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Multi-platform assessment of coastal protection and carbon sequestration in the Venice Lagoon under future scenarios

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Summary

In recent decades, the rapid development of coastal regions, driven by sustained economic growth and population migration, has amplified their susceptibility to climate-induced hazards. The need to address these challenges in socio-economic coastal hotspots has become a pressing concern, requiring research and analysis to empower local decision-makers to undertake timely and appropriate adaptation measures. Simultaneously, many of these coastal areas boast rich natural habitats, which offer a diverse array of ecosystem services that can enhance climate resilience through both adaptation and mitigation efforts. This study, focuses on the Venice Lagoon, a region particularly vulnerable to natural hazards like sea-level rise, erosion, and flooding due to its low-lying coastal areas, seeks to examine the coastal protection and carbon sequestration services provided by seagrasses and salt marshes. Leveraging the InVEST platform known for its capabilities in valuing ecosystem services and assessing interventions for the protection and restoration of natural capital, this research takes a multi-platform approach by integrating the Coastal Vulnerability and Coastal Blue Carbon models to compute a composite index of these two ecosystem services. Additionally, we incorporate other tools that aid in the computation of the inputs to the InVEST models such as ARIES (Artificial Intelligence for Environment & Sustainability) and the QGIS plugins Molusce and SCP. We also provide estimates of carbon stocks, net carbon sequestration, and the economic value of these habitats for 2040 and 2060. The main outcome of this study is a combined index of coastal protection and carbon sequestration services developed to highlight crucial areas for the provisioning of these services, emphasizing the interconnectedness of socio-ecosystem components in coastal regions. In this study, we highlight the importance of using integrated assessment of ecosystem services in the context of climate change.

Keywords: Climate change adaptation; coastal protection; Venice; future scenarios, ecosystem service

JEL classification: Q01, Q51, Q54, Q57

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Abstract

In recent decades, the rapid development of coastal regions, driven by sustained economic growth and population migration, has amplified their susceptibility to climate-induced hazards. The need to address these challenges in socio-economic coastal hotspots has become a pressing concern, requiring research and analysis to empower local decision-makers to undertake timely and appropriate adaptation measures. Simultaneously, many of these coastal areas boast rich natural habitats which offer a diverse array of ecosystem services that can enhance climate resilience through both adaptation and mitigation efforts. This study, focuses on the Venice Lagoon, a region particularly vulnerable to natural hazards like sea-level rise, erosion, and flooding due to its low-lying coastal areas, seeks to examine the coastal protection and carbon sequestration services provided by seagrasses and salt marshes. Leveraging the InVEST platform known for its capabilities in valuing ecosystem services and assessing interventions for the protection and restoration of natural capital, this research takes a multi-platform approach by integrating the Coastal Vulnerability and Coastal Blue Carbon models to compute a composite index of these two ecosystem services. Additionally, we incorporate other tools that aid in the computation of the inputs to the InVEST models such as ARIES (Artificial Intelligence for Environment & Sustainability) and the QGIS plugins Molusce and SCP.

We also provide estimates of carbon stocks, net carbon sequestration, and the economic value of these habitats for 2040 and 2060. The main outcome of this study is a combined index of coastal protection and carbon sequestration services developed to highlight crucial areas for the provisioning of these services, emphasizing the interconnectedness of socio-ecosystem components in coastal regions. In this study, we highlight the importance of using integrated assessment of ecosystem services in the context of climate change.

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1 Introduction

Coastal regions are facing escalating challenges linked to rising sea levels, making flooding and coastal erosion a pressing global issue (Hinkel et al., 2014; Kirezci et al., 2020; Kumar & Taylor, 2015). These concerns are heightened when taking into account that 65% of the world's major cities are situated within 100 kilometers of coastlines, and approximately one billion people reside within 10 meters of today's high tide lines (Guerry et al., 2022). Sea level rise (SLR), coastal flooding, and erosion are complex problems with manifold underlying and dynamic factors that interact such as waves, tides, currents, winds and storm surges, that vary across temporal and spatial scales (Cunha et al., 2021; Vousdoukas et al., 2018). Moreover, the overexploitation and urbanization of coastal areas increase the pressures on coastal ecosystems (Barbier, 2011), and increasing erosion due to sediment retention phenomena (Cunha et al., 2021). Despite the global nature of the different drivers and factors involved, the impacts of SLR and climate-related extreme events are felt locally, requiring prompt actions by local governments in implementing adaptation plans (IPCC, 2022). Adaptation strategies now focus on nature-based solutions, such as preserving or restoring ecosystems like marshes and seagrass beds, which offer crucial coastal protection (Arkema et al., 2013; James et al., 2023). These ecosystems can dissipate wave energy, stabilize sediments, and mitigate wave and storm surge effects, reducing coastal vulnerability (Arkema et al., 2013; James et al., 2023). Additionally, they contribute to mitigation strategies, like carbon sequestration (Guerry et al., 2022).

The Venice Lagoon located in the Northern Italian Adriatic Sea (NAIS) is selected as the study area of this research, given its vulnerability to coastal hazards and presence of natural ecosystems (Bonaldo et al., 2019; Pesce et al., 2019). The NAIS comprises the Italian regions of Veneto, Friuli-Venezia Giulia and Emilia Romagna.

The Venice Lagoon, encompassing a vast expanse of approximately 550 km^2, stands as the largest coastal wetland within Italy. This ecological area is characterized by its unique tidal system, and its history interwoven with over a millennium of human interventions and interactions. Within the lagoon, a diverse array of distinctive biotypes thrives, including salt marshes, reed beds, seagrass meadows, and mudflats, creating a biodiverse ecosystem of significant importance (Ravera, 2000).

However, the Venetian Lagoon faces a multitude of pressing challenges that threaten its ecological integrity and sustainability. One of the foremost concerns is the extensive loss of salt marshes, both in terms of quality and quantity over the last The centuries (Munaretto, 2011). Additionally, ongoing erosion poses a persistent threat to the lagoon's delicate balance. Moreover, the lagoon grapples with limited sediment inputs and faces the issue of large volumes of sediments being exported to the sea, further compromising its stability (Sarretta et al., 2010).

These challenges are further exacerbated by various anthropogenic factors. Urbanization has encroached upon the lagoon's margins, compounding environmental stresses. The erosion caused by shipping and local water traffic, along with canal dredging, further intensifies the lagoon's vulnerability. Indeed, the whole NAIS is characterized by an enormous pressure of human presence, which is captured by the Human Modification Index developed by NASA's Socioeconomic Data and Applications Center (see Fig. 1).

In recognition of its exceptional cultural and environmental significance, the Venice Lagoon was designated as a UNESCO World Heritage site in 1987 (UNESCO, 2006). This acknowledgment underscores the urgent need for concerted efforts to address and mitigate the threats faced by this invaluable coastal wetland with a complex interplay between nature and human civilization in a fragile and historically rich environment.

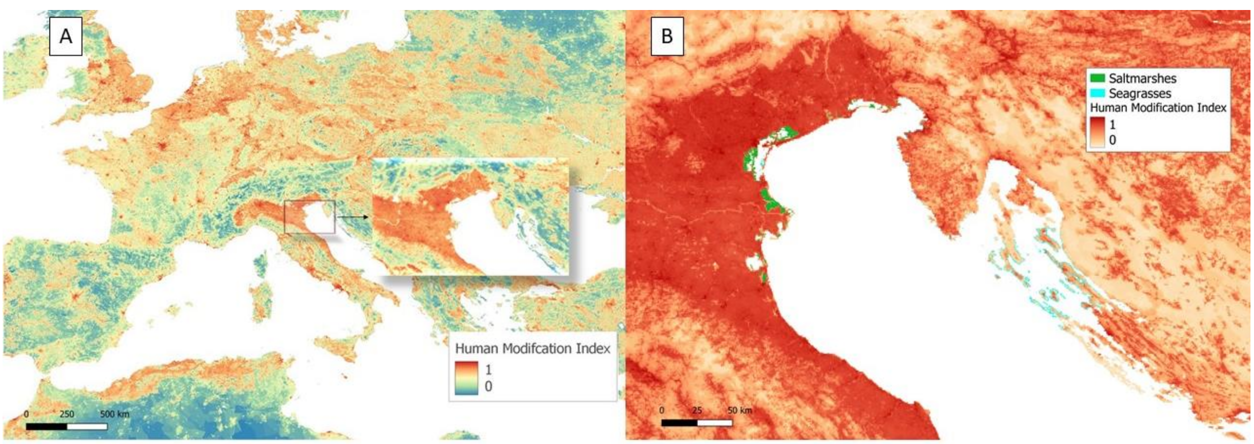


Figure 1: A) The Human Modification Index (HMI) in Europe. We zoom into the NAIS region where Venice is located, to highlight the degree of human pressure surrounding the lagoon. B) We use the HMI with a different color scale to better highlight the natural ecosystems still present in the NAIS region, the Venice lagoon has both salt marshes and seagrasses in a more abundant quantity with respect to other NAIS locations.

In this study, we adopt a multi-platform approach, integrating various softwares and models to analyze and quantify the ecosystem services, with a specific focus on coastal protection and carbon storage, offered by salt marshes and seagrasses. InVEST provided the two main models used in this study, this platform is widely used for the assessment of ecosystem services. It is particularly valuable in assessing coastal risks, accounting for the protective functions of ecosystems, and the carbon dynamics in blue carbon habitats. We have employed the Coastal Vulnerability Model

(CV Model) and the Coastal Blue Carbon Model (CBC Model), to compute a composite index of these two ecosystem services which we have labeled as Protection & Carbon (P&C) Index . The Coastal Vulnerability Model is key for evaluating the risk and protection associated with various ecosystems, while the Coastal Blue Carbon model quantifies carbon storage and sequestration in marine ecosystems. One of the main inputs of the CBC Model is the Hazard to Sea Level Rise layer computed in the Artificial Intelligence for Environment and Sustainability (ARIES), which is a multipurpose tool that can also address coastal risk and vulnerability (Villa et al., 2014). This platform enables to semantically connect information to automatically select the most accurate data within the spatial and temporal context of analysis (Balbi et al., 2022). This means that once our model for hazard has been defined, ARIES algorithms (the "reasoner") will automatically select the best available data in the context specified by the user. Furthermore, the CBC Model requires a set of scenarios to compute carbon stocks at the different snapshot years. To compute the future scenarios simulations we have employed the MOLUSCE plugin in QGIS 218. In turn, the MOLUSCE plugin requires at least two different years to derive the trend of the future category of each pixel, to obtain a classification suited for our study we perform the Land Classification for the years 2000 and 2020 using Landsat 7 satellite imagery in the SCP plugin in QGIS 3.28.8. Until now this suite of tools has not been used to conduct risk assessments considering both, the protective role of natural habitats and their carbon stock (Arkema et al., 2013; Cabral et al., 2017). Moreover, there is an even less significant number of studies valuing, in monetary terms, the coastal protection services provided by different natural habitats (Barbier, 2013; Costanza et al., 2008; Cunha et al., 2021; Sutton-Grier et al., 2015). There are fewer studies that have valued the coastal protection services provided by salt marshes, sea grasses, beaches and dunes (Maldonado et al., 2020).
The aim of the present study is to obtain a quantification of the coastal protection and carbon sequestration services offered by seagrasses and salt marshes in the Venice lagoon by computing a composite index considering the habitat role in protecting the coast and the carbon stock at the baseline year (2020) and the projected year under a moderate climate change scenario i.e. Representative Concentration Pathways RCP4.5.
The present work is structured in five sections. Section one presents the methodology which comprises the study area, a detailed description of the two Modelling Tools, the data used as well as the scenarios considered for the CV and CBC Models, this section also includes a description on how the P&C Index was computed. Section three shows the main results obtained for the two main models and the P&C Index. Section four presents a discussion of the main results, their weaknesses and possible improvements. Finally, Section five presents our conclusions.

2 Methodology

2.1 Study area

This study focuses on the Venice Lagoon which, as mentioned by Settis (2016), represents an open-air laboratory of what the coastal cities of the future will be up against concerning climate change risks due to its unique morphology, cultural and natural capital. Fig. 2A shows the location of the Venice lagoon within Italy. While Fig. 2B displays Land Cover and Land Uses of the Venice lagoon and surrounding areas. We observe a predominant anthropogenic use of the surrounding areas of the lagoon.

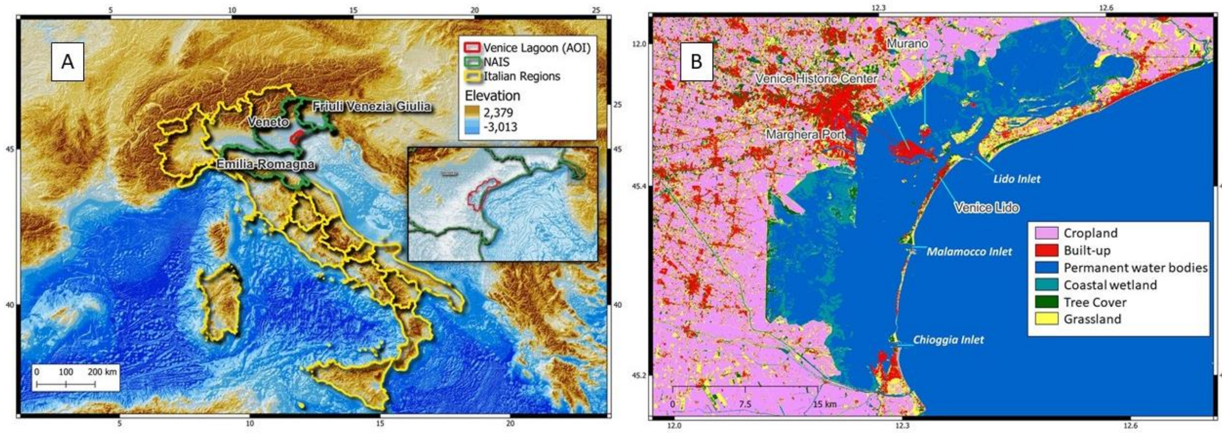


Figure 2: A) The Venice Lagoon is located in the north-east of Italy, we also identify the NAIS within Italy. B) Land use and land cover in the Venice Lagoon and surrounding areas. The land use data is based on ESA's World Map 2020.

The coastal area of Venice exhibits a heightened vulnerability owing to its distinctive morphological configuration, compounded by the diverse array of natural and anthropogenic influences operating across varying spatial and temporal dimensions. Moreover, the combination of multiple and intricate climatic and topological factors such as astronomical tides, atmospheric fluctuations forced by the sea, the relative rise in sea level exacerbated by global warming, and vertical land movements make the Venice coastline and lagoon subject to extreme sea levels (Fogarin et al., 2023; Lionello et al., 2020; Zanchettin et al., 2021). The best estimate of relative sea level rise (RSLR) in the Venice Lagoon during the period 1872-2019 is approximately 1.2 mm/year when removing the effect of subsidence (Zanchettin et al., 2021).

The Venice lagoon constitutes a noteworthy hotspot for inundation risk within the Italian northern Adriatic basin due to the significant presence of low-lying coastal areas (Furlan et al., 2022). Particularly, the area surrounding Venice is entirely characterized by low elevation coastal. This area is among the most hazard-prone and vulnerable on the entire Italian coast. The Venice lagoon and neighboring coastal systems present a distinctive variety of wetlands, lagoons, and nature reserves, but due to the combination of subsidence, low elevation, and the projected extreme sea level, these areas are prone to loss of ecosystem services (Furlan et al., 2022).

2.2 Modelling Tools

2.2.1 InVEST - Coastal Vulnerability Model

The Coastal Vulnerability Model (CVM) is one of the suite of models available in the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software which is a widely used model to quantify coastal vulnerability to erosion and inundation, providing a qualitative index for coastal points. Additionally, it offers summaries of human population density - or other chosen indices describing local socio-economic characteristics - in proximity to the coastline at the same scale of the produced exposure index.

It should be noted that the model does not assign a direct value to the ecosystem service of coastal protection provided by natural elements, but rather categorizes coastal tracts into low, moderate, or high-risk zones for erosion and inundation. The coastal protection role of targeted habitats can be extrapolated by observing the change in coastal exposure across scenarios (Sharp et al., 2020).

This model serves as a valuable tool for analyzing the role of natural habitats in mitigating exposure while identifying areas where coastal populations or human capital face threats. It facilitates investigations into the potential impact of management actions or changes in land use on human exposure to erosion and inundation (Sharp et al., 2020).

The construction of the Exposure Index (EI) relies on different bio-geophysical variables, including coastline geomorphology characteristics (R_G), relief (R_R), coastal habitats extent (R_H), sea-level rise projections (R_{SLR}), local bathymetry and the wind (R_{Wi}) and wave (R_{Wa}) dynamics needed for analyzing storm surge potential. To compute the EI, each of the provided inputs is qualitatively ranked from very low exposure (rank = 1) to very high exposure (rank = 5), based on methods proposed by Gornitz (1990), and Hammar-Klose and Thieler (2001). The EI is computed with the following formula:

$$EI = \sqrt[7]{R_G \cdot R_R \cdot R_H \cdot R_{SLR} \cdot R_{Wi} \cdot R_{Wa} \cdot R_S}$$

In this equation, each variable multiplies each of the ranks denoted as *R* with its corresponding indicator and takes the seventh root.

This model evaluates the exposure of each shoreline segment within the specified domain in relation to all other segments and is adaptable for exposed, heterogeneous and sheltered coastlines.

2.2.1.1 Data

InVEST's data inputs are mainly of spatial nature, therefore, we decided preliminarily on a resolution of 1000 meters for this study, this entails that the interval between the shoreline points along the coastline for which the exposure index is computed by the model is of 1000 meters. For the Digital Elevation Model input, we retrieve the global topography of Tozer et al. (2019) from OpenTopography, and the elevation averaging radius to be considered by the CVM was set at 700 meters.

To prepare the geomorphology input, as in Manno et al. (2022), we use the ISPRA 'linea di costa 2020' layer, presenting the entire Italian coastline classified in terms of geomorphological and geological settings. Relative exposure scores are then assigned in the R environment to each coastal stretch type based on natural and artificial characteristics following Sharp et al. (2020) and Manno et al. (2022) (see the SI for the detailed exposure rank assignment). We assign an exposure rank of 3 to any shore point that was not close to any segment in the geomorphology vector.

For the computation of the wind and wave exposure ranking and storm surge potential of each shoreline point, InVEST requires a map of gridded wind and wave data. Many of the existing studies that have applied the CVM (Cunha et al., 2021; Hernández-Blanco et al., 2022) have used global sample data already provided by InVEST and based on the NOAA WaveWatchIII model (Tolman, 2009). However, these sample data has two main limitations. The first limitation is that the data is not up-to-date. The second limitation concerns the lack of coverage of WWIII analyses and data for the Mediterranean Sea. For this reason, we have performed own calculations for the wind and wave data in the format required for the CV Model. We have used as our main reference the methodology laid out by Re et al. (2023) using ERA5 wind and wave data. For our analysis we have calculated the 10m u-component of wind, 10m v-component of wind, mean wave direction, significant height of combined wind waves and swell, and peak wave for the period 1993-2022 to construct a shapefile of gridded wind and wave data as requested by the InVEST CVM. The period 1993-2022 is chosen since a thirty-year period is commonly recommended in climatology for calculating climatological normals, assuming it adequately represents stable climate patterns (Brázdil et al., 2022). The maximum fetch distance was set to the default value of 12,000 meters (Sharp et al., 2020). Table 1 shows all the variables used for the Coastal Vulnerability Model, their original resolution and the source.

Variable	*Spatial resolution*	*Source*
Administrative Limits	Shapefile	GADM
Bathymetry Venice	10 m	Venice Water Authority
Digital Elevation Model	15 m	OpenTopography
Geomorphology	Shapefile	Istituto superiore per la protezione e la ricerca ambientale
Human Modification Index	1000 m	Socioeconomic Data and Applications Center
ERA5 Wind & Wave	Shapefile	Copernicus
Saltmarsh's extent	Shapefile	Geoportale Veneto
Seagrass's extent	Shapefile	Curiel et al. (2017)

Table 1: Data sources for the Coastal Vulnerability Model.

Also, we have employed JRC's Global Extreme Sea Level projections (Vousdoukas et al., 2018). Specifically, the relative sea level rise data for the year 2050 under RCP 4.5 to create the required relative sea level rise median value layer for the CV Model.

The focal elements of the model are the salt marsh and seagrass extent in the Venice lagoon (see Fig. 3). To test the extreme protection that salt marshes and seagrasses can provide against their current extension, we calculate the theoretical maximized configurations of salt marsh and seagrass extent based on their optimal bathymetry. Seagrasses display an optimal bathymetry at an interval of 0 to 4 m depth (Curiel et al., 2021), and saltmarshes range from 0 to 1 meter depth (Defina et al. (2007); Carniello et al. (2009)). These optimal bathymetries allow to use a maximum extent of both habitats without overlap. These scenarios represent only a theoretical effort to understand the maximum protection possible to coastal zones, they are not grounded on ecological viability. The related figures for these theoretical scenarios can be found in the Supporting Information.

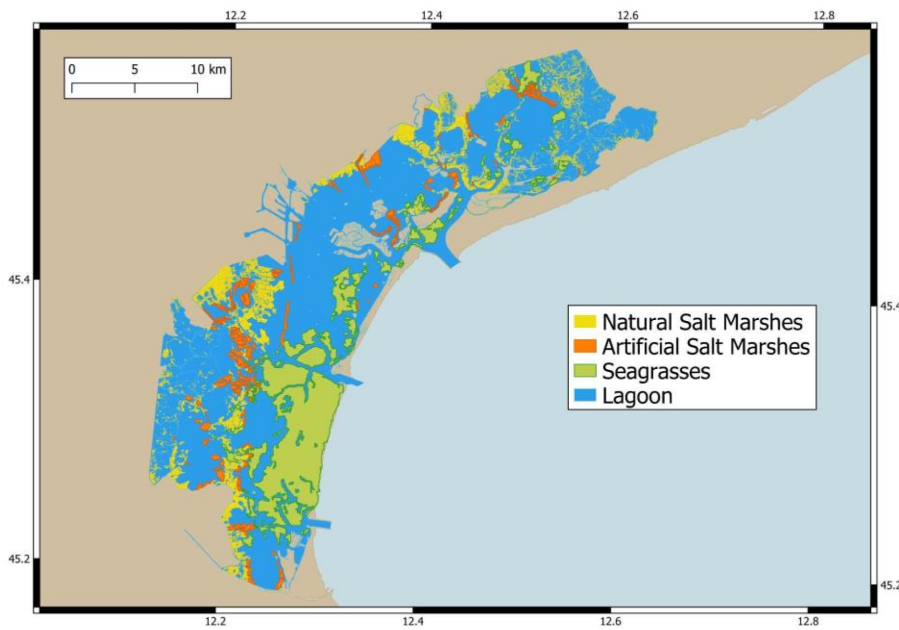


Figure 3: Natural salt marshes, artificial salt marshes, seagrasses and the lagoon extension.

One of the main inputs of the CV Model is the input habitat table. To create it, we assign a rank from 1 to 5 to each of the studied habitats, in our case to seagrasses and saltmarshes, indicating the relative coastline protection they provide. We assign a habitat protection rank of 4 to seagrasses (low protection), while saltmarshes habitat receive a rank of 2 (high protection). Additionally, seagrass habitat has a protection buffer of 500 meters, as in Sharp et al. (2020), and salt marsh habitat has a protection buffer of 300 meters, following Cunha et al. (2021).
For the human population model input, we use NASA's Global Human Modification of Terrestrial Systems data (Theobald et al., 2020). This dataset measures human modification on a 0 to 1 scale, reflecting the proportion of modified landscape at a 1 km resolution, based on various anthropogenic stressors. It accounts for population density, built-up areas and croplands based on data from 2016 (see Fig. 1). The model calculates the average human modification index within a 500-meter radius of each shoreline point. Fig. 1 depicts the degree of human modification surrounding the Venice lagoon.
Urban development near the coast contributes greatly to the high vulnerability of human infrastructure to extreme events (Cunha et al., 2021). Hence, the ecosystem service of coastal protection can be deemed more important and needed where the presence of humans and human-made infrastructure is higher.

2.2.1.2 Scenarios

We have tested the sensibility of The Exposure Index calculated by the CV Model under different scenarios, specifically by increasing the extension of seagrasses and saltmarshes in the lagoon, since the default output in InVEST already calculates the Exposure Index without habitats. The scenarios considered are based on two elements: sea-level and the extent of seagrass and salt marsh habitats. For sea level, we have included two conditions of sea level, the current sea level condition and sea level rise under a moderate emission-mitigation policy which corresponds to RCP 4.5 (Vousdoukas et al., 2018).
For the seagrass and salt marsh's habitat extent, we have considered three conditions. First, we have considered their latest available extent. The second scenario considers the maximum extent of seagrass habitat based on a theoretical optimal bathymetry, added to the current extent of salt marshes. The third condition is the current extent of seagrass habitat combined with the maximum extent of salt marsh habitat based on a theoretical optimal bathymetry. Finally, we have included the maximum extent of both seagrass' and salt marsh' habitat based on their theoretical optimal

bathymetry. The different combinations of sea-level conditions and extents of seagrass and salt marsh habitats for structuring the diverse scenarios is presented in Fig. 4. A total of 8 scenarios have been produced.

Figure 4: The eight scenarios produced by different combinations of sea-level conditions and the extent of seagrass and salt marsh habitats used in the CV model.

2.2.2 InVEST - Coastal Blue Carbon Model

The InVEST Coastal Blue Carbon (CBC) model produces spatially explicit models showing the value of coastal ecosystem services such as carbon storage and sequestration by analyzing changes in carbon storage over time and comparing them to alternative management scenarios. In this model, users are able to provide spatial data on vegetation disturbance caused by climate change and human activities. Furthermore, the CBC model can be used to determine where net carbon gains or losses occur over time. Finally, this model allows us to assess the economic value of carbon sequestration.

The CBC model is divided into two different modules in InVEST: the Coastal Blue Carbon preprocessor and the Coastal Blue Carbon. The first module generates two tables required for the second module: one table containing the carbon pools and a second one indicating whether the transition from one land use to another accumulates, disturbs or does not change the carbon content.

The inputs necessary to run the CBC model are:

1. At least 3 different snapshot years, usually a baseline year and two simulated years.
2. Biophysical table: indicating whether a transition accumulates, disturbs or does not change the carbon content.
3. Landcover transitions table: containing the carbon pool values.
4. Analysis year: should be equal or greater than the last snapshot year.

The economic valuation is optional and requires the following inputs:

1. A price table, indicating the prices at each year.
2. Discount rate.

Or as an alternative:

1. The CO_2e price at the baseline year.
2. Interest rate.
3. Discount rate.

For this study we have set the price of carbon to 91 Euros per tonnes of equivalent CO_2. To convert this price into the price of C, we have divided it by 3.76 to reflect the difference in the atomic mass between CO_2 and elemental carbon . This price is the mean price during 2023 according to Trading Economics. For the calculation of the Net Present Value (NPV) calculations, we have set a 3% discount rate and interest rate.
The NPV is a method used to determine the return on investment (ROI) for a project or expenditure. By evaluating the total anticipated financial gains from the investment and converting those returns into present-day currency value. It allows making more informed decisions about a project's viability (Gallo, 2014). The formula used by InVEST to obtain the NPV – where the NPV is denoted by *V* – is the following:

$$V = \sum_{t=0}^{T} \frac{p_t(S_t - S_{t-1})}{(1+d)^t}$$

Where:

- T is the number of years between $t_{baseline}$ and the snapshot year s. 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

Finally, the following diagram summarizes the steps we follow to obtain the two snapshot years and the future scenarios. These two inputs of the CBC model require previous preprocessing on different softwares. For the land use classification we use the Semi-Automatic Classificator plugin in QGIS 3.28.8, meanwhile to generate the future scenarios we use the Molusce plugin which works only in an older version of QGIS (QGIS 2.18).

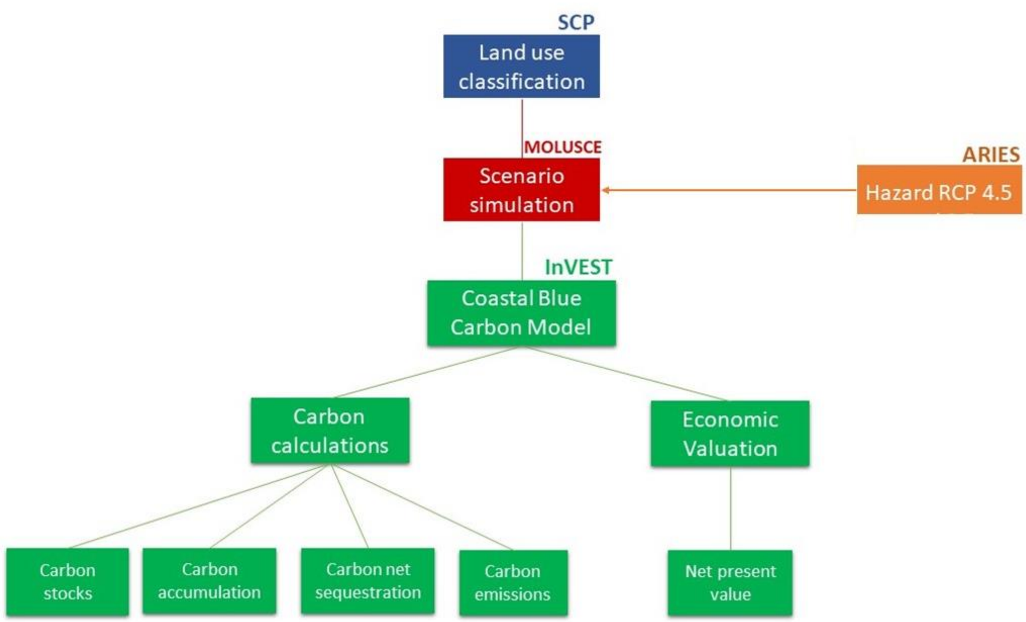


Figure 5: Diagram of the processes, softwares and outputs we follow to run the Coastal Blue Carbon Model.

2.2.2.1 Data

2.2.2.1.1 Land use land cover classification

The land use/land cover classification of the Venice area are the main inputs for the simulation of the future scenarios, and since there is no available information online on the geolocation of urban areas, non-urban areas, seagrasses and salt marshes for two different years, we decide to perform the land classification for the Venice Lagoon. We decide to classify the years 2000 and 2020 to understand the land cover changes trend in Venice over a period of time that would allow us to observe a significant change. The classification is performed in QGIS 3.28.8 using the Semi-Automatic Classification plugin (SCP). The selected pixel size for this study is 30x30 m (600 m^2) and all layers are projected to Universal Transverse Marcator (UTM) zone 33N to allow for distance calculations in meters.
The first step in the classification process is to identify satellite images with a minimal cloud coverage, in our case, we select Landsat 7 images with a cloud coverage < 10%. Once the bandset for the desired region is defined in SCP, the different samples are selected for the desired classes. For this model, the classes defined for the CBC model are:

1. Saltmarshes
2. Seagrasses
3. Water
4. Developed dry land (urban areas)
5. Undeveloped dry land (non urban areas and non blue carbon habitats).

Next, we calculate the spectral signatures of the classes, followed by running the different classification models, and then we confront them. We select the Minimum Distance classification, since it was the one yielding the highest Overall Accuracy. To eliminate the salt and pepper effect in some areas of the map we sieved it, this further increased the accuracy of the classification.
The classification results are shown in Fig. 6.

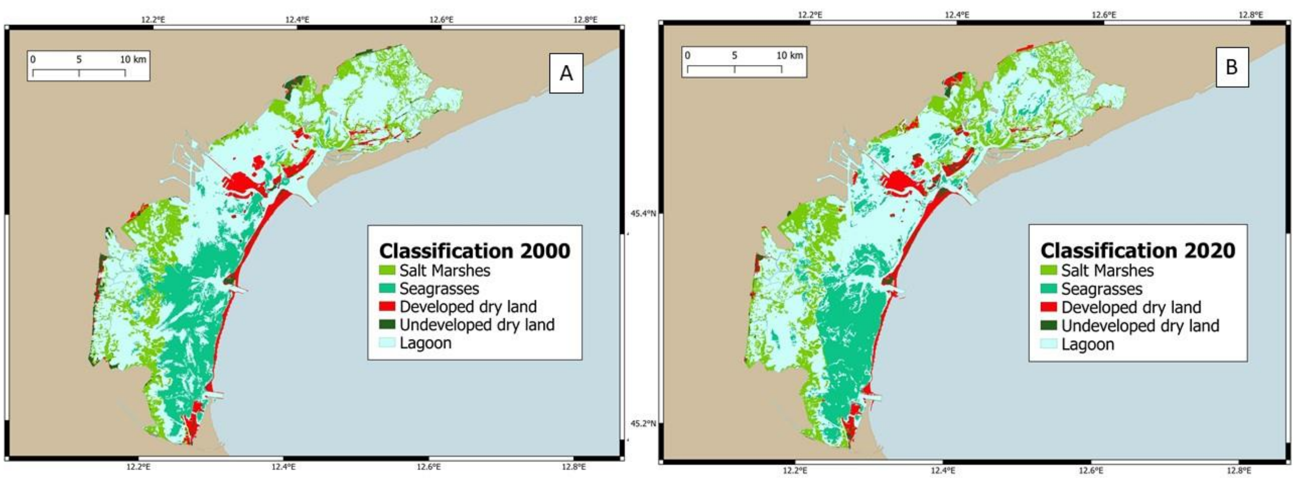


Figure 6: Land use classification performed with the Semi-Automatic Classificator in QGIS for the years A) 2000 and, B) 2020.

2.2.2.1.2 ARIES - Hazard Index

We use the Hazard layer based on RCP 4.5 in ARIES as the main layer to produce future scenarios in Molusce. This work represents one of the first examples of the employment of the coastal risk analysis application in development within the ARIES platform. Within this application, it is possible to examine exposure to coastal hazards. At the moment, it is possible to produce hazard and exposure layers.

The hazard layer in ARIES combines spatially explicit information on extreme sea levels (ESL) and elevation to determine which areas could be flooded under an extreme event and at which depth. ESL data comes in the form of regular points sampled along the coastline, presenting information on the water levels reached during an extreme event with return frequencies of 1:100 years, under baseline and Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios (Vousdoukas et al., 2018). For this study we have only considered a moderate climate change scenario which is RCP 4.5 (Thomson et al., 2011). Those points are interpolated along the coastline with the Barnes surface interpolation algorithm to produce a continuous surface. Then, a planar flooding model is employed (Kirezci et al., 2020), iteratively comparing local flood levels with the elevation of the surrounding cells using the 8-connectivity rule.

Further developments of the application will integrate the hazard and vulnerability components to develop a complete risk framework as defined in IPCC (2012). Furthermore, the hazard layer does not take into account local flood, defenses and the hydrological model employed is naive, even if generally acceptable for global scale analyses (Kirezci et al., 2020).

2.2.2.2 Scenarios

MOLUSCE is a QGIS plugin for Land Use Change Evaluation. MOLUSCE stands for *Methods Of Land Use Change Evaluation* (GIS Lab, 2014)). To produce the simulations in MOLUSCE, we implement the following steps:

1. Read in the land use categories raster for the first available year (2000), and the second year (2020), as well as the explanatory variable or factors raster. The explanatory variable used in this simulation is the Hazard layer produced in ARIES using RCP 4.5.
2. Train a model that predicts land use changes using Neural Networks.
3. Predict future land use changes using a derived model for the years 2040 (first iteration of the algorithm), and 2060 (second iteration). The iterations are calculated from the distance between the two input rasters. Since the time distance between them is 20 years, the first iteration *i* is calculated in the following way: $i_1 = 2020 + (20 \cdot 1)$, while the second iteration produces $i_2 = 2020 + (20 \cdot 2)$.

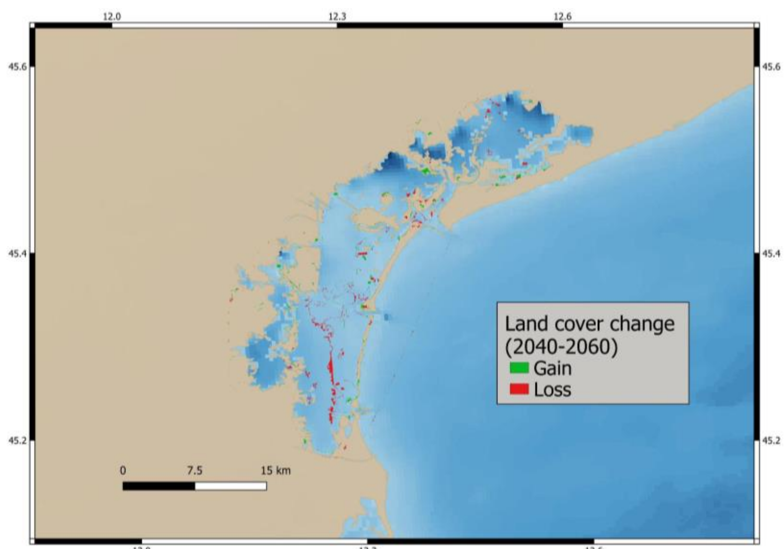


Figure 7: Gain and loss extension between the two simulated layers in Molusce for the projected years 2040 and 2060.

Following Fig. 7, it is possible to observe that seagrasses undergo most of the loss under scenario RCP 4.5, while salt marshes increase slightly their extension. The reason is that artificial salt marshes were introduced between 2000 and 2020, which were the baseline years, while there was a reduction in the seagrasses, this trend is captured in the simulations.

2.3 The Protection & Carbon Index

The Protection & Carbon Index (P&C Index) is a composite index derived from the Habitat Role Index of the CV model and the carbon stock data from the CBC model, utilizing data from both the initial and final snapshot years of the study. The process begins by standardizing the Habitat Role Index and Carbon Stock layer, ensuring that both datasets are represented on a common scale, ranging from 0 to 1.

Subsequently, interpolation is applied to the Habitat Role Index layer to create a continuous representation of the index along the Venice Lagoon. The interpolation is not uniform; it is selectively weighted by the Habitat Role Index. This weighting prioritizes the influence of habitat characteristics and their ecological significance in shaping the final P&C Index (see Fig. 8). This approach enhances the representation of the role of salt marshes and seagrasses in the protection of the coast and in its carbon stock.

In essence, the P&C Index serves as a tool for evaluating and tracking coastal protection and carbon storage capacities in coastal areas. By fusing data from two distinct models, standardizing these datasets for meaningful comparisons, and employing weighted interpolation, the index provides a nuanced view of the ecosystem's performance.

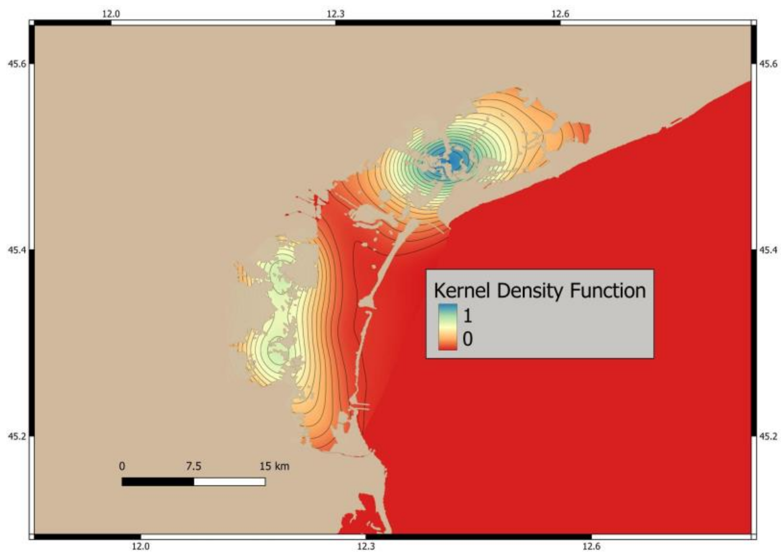


Figure 8: Normalized Kernel Density Function of the Habitat Role Index.

3 Results

3.1 Coastal Vulnerability Model

One of the primary outputs of the CV model is the habitat role (see Fig. 9), which represents the difference between the exposure index with and without seagrasses and salt marshes. There are two primary areas where the protective role of seagrasses and salt marshes along the coast is particularly evident. The first zone is located in the southwest of the lagoon, and the second zone is in the north. The city center of Venice has a habitat role of zero because there are no seagrasses or salt marshes within a 200-meter fetch distance and therefore there is no protection to floodings and erosion.

In general, the protective role of seagrasses and salt marshes does not reach a value of 1, as we have not ranked either of these habitats to provide maximum protection, the scale starts at 0 and reaches the value of 0.45.

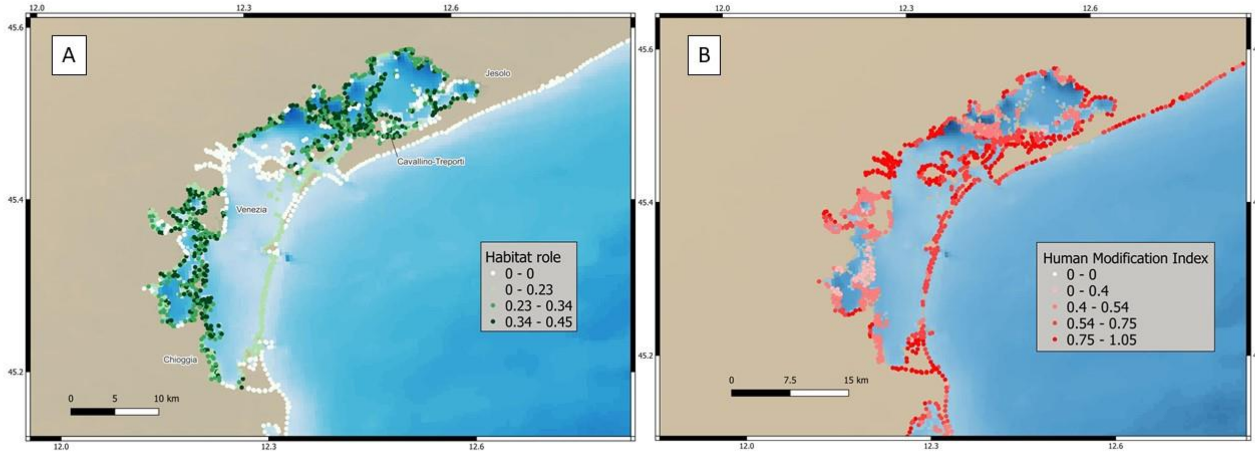


Figure 9: A) Habitat Role map. The habitat role is a measure of the protection offered by the habitats, it is calculated as the difference between the Exposure Index including seagrasses and salt marshes and the Exposure Index without those habitats for each 250 m coastline segment for the entire study area. The role of habitats is a relative measure of how mangroves reduce exposure to coastal flooding and erosion. B) Human Modification Index map.

Since the storm surge potential in the CV model is not influenced by sea level rise (Sharp et al., 2020) and the wind and wave model input remain unchanged, the presented relative risk of exposure to storm surge remains the same for all considered scenarios. We have performed a simple statistical analysis presented in Table 3 of considering all the points under the 8 scenarios shown in Fig. 4.We have included the statistics of the points with a high Human [illegible] Index, where the protective role has a higher significance.

Habitat	With Habitats				Without Habitats	With Habitats				Without Habitats
1–Very low	-	-	-	-	-	-	-	-	-	-
2–Low	109	113	121	123	87	142	144	146	147	114
3–Moderate	204	207	195	199	216	231	232	231	231	250
4–High	105	98	102	96	114	46	43	42	41	55
5–Very high	3	3	3	3	4	2	2	2	2	2

Table 2: Distribution of Exposure Index values across the considered scenarios, with and without habitats, for the coastal points with a high human land modification index (greater than or equal to 0.8). SG stands for seagrasses and SM for saltmarshes. The = sign indicates no modification in the extension of that ecosystem, while a + sign indicates increased extension of that ecosystem.

	No SLR				**SLR**			
Habitat Role Statistics	**= SG = SM**	**= SG + SM**	**+ SG = SM**	**+ SG + SM**	**= SG = SM**	**= SG + SM**	**+ SG = SM**	**+ SG + SM**
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	0.45	0.45	0.45	0.45	0.35	0.35	0.35	0.36
Mean	**0.06**	0.09	0.09	0.10	**0.05**	0.07	0.07	0.08
Std. Dev.	0.12	0.14	0.12	0.13	**0.09**	0.10	**0.09**	0.10

Table 3: Habitat Role statistics calculated for the coastal points with a high human land modification index (greater than or equal to 0.8).

3.2 Coastal Blue Carbon

The Coastal Blue Carbon model provides calculations of the carbon stock, carbon accumulation, total net carbon sequestration and the net present value, as presented in Table 4. In column 3 of the table, we have calculated the net change from the previous period, if available, for the same type of calculation. We can observe from this table that there is a decreasing growth – the carbon stock almost halves between the two studied periods – in the carbon stock between 2040 and 2060 in contrast to the previous period (2020-2040). We also observe that the carbon accumulation percentage is negative in the second period. The next calculation is the total net carbon sequestration. In InVEST, the total net carbon sequestration for the second period is not provided in the outputs, but it can be easily calculated by subtracting the total of both periods, minus the first period. We have also calculated the net change in %, where we observe a drastic reduction in the total net carbon sequestration – which is given by subtracting the emissions from the sequestration. We observe a reduction of 17% in the total net carbon sequestration during the second period.

Measure and period	*Value*	*% net change from previous period*	*Unit of measurement*
Carbon stock (2020)	16,243,438	-	Mt C
Carbon stock (2040)	24,247,547	49%	Mt C
Carbon stock (2060)	30,849,071	27%	Mt C
Carbon accum. (2020-2040)	8,004,109	-	Mt C
Carbon accum. (2040-2060)	7,621,084	-5%	Mt C
Net carbon sequestration (2020 -2040)	8,004,109	-	Mt C
Net carbon sequestration (2040 -2060)	6,601,510	-17%	Mt C
Net carbon sequestration (2020 -2060)	14,605,620	-	Mt C
Net present value (2040)	14,218,789,376	-	Euros
Net present value (2060)	51,891,905,125	27%	Euros

Table 4: Total values of the CBC Model outputs for the entire Venice lagoon. All values were divided by a factor of 3.76 to convert from CO_2e to C values.

3.3 Protection & Carbon Index

The Protection & Carbon Index (P&C Index) measures the degree to which coastal protection and carbon is stocked and by combining these two indices we get a measure of the combined provision of these services by seagrasses and saltmarshes in the Venice lagoon for two different years, 2020 and 2060. We observe that seagrasses have a lower P&C Index located in the southeast of the lagoon. Meanwhile, saltmarshes offer a higher P&C Index due to a higher carbon stock and coastal protection from flooding and erosion. The highest P&C Index can be observed in the northern of the lagoon.

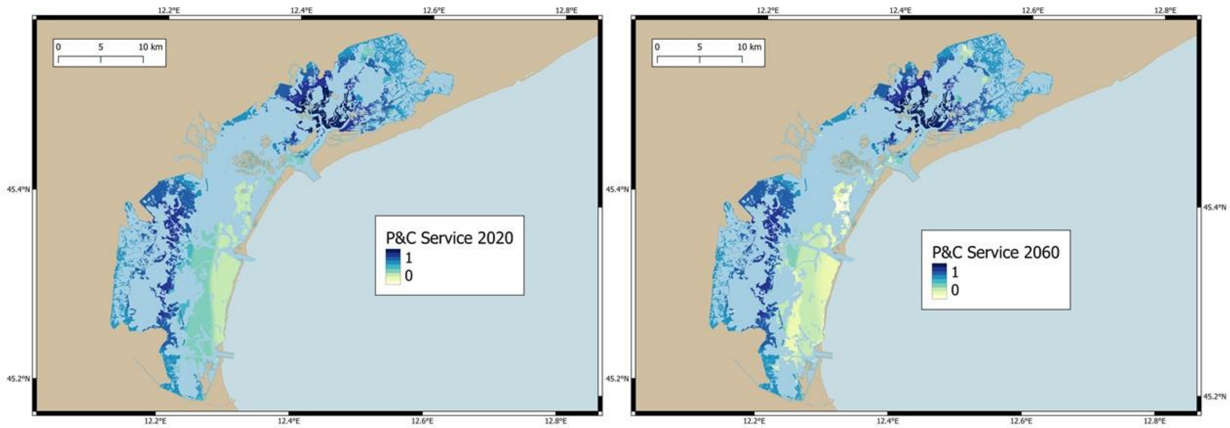


Figure 10: The P&C Index Map for the years 2020, which is the beginning of the studied period and 2060, which is the last year of the study.

The distinctions between both years are subtly depicted in , hence, we perform an analysis of the variations in P&C Index between 2020 and the projected year 2060. As illustrated in Fig. 10, the decline in seagrass habitats over this period impacts the provisioning of ecosystem services within the lagoon, even under a moderate disturbance scenario such as RCP 4.5.

Notably, the P&C's Index overall mean is negative, with the negative values outweighing the positive ones when considering the sum of pixels. This indicates a net decline in habitat service provisioning over time, emphasizing the growing challenges faced by coastal ecosystems in their roles as carbon reservoirs and protectors against flooding and erosion.

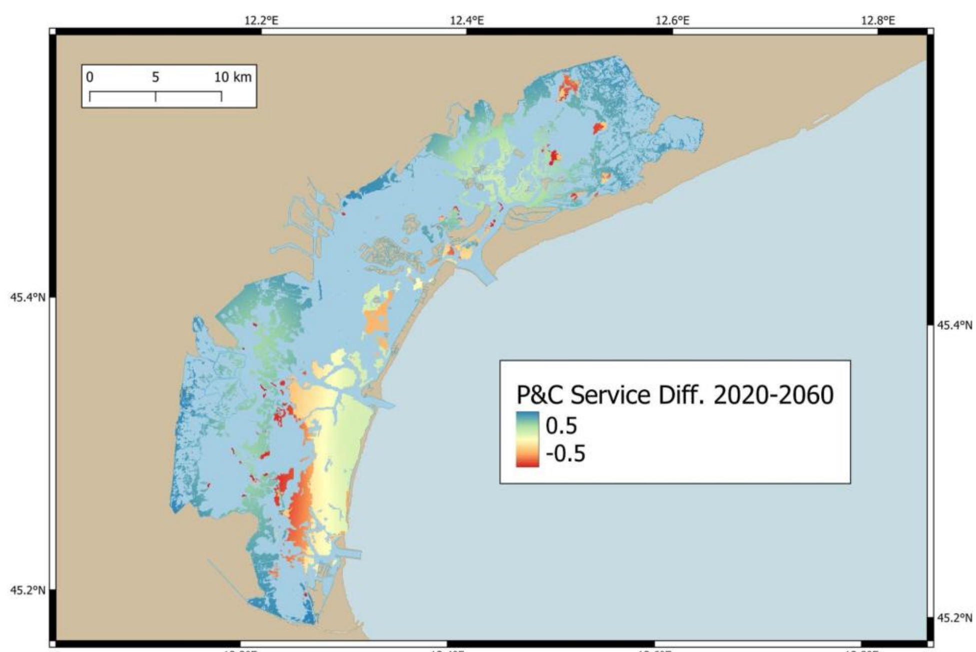


Figure 11: The difference between the P&C Index in the year 2020 and the year 2060. The total sum of pixels is equal to -9130 and the mean value is -0.004, indicating a general decrease in the P&R index across the lagoon, even with a small disturbance.

4 Discussion

In this discussion, we delve into the methodological insights of our study, shedding light on the intricate relationship between coastal habitat dynamics and the provisioning of vital ecosystem services in the context of climate change, sea-level rise, and human impacts. The present study presents a unique opportunity to unravel the technical intricacies of the InVEST Coastal Vulnerability Model and the Coastal Blue Carbon Model application, often overlooked in previous applications. Here, we provide a comprehensive methodological framework that could serve as a valuable guide for future applications.

One of the salient observations of our study relates to the pronounced impact of current habitats when considering the 2050 Relative Sea Level Rise (RSLR) scenario using RCP 4.5. Notably, the integration of habitats into this scenario results in a significant reduction in the number of coastal points classified in exposure classes 4 and 5. This finding highlights the crucial role of coastal ecosystems in mitigating the risks associated with rising sea levels.

Furthermore, our study underscores the nuanced interplay between seagrasses and salt marshes concerning their coastal protection role. In scenarios with 2050 RSLR45, seagrasses emerge as prominent contributors to coastal protection, outperforming salt marshes. However, in scenarios without sea-level rise input data, salt marshes exhibit a more substantial coastal protection role. This dynamic underscores the context-dependent nature of ecosystem services, influenced by changing environmental conditions. On the other hand, the carbon stock provided by salt marshes is also higher than that provided by seagrasses, thus, the P&C Index is much higher for salt marshes.

One of the main findings from our study is the distribution of coastal protection services, particularly in areas highly vulnerable to erosion and inundation. Notably, regions of significant human land modification and dense human assets, such as Venice's historic center, Porto Marghera's industrial hub, and Murano, receive minimal coastal protection from vegetation. This deficiency is closely linked to the historical human-induced habitat degradation and removal in these areas. Thus, the places most in need of coastal protection receive the least, underscoring the need for targeted restoration and conservation efforts.

It is also worth noting that our study adopts a simplified carbon model, assuming a flat distribution of carbon across the lagoon with uniform values for seagrasses and salt marshes. While this simplification may not capture the full carbon complexity, it provides a valuable starting point for further investigation into carbon dynamics within coastal ecosystems.

In an effort to enhance the precision of the Habitat Role Index across the lagoon, we introduce a Kernel Density Function weighted by the index. This approach offers a gradual decline from the data points, offering a more nuanced perspective on the ecological significance of different habitat areas compared to buffering of the points and then create single polygons for overlapping points as introduced by Hernández-Blanco et al. (2022)

Our study offers insights into the relationships between coastal habitats, sea-level rise, and ecosystem services and offers a methodological blueprint for future combined InVEST applications. It underscores the dynamic nature of habitat roles, and the importance of tailored restoration efforts in vulnerable areas. As we continue to grapple with climate change and environmental degradation, these insights will be pivotal in designing effective strategies for coastal protection and conservation.

5 Conclusions

The results of our study provide valuable insights into the coastal dynamics of the Venice lagoon, emphasizing the pivotal role of seagrasses and salt marshes in mitigating coastal vulnerability and carbon sequestration. We discuss the key findings of each modeling component and their implications.

The Coastal Vulnerability Model (CV) yielded significant insights into the protective role of seagrasses and salt marshes along the Venice lagoon's coastline. Two primary zones, one in the southwest and another in the north, emerged as areas where these habitats reduce exposure to flooding and erosion. However, the absence of these habitats in Venice's city center underscores the vulnerability of this historic area to natural hazards.

It's worth noting that the protective role of seagrasses and salt marshes did not reach a maximum value of 1 considering their protective role against other ecosystems such as mangroves which offer a higher protection against flooding and erosion.
Despite changes in sea-level rise scenarios, the relative risk of exposure to storm surge remained consistent across all scenarios, underscoring the robustness of the CV model's results.
The Coastal Blue Carbon model offered some insights into carbon dynamics within the Venice lagoon under RCP 4.5. Notably, our study revealed a notable decrease net carbon sequestration between 2040 and 2060, we observe a drastic reduction of 46% during the second period. This reduction is attributed to changes in emissions and sequestration, emphasizing the importance of monitoring and managing carbon dynamics in coastal ecosystems.
The Net Present Value (NPV) analysis, which assesses the return on investment for carbon sequestration, provides a useful economic perspective on the value of carbon in these ecosystems. The NPV results suggest the potential financial benefits of carbon management efforts in the Venice lagoon, whose overall value increases by 26% notwithstanding the loss of seagrases.
The main result of this study is the P&C Index which combined provision of carbon storage and coastal protection by seagrasses and saltmarshes in the Venice lagoon for two different years, 2020 and 2060. The index results showcased variations in habitat service provisioning, with salt marshes exhibiting a higher P&C Index due to their superior carbon stock and coastal protection capabilities.
However, seagrasses played a vital role, particularly in the southeast of the lagoon, emphasizing their importance in supporting ecosystem services. The northern region of the lagoon stood out as a hotspot for habitat services.
Despite relatively subtle differences in the P&C Index between 2020 and 2060, a more detailed analysis revealed that the loss of seagrasses significantly impacted habitat service provisioning, even under a moderate disturbance scenario (RCP 4.5).
In conclusion, our study highlights the ecological and economic importance of seagrasses and salt marshes in the Venice lagoon. These habitats play a critical role in coastal protection, carbon sequestration, and financial value. These findings underscore the need for informed conservation and restoration efforts to enhance the resilience and sustainability of coastal ecosystems in the face of environmental changes and human impacts. Moreover, our study provides valuable insights and a comprehensive understanding of the interplay between habitats, climate change, and ecosystem services, which can guide future conservation and management strategies for the Venice lagoon and similar coastal regions.

6 Bibliography

Arkema, K. K., Guannel, G., Verutes, G., Wood, S. A., Guerry, A., Ruckelshaus, M., Kareiva, P., Lacayo, M., & Silver, J. M. (2013). Coastal habitats shield people and property from sea-level rise and storms. *Nature Climate Change*, *3*(10), 913–918.

Balbi, S., Bagstad, K. J., Magrach, A., Sanz, M. J., Aguilar-Amuchastegui, N., Giupponi, C., & Villa, F. (2022). The global environmental agenda urgently needs a semantic web of knowledge. *Environmental Evidence*, *11*(1), 5. https://doi.org/10.1186/s13750-022-00258-y

Barbier, E. B. (2011). *Capitalizing on nature: Ecosystems as natural assets*. Cambridge University Press.

Barbier, E. B. (2013). Valuing ecosystem services for coastal wetland protection and restoration: Progress and challenges. *Resources*, *2*(3), 213–230.

Bonaldo, D., Antonioli, F., Archetti, R., Bezzi, A., Correggiari, A., Davolio, S., De Falco, G., Fantini, M., Fontolan, G., Furlani, S., & others. (2019). Integrating multidisciplinary instruments for assessing coastal vulnerability to erosion and sea level rise: Lessons and challenges from the Adriatic Sea, Italy. *Journal of Coastal Conservation*, *23*, 19–37.

Brázdil, R., Zahradníček, P., Dobrovolnỳ, P., Řehoř, J., Trnka, M., Lhotka, O., & Štěpánek, P. (2022). Circulation and climate variability in the Czech Republic between 1961 and 2020: A comparison of changes for two "normal" periods. *Atmosphere*, *13*(1), 137.

Cabral, P., Augusto, G., Akande, A., Costa, A., Amade, N., Niquisse, S., Atumane, A., Cuna, A., Kazemi, K., Mlucasse, R., & others. (2017). Assessing Mozambique's exposure to coastal climate hazards and erosion. *International Journal of Disaster Risk Reduction*, *23*, 45–52.

Carniello, L., Defina, A., & D'Alpaos, L. (2009). Morphological evolution of the Venice lagoon: Evidence from the past and trend for the future. *Journal of Geophysical Research: Earth Surface*, *114*(F4).

Costanza, R., Pérez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., & Mulder, K. (2008). The value of coastal wetlands for hurricane protection. *Ambio*, 241–248.

Cunha, J., Cardona, F. S., Bio, A., & Ramos, S. (2021). Importance of protection service against erosion and storm events provided by coastal ecosystems under climate change scenarios. *Frontiers in Marine Science*, *8*, 726145.

Defina, A., Carniello, L., Fagherazzi, S., & D'Alpaos, L. (2007). Self-organization of shallow basins in tidal flats and salt marshes. *Journal of Geophysical Research: Earth Surface*, *112*(F3).

Fogarin, S., Zanetti, M., Dal Barco, M., Zennaro, F., Furlan, E., Torresan, S., Pham, H., & Critto, A. (2023). Combining remote sensing analysis with machine learning to evaluate short-term coastal evolution trend in the shoreline of Venice. *Science of The Total Environment*, *859*, 160293.

Furlan, E., Derepasko, D., Torresan, S., Pham, H. V., Fogarin, S., & Critto, A. (2022). Ecosystem services at risk in Italy from coastal inundation under extreme sea level scenarios up to 2050: A spatially resolved approach supporting climate change adaptation. *Integrated Environmental Assessment and Management*, *18*(6), 1564–1577.

Gallo, A. (2014). A refresher on net present value. *Harvard Business Review*, *19*, 1–6.

GIS Lab. (2014). *Landscape change analysis with MOLUSCE - methods and algorithms—GIS-Lab*. https://wiki.gis-lab.info/w/Landscape_change_analysis_with_MOLUSCE_-_methods_and_algorithms

Gornitz, V. (1990). Vulnerability of the East Coast, USA to future sea level rise. *Journal of Coastal Research*, 201–237.

Guerry, A., Silver, J., Beagle, J., Wyatt, K., Arkema, K., Lowe, J., Hamel, P., Griffin, R., Wolny, S., Plane, E., & others. (2022). Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise. *Npj Urban Sustainability*, *2*(1), 13.

Hammar-Klose, E. S., & Thieler, E. R. (2001). *Coastal vulnerability to sea-level rise: A preliminary database for the US Atlantic, Pacific, and Gulf of Mexico coasts*. US Geological Survey,.

Hernández-Blanco, M., Moritsch, M., Manrow, M., & Raes, L. (2022). Coastal ecosystem services modeling in Latin America to guide conservation and restoration strategies: The case of mangroves in Guatemala and El Salvador. *Frontiers in Ecology and Evolution*, *10*, 843145.

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S., Marzeion, B., Fettweis, X., Ionescu, C., & Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, *111*(9), 3292–3297.

IPCC. (2022). *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157964

Kirezci, E., Young, I. R., Ranasinghe, R., Muis, S., Nicholls, R. J., Lincke, D., & Hinkel, J. (2020). Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Scientific Reports*, *10*(1), 11629.

Kumar, L., & Taylor, S. (2015). Exposure of coastal built assets in the South Pacific to climate risks. *Nature Climate Change*, *5*(11), 992–996.

Lionello, P., Barriopedro, D., Ferrarin, C., Nicholls, R. J., Orlic, M., Raicich, F., Reale, M., Umgiesser, G., Vousdoukas, M., & Zanchettin, D. (2020). Extremes floods of Venice: Characteristics, dynamics, past and future evolution. *Natural Hazards and Earth System Sciences Discussions*, *2020*, 1–34.

Maldonado, J. H., Sánchez, R. del P. M., Morales, M. E. V., Henao, J. P. H., Tarazona, Y. G., Compeán, R. G., & Schling, M. (2020). *Innovation in economic analysis and evaluation approaches for coastal protection and restoration investments in the Caribbean*.

Manno, G., Azzara, G., Lo Re, C., Martinello, C., Basile, M., Rotigliano, E., & Ciraolo, G. (2022). An Approach for the Validation of a Coastal Erosion Vulnerability Index: An Application in Sicily. *Journal of Marine*

Science and Engineering, *11*(1), 23.

Munaretto, S. (2011). *Governing water and environment in times of climate change: The case of the Venice lagoon*.

Pesce, M., Critto, A., Torresan, S., Giubilato, E., Pizzol, L., & Marcomini, A. (2019). Assessing uncertainty of hydrological and ecological parameters originating from the application of an ensemble of ten global-regional climate model projections in a coastal ecosystem of the lagoon of Venice, Italy. *Ecological Engineering*, *133*, 121–136.

Ravera, O. (2000). The Lagoon of Venice: The result of both natural factors and human influence. *Journal of Limnology*, *59*(1), 19–30.

Re, A., Minola, L., & Pezzoli, A. (2023). Climate Scenarios for Coastal Flood Vulnerability Assessments: A Case Study for the Ligurian Coastal Region. *Climate*, *11*(3), 56.

Sarretta, A., Pillon, S., Molinaroli, E., Guerzoni, S., & Fontolan, G. (2010). Sediment budget in the Lagoon of Venice, Italy. *Continental Shelf Research*, *30*(8), 934–949.

Settis, S. (2016). *If Venice Dies*. New Vessel Press.

Sharp, R., Douglass, J., Wolny, S., Arkema, K., Bernhardt, J., Bierbower, W., Chaumont, N., Denu, D., Fisher, D., Glowinski, K., & others. (2020). InVEST 3.8. 7. User's Guide. *The Natural Capital Project, Standford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund: Standford, CA, USA*.

Sutton-Grier, A. E., Wowk, K., & Bamford, H. (2015). Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy*, *51*, 137–148.

Theobald, D. M., Kennedy, C., Chen, B., Oakleaf, J., Baruch-Mordo, S., & Kiesecker, J. (2020). Earth transformed: Detailed mapping of global human modification from 1990 to 2017. *Earth System Science Data*, *12*(3), 1953–1972.

Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M. A., Clarke, L. E., & Edmonds, J. A. (2011). RCP4.5: A pathway for stabilization of radiative forcing by 2100. *Climatic Change*, *109*(1), 77. https://doi.org/10.1007/s10584-011-0151-4

Tolman, H. L. (2009). User manual and system documentation of WAVEWATCH III TM version 3.14. *Technical Note*, *MMAB Contribution*, *276*(220).

Tozer, B., Sandwell, D. T., Smith, W. H., Olson, C., Beale, J., & Wessel, P. (2019). Global bathymetry and topography at 15 arc sec: SRTM15+. *Earth and Space Science*, *6*(10), 1847–1864.

UNESCO. (2006). *Venice and its Lagoon – UNESCO Site*. https://www.veniceandlagoon.net/web/en/unesco_site/

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P., & Feyen, L. (2018). Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nature Communications*, *9*(1), 2360.

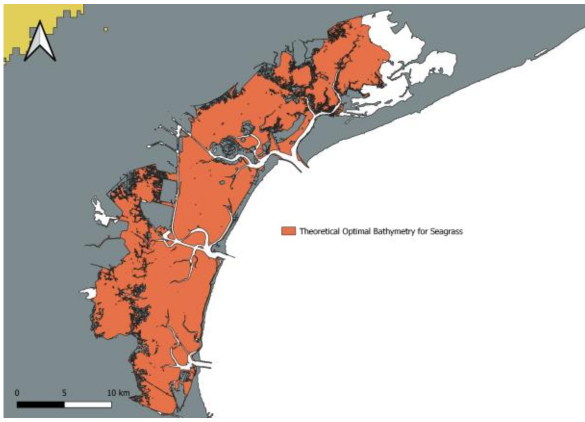
Zanchettin, D., Bruni, S., Raicich, F., Lionello, P., Adloff, F., Androsov, A., Antonioli, F., Artale, V., Carminati, E., Ferrarin, C., & others. (2021). Sea-level rise in Venice: Historic and future trends. *Natural Hazards and Earth System Sciences*, *21*(8), 2643–2678.

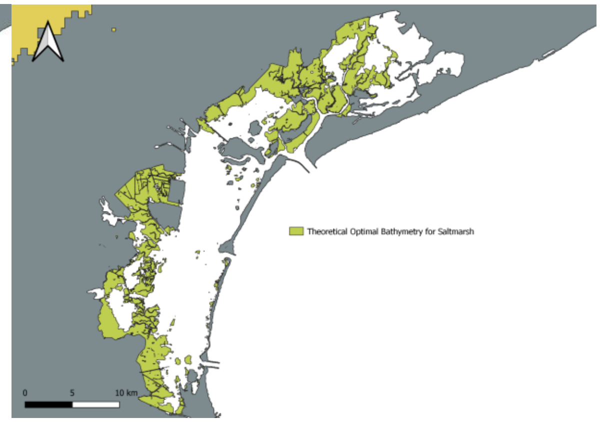
7 Supplementary Information

SI.1: Geomorphology rank assignment, representing the relative exposure of the particular segment of coastline.

Coastal features (natural and/or artificial)	Assigned Rank
Alta Rocciosa	1
Altro (lidi, pontili, ecc.)	3
Bassa Ciottolosa	4
Bassa	5
Bassa Rocciosa	4
Bassa Sabbiosa	5
Bassa Sabbiosa con massi	5
Collegamento colmata	3
Collegamento foce del fiume	5
Collegamento laguna	4
Collegamento opera	3
Collegamento opere portuali	3
Collegamento sponde del fiume	4
Colmata	3
Opere di difesa costiera	2
Opere Portuali	2
Sponde del fiume	4

SI.2: Theoretical optimal bathymetry of seagrasses (upper-left) and saltmarshes (upper-right) and Ideal maximized extent of seagrasses (bottom-left) and saltmarshes (bottom-right) in the VL.





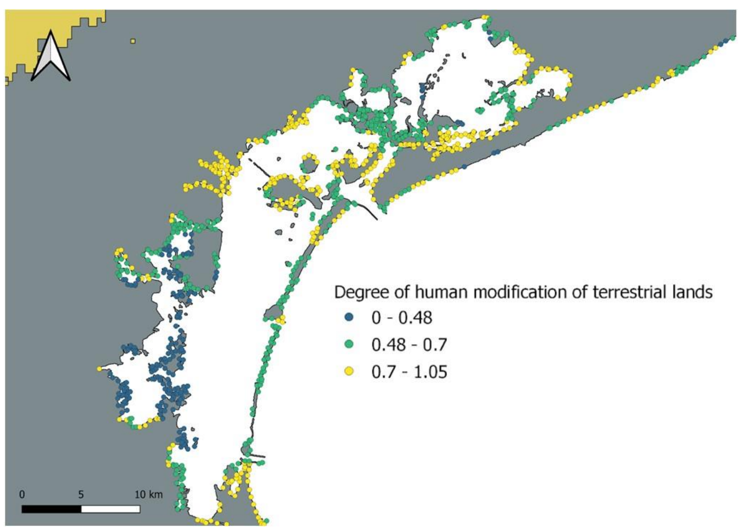
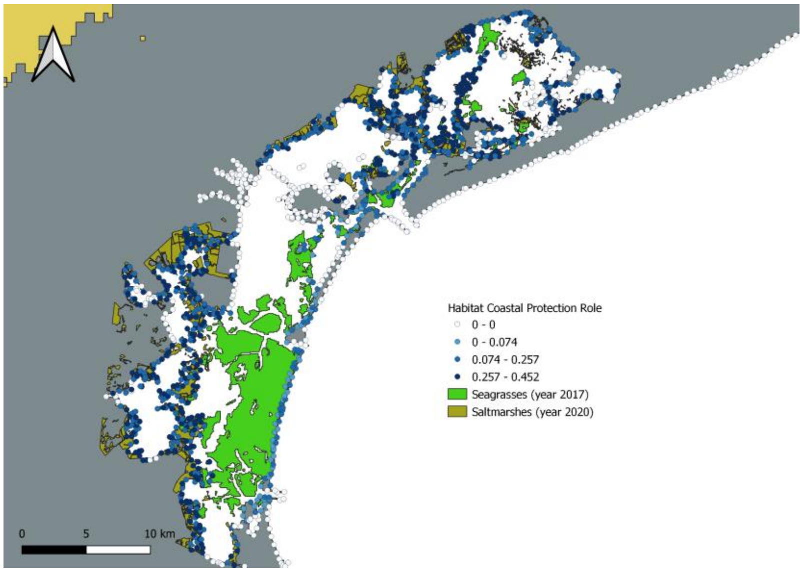
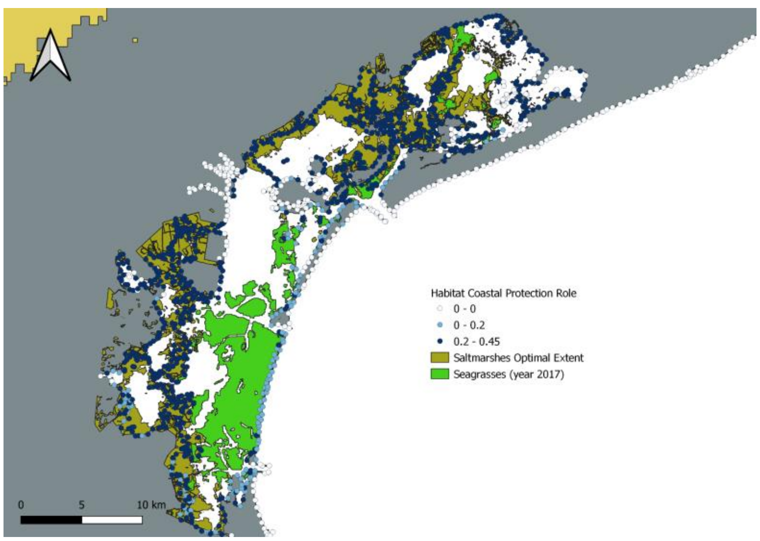


Figure 10: Degree of human modification of terrestrial lands across the AOI.

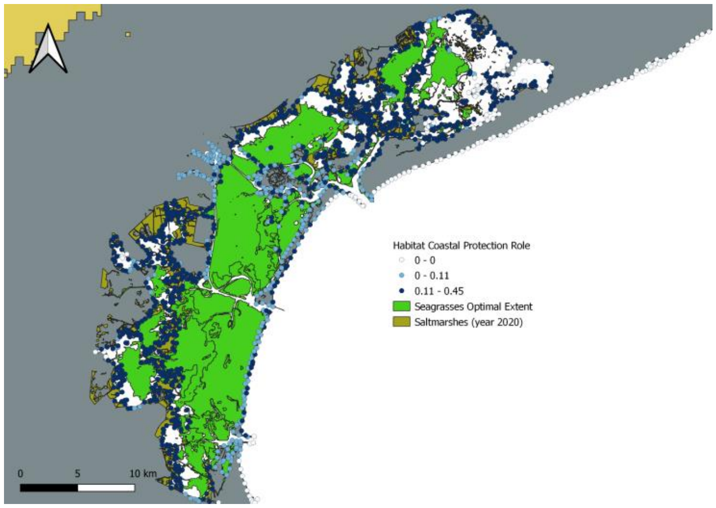
SI.3: Habitats coastal protection role of Current Sea Level conditions (No SLR input) + Current Habitats Scenario



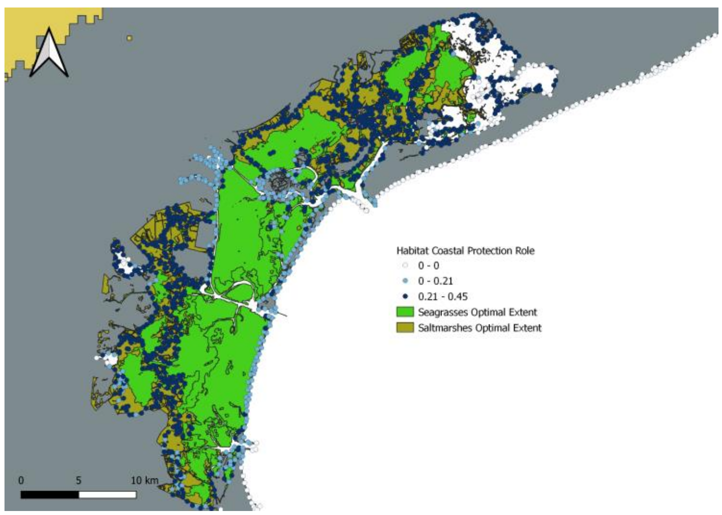
SI.4: Habitat coastal protection role Current Sea Level conditions (No SLR input) + Current Seagrass Habitat and Augmented Saltmarsh Habitat Scenario



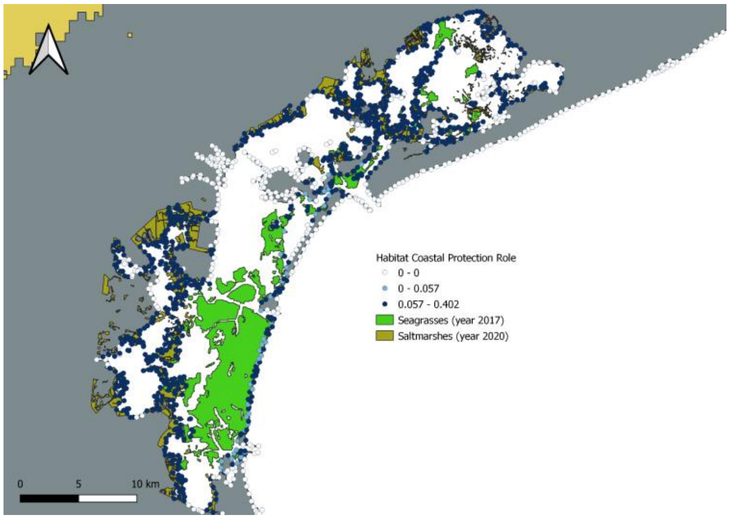
SI.5: Habitat coastal protection role Scenario No SLR - Augmented Seagrass Habitat and Current Saltmarsh Habitat



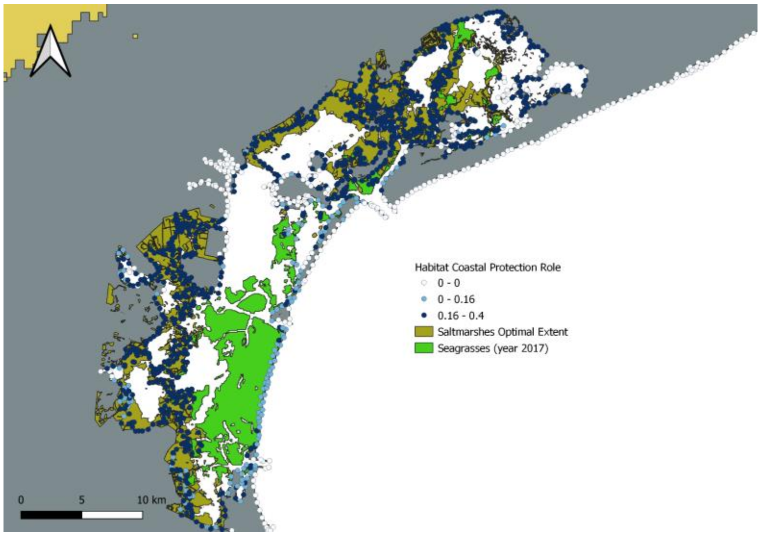
SI.6: Habitat coastal protection role Scenario No SLR - Augmented Seagrass Habitat and Augmented Saltmarsh Habitat



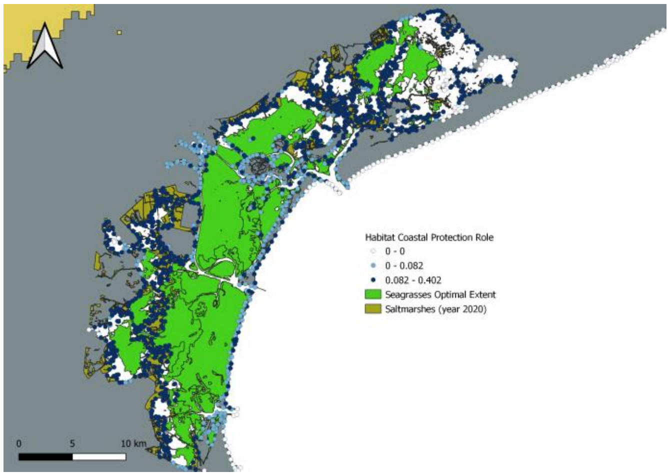
SI.7: Habitat coastal protection role Scenario RSLR 4.5 year 2050 - Current Habitats



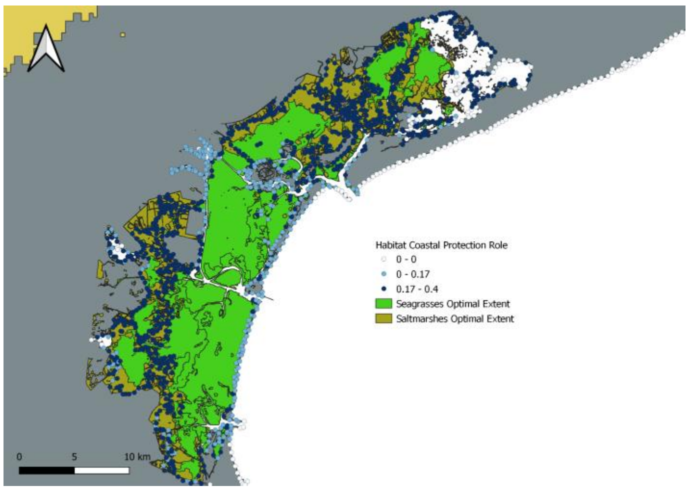
SI.8: Habitat coastal protection role Scenario RSLR 4.5 year 2050 - Current Seagrass Habitat and Augmented Saltmarsh Habitat



SI.9: Habitat coastal protection role Scenario RSLR 4.5 year 2050 - Augmented Seagrass Habitat and Current Saltmarsh Habitat



SI.10: Habitat coastal protection role Scenario RSLR 4.5 year 2050 - Augmented Seagrass Habitat and Augmented Saltmarsh Habitat



SI.11: Relative risk of exposure to storm surge for the Venice Lagoon Coastal Areas.

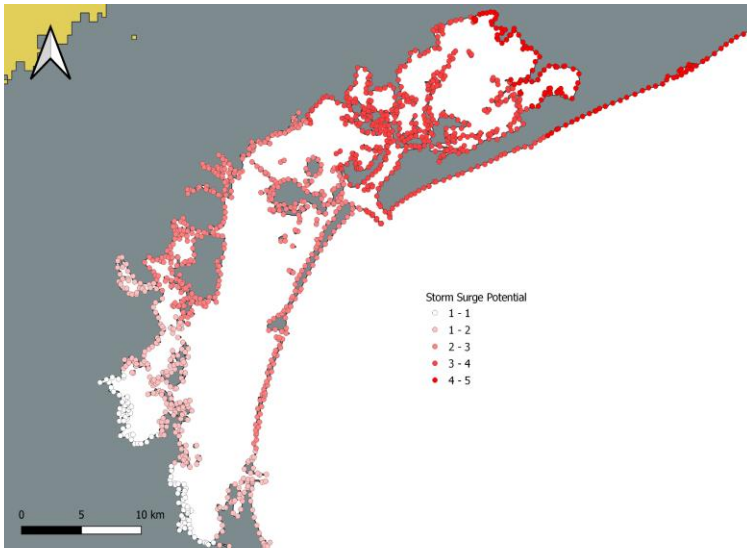
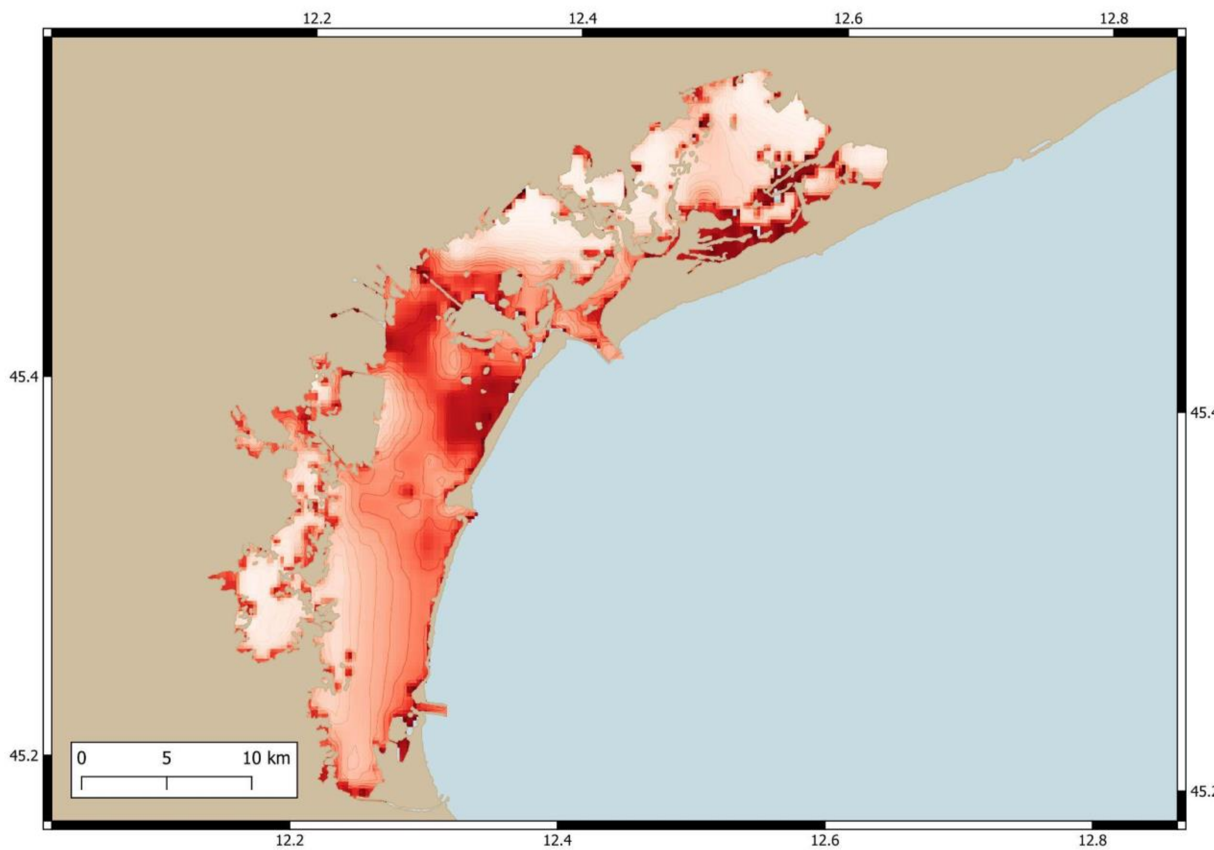


Figure 11: Relative risk of exposure to storm surge for the Venice Lagoon Coastal Areas.

SI.13: Hazard Risk Layer computed in ARIES using future scenario RCP 4.5.



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