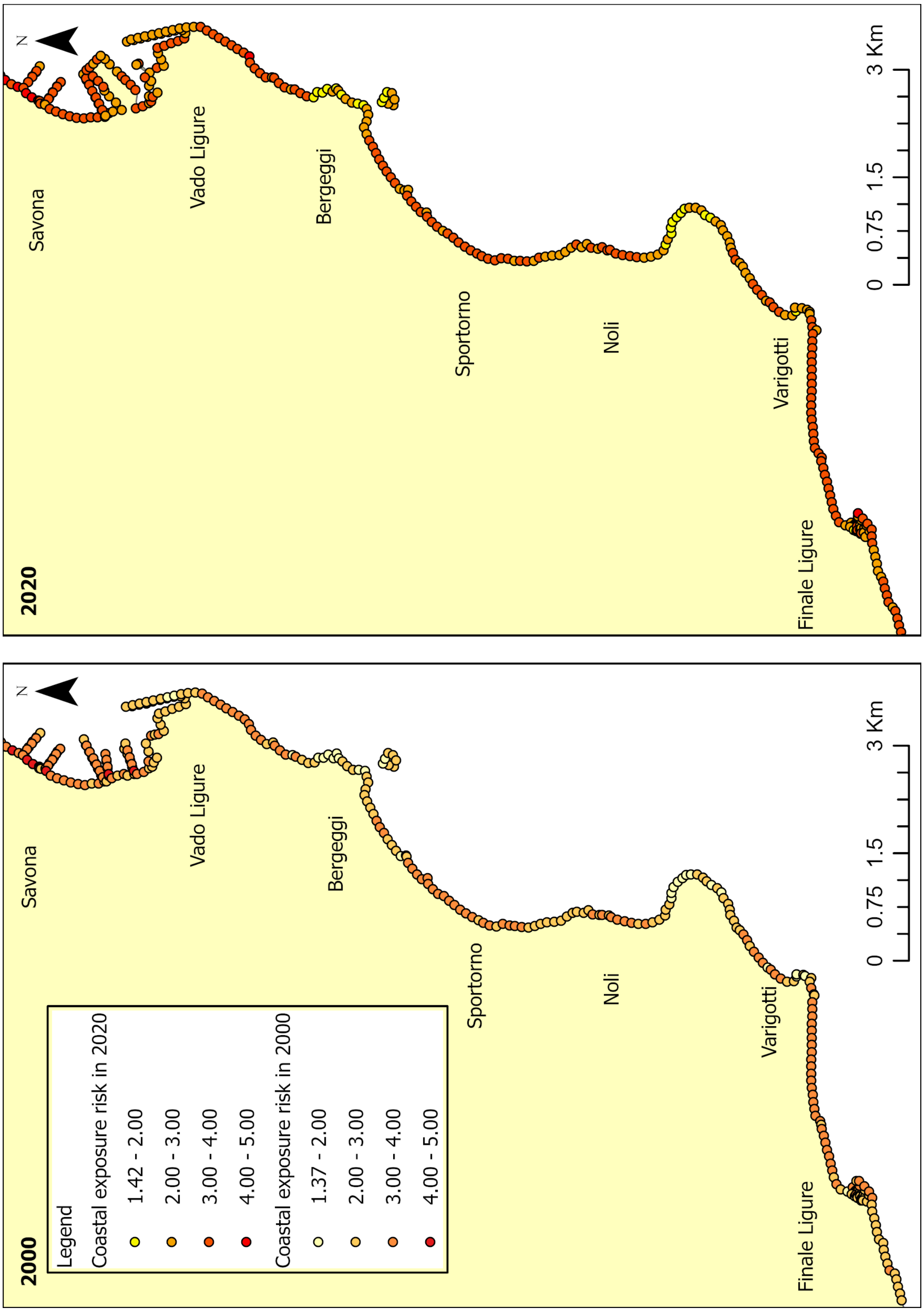

Figure C7: Overall result of CV application expressed in EI values, GIS overview.

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Giulia Tommaso Marco Francesco
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...e tutti quelli che hanno
contribuito

Tack så mycket

"Che le stelle ti guidino sempre e la strada ti porti lontano"