

MESTRADO EM CIÊNCIAS DO MAR – RECURSOS MARINHOS
BIOLOGIA E ECOLOGIA MARINHAS

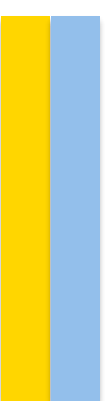
Climate change vulnerability
Assessment of Coastal Marine Habitats
on the Northern Coast of Portugal
Óscar Babé Gomez

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INSTITUTO DE CIÊNCIAS BIOMÉDICAS ABEL SALAZAR



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Matosinhos, 26 de setembro de 2024

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Climate change vulnerability Assessment of Coastal Marine Habitats on the Northern Coast of Portugal

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Abstract

Marine forests are vital components of coastal ecosystems, providing numerous ecological benefits and supporting a multitude of marine species. However, these systems are increasingly threatened by climate change and other anthropogenic stressors, which can lead to population instability, distribution changes, and significant mortality events. This research aimed to assess the vulnerability of intertidal marine forests along the northern Portuguese coast to the impacts of climate change. Through a combination of species distribution data, environmental monitoring, and ecological modelling, we identified areas of critical vulnerability. Our analysis demonstrated that environmental variables significantly influence the presence of brown seaweed, with specific factors such as platform width and elevation having notable positive effects, while other variables showed little to no impact. Furthermore, we projected future habitat changes under various sea-level rise scenarios, revealing substantial potential losses in suitable habitat for brown seaweeds. These findings highlight the urgent need for conservation strategies to mitigate the impacts of climate change on these essential marine ecosystems and to safeguard their ecological functions.

Keywords: marine forests, brown seaweeds, intertidal habitats, climate change

Resumo

As florestas marinhas são componentes vitais dos ecossistemas costeiros, proporcionando numerosos benefícios ecológicos e sustentando uma multitude de espécies marinhas. No entanto, estes sistemas estão cada vez mais ameaçados pelas alterações climáticas e outros fatores antropogénicos, que podem levar à instabilidade populacional, alterações na distribuição e a eventos de mortalidade significativos. Esta investigação teve como objetivo avaliar a vulnerabilidade das florestas marinhas intertidais ao longo da costa norte de Portugal face aos impactos das alterações climáticas. Através de uma combinação de dados sobre distribuição de espécies, monitorização ambiental e modelagem ecológica, identificámos áreas críticas de vulnerabilidade. A nossa análise demonstrou que variáveis ambientais influenciam significativamente a presença de algas castanhas, com fatores específicos, como a largura da plataforma e a elevação, a apresentarem efeitos positivos notáveis, enquanto outras variáveis mostraram pouco ou nenhum impacto. Além disso, projetámos futuras alterações de habitat sob vários cenários de subida do nível do mar, revelando perdas potenciais substanciais no habitat adequado para algas castanhas. Estes resultados destacam a necessidade urgente de estratégias de conservação para mitigar os impactos das alterações climáticas sobre estes ecossistemas marinhos essenciais e para proteger as suas funções ecológicas.

Palavras-chave: florestas marinhas, algas castanhas, habitats intertidais, alterações climáticas

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1. Introduction

The northern coast of Portugal is home to a biodiverse marine ecosystem, enriched by nutrient-rich upwellings, and serves as a vital resource for both the fishing industry and tourism. Here, *Sabellaria* reefs and mussel and barnacle assemblages dominate the intertidal of the most exposed shores, while fucoids (i.e., *Ascophyllum nodosum*, *Fucus* spp.) are found in more sheltered rock-shores (Boaventura et al., 2002; Hawkins et al., 2019). These foundation seaweeds not only provide a crucial habitat for a wide variety of marine species but also play a critical role in regulating the nutrient cycle and absorbing oceanic CO₂, thus contributing to climate change mitigation. However, these species are particularly vulnerable to several stressors. Climate change, with rising sea water levels and temperatures and ocean acidification, along with coastal pollution and other local stressors, pose imminent threats to their survival.

The objective of this research is to test the viability of using remote sensing techniques for mapping intertidal fucoid-dominated marine forests and to assess their vulnerability to climate change on the northern coast of Portugal, including the identification of critical vulnerability areas. The methodology involves the collection and analysis of environmental and species distribution data, utilizing ecological models and geospatial mapping tools.

The findings will enable the identification of areas with the highest vulnerability among marine habitats and also identify Climate Change refuge areas, providing essential information for the sustainable management of marine resources and the conservation of coastal biodiversity. Furthermore, this research aims to raise awareness of the urgent need to address climate change and its impacts on the marine ecosystem, thereby contributing to its protection and preservation.

1.1 Marine forests in Portugal

Brown seaweeds, mainly belonging to the genus Laminariales and Fucales, are the dominant habitat-engineers in cold-temperate waters (fig.1). These diverse and productive systems are found worldwide, occupying both intertidal and subtidal environments (Steneck et al., 2002).

In Portugal, fucoids dominate intertidal rocky shores, forming extensive canopies, and playing a fundamental role in supporting coastal ecosystems. These species can significantly modify local habitats, impacting their structure and function (Steneck, 2002). Fucoids foster the formation of complex three-dimensional biogenic habitats, thereby increasing associated biodiversity (Dayton, 1985; Duggins et al., 1989). They are also often

used as a substrate by sessile organisms (Dunton & Schell, 1987), and provide habitat and nursery grounds for a variety of species, offering shelter and food for numerous pelagic and benthic organisms, including economically important species (Steneck et al., 2002; Graham, 2004). Their dense coverage also reduces available light, creating favorable conditions for shade-adapted species (Santelices & Ojeda, 1984). Due to their morphological features, impressive biomass, and persistence, fucoids play a crucial role in reducing wave action, thereby affecting coastal processes such as erosion, sedimentation, and the recruitment of benthic invertebrates (Duggins et al., 1990). These species are vital primary producers, contributing significant amounts of macroalgal detritus that serve as a key food source for detritivores and suspension feeders. This process, in turn, boosts secondary productivity and sustains complex food webs (Krumhansl & Scheibling, 2012). From a human perspective, kelp beds provide numerous ecosystem services valued in the billions annually. They act as natural buffers, protecting coastlines from erosion by absorbing wave energy, support commercial and recreational fisheries, contribute to carbon sequestration, and offer ecotourism opportunities (Smale et al., 2013; Vásquez et al., 2014; Bennett et al., 2016).

The west coast of the Iberian Peninsula is home to several cold-adapted species, such as *Fucus serratus*, *Ascophyllum nodosum*, and *Pelvetia caniculata*, which find in the Portuguese northern coast their southern distribution limit (Araujo et al., 2009; Lalegerie & Stengel, 2022). The presence of these populations at these latitudes is determined by the local features of the Iberian upwelling that provides cold, nutrient-rich oceanic water during the summer.

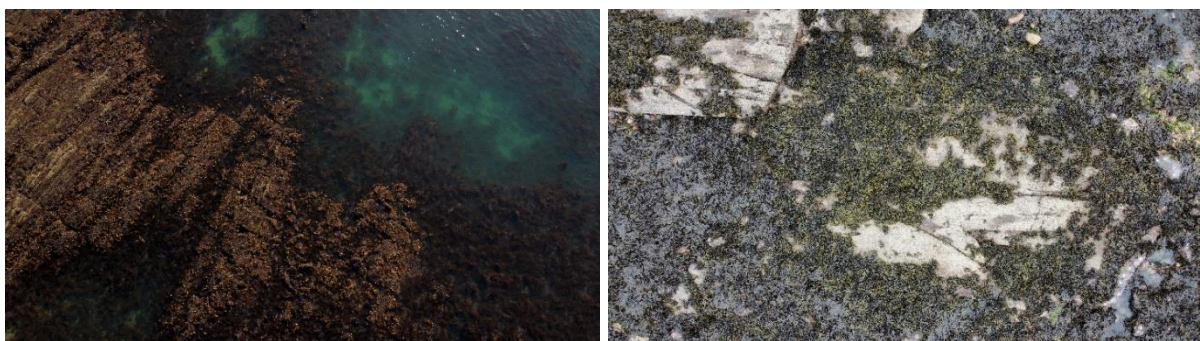


Figure 1: Marine forests formed by kelps (left) and fucoids (right). Copyright: Silvia Chemello, used with permission

Main canopy-forming species in northern Portugal:

- *Fucus* spp.

The brown algal genus *Fucus* (Fucales, Phaeophyceae, Ochrophyta) plays a key role as an ecosystem engineer on sheltered and moderately exposed rocky shores in the North Pacific, North Atlantic and Baltic Sea (Lüning, 1990). Only one species, the cold-adapted *Fucus distichus* Linnaeus, 1767, is found in both the Pacific and Atlantic Oceans, while other species are restricted to the North Atlantic (Wahl et al., 2011). Rocky intertidal shores of the North Atlantic are usually characterized by at least 2–3 species of *Fucus* commonly co-existing along with the large fucoid *Ascophyllum nodosum* and the high intertidal species *Pelvetia canaliculata* (fig.2). Here, *Fucus* species range from northern Canada and Norway to the Iberian Peninsula, which marks the southern limit for many species. However, while the distributions of *Fucus serratus* Linnaeus, 1753 and *F. vesiculosus* Linnaeus, 1753 end in northern and southern Portugal, respectively, the southern form of *F. spiralis* extends to southern Portugal, the Canary Islands, the Azores, and northern Morocco (Coyer et al., 2003; Billard et al., 2010). The diversity of genetic entities within the former *Fucus spiralis* taxa along the Atlantic shores has been a focus of research over the past decade (see Almeida et al., 2022). Currently, two species are recognized in the region: *Fucus spiralis* and *Fucus macrogyryi*. Due to the challenges in distinguishing between these species, we will refer to them collectively as *Fucus spiralis sensu lato*.

Most of the *Fucus* species are dioecious, and sex can often be visually distinguished in the field during reproduction: male receptacles appear red/orange due to carotenoids (Decaisne & Thuret, 1845), while female receptacles are green or brown because of chloroplasts in the eggs (Whitaker, 1931). Reproductive individuals of *Fucus* produce numerous receptacles at the tips of their branches, each containing many conceptacles. All *Fucus* species reproduce sexually, but sexual reproduction is challenging in brackish environments. As a result, asexual reproduction through fragmentation is common in populations living in these marginal environments (Johannesson et al., 2011).

Egg fertilization in *Fucus* occurs near or on the female, with the diploid zygotes typically settling and developing within few meters of the parent (Pearson & Serrão, 2006; Schiel & Foster, 2006). Fertilization success depends on water movement and temperature. In *Fucus vesiculosus*, gamete release usually occurs during periods of low turbulence and daylight (Pearson & Serrão, 2006). Calm water conditions are essential for successful fertilization and recruitment of the non-dispersive zygotes within the adult habitat.

Fucus species typically have a lifespan of 5–10 years. However, due to high mortality rates during early life stages (survival rates for *Fucus* from an egg to a benthic settler are

estimated to range between 1.5% and 10%, while the survival from a settler to a visible germling is between 5% and 12%; Chapman, 1995), juvenile individuals are often scarce in mature populations, making these stands vulnerable to catastrophic events that could lead to significant population decline (Dudgeon & Petraitis, 2005). Due to their characteristics, these species are particularly vulnerable to the effect of climate change, with latitudinal range shifts already been observed along the Portuguese coast, as a result of rising sea surface temperatures (Lima et al., 2007).



Figure 2: *Fucus* spp. form dense stands in the upper intertidal: on the left, a canopy of *F. serratus*; on the right, particular of *F. vesiculosus* fronds. Copyright: Óscar Babé

- *Ascophyllum nodosum*

Ascophyllum nodosum (Linneus) Le Jolie is a brown alga belonging to the family Fucaceae (Fucales, Phaeophyceae, Ochrophyta), which is prevalently found on sheltered rocky shores (South & Tittley, 1986; fig.3).

The adult thalli are greenish-yellow, blackening from desiccation. The thallus is generally 30–150 cm, but can reach up to 6 m in length and it is fixed to the substrate by a long, flat disc. Its elongated fronds, resembling strands, present egg-shaped air bladders, which enhance buoyancy and facilitate photosynthesis (Pereira et al., 2020). The species is dioecious, with male and female reproductive structure (receptacles) on separate individuals. Male receptacles are bright orange-yellow, while female ones have a greenish-yellow colour (Printz, 1956). Reproduction occurs during winter, from November to

February, although it can be affected by seawater temperatures, and the receptacles appear between June and July (Ugarte & Sharp, 2012).

The species is commonly found along the north-western coast of Europe, from Arctic Canada, Greenland, Iceland, and northern Norway to its southernmost boundaries around 42°N, reaching northern Portugal and Long Island, New York in the west Atlantic. The southern limits of its distribution range seem to be determined by summer sea surface temperatures (Luening 1990). *A. nodosum* has the same vertical distribution as *Fucus vesiculosus*, which usually replaces in sheltered conditions. Its vertical range, however, is wider than that of *F. vesiculosus* and it can overlap with *F. spiralis* and *F. serratus* (Hamel 1931–1939).

Despite the effect of climate change and, in particular, the rising seawater temperature, *A. nodosum* maintained its southern distributional limit along the Portuguese coast for at least the past 50 years, persisting as a small, isolated population in the northern coast (Araújo et al., 2011). Beside climate change, there are other stressors that can affect its persistence, contributing to the rapid distributional shifts, such as grazing pressure, competition with opportunistic species, and strong wave action (Araújo et al., 2015). For example, the slow growth rate of *A. nodosum* make its germlings particularly sensitive to the pressure of diatoms and grazers, especially as the juveniles develop beneath the adult canopy, where competition for space and light resources make their survival extremely challenging (Pereira et al., 2020).



Figure 3: Close-up of *A. nodosum* fronds. Copyright: Óscar Babé

- *Pelvetia canaliculata*

Pelvetia canaliculata (Linnaeus) Linnaeus) Decaisne & Thuret 1845 is a perennial brown macroalga belonging to the Fucaceae family (Fucales, Phaeophyceae, Ochrophyta) and is the sole species of the monotypic genus *Pelvetia* (Lalegerie & Stengel, 2022).

The adult thallus reaches a length of 10–15 cm, with dichotomous branches. The branches are curled inwardly, folding into narrow channels that help retain moisture, or even water, particularly at the beginning of emersion. When desiccated, the thalli develop a black, crispy texture but can quickly absorb moisture from humid air or rainfall, enabling survival through prolonged periods of emersion between tidal cycles. The thalli attach to rocky surfaces by a small basal disc, shaped like a truncated cone, measuring 4–6 mm wide and 3–5 mm high

(Almaraz et al., 1995). During the reproductive season in summer, yellow-orange receptacles, 1–2 cm in length, appear at the tips of the branches (Subrahmanyam, 1957).

Commonly found on sheltered rocky shores, it forms a distinctive horizontal band at the uppermost edge of the intertidal zone, positioned between maritime lichens and species of *Fucus* (fig.4). The species is found from the Arctic Ocean and Norwegian Sea to the Atlantic coasts of the Iberian Peninsula, including the North Sea and the English Channel (Lalegerie & Stengel, 2022).

Previous studies suggest that *P. canaliculata* underwent a significant post-glacial range shift and that populations at its southern limit may face risks from climate change (Neiva et al., 2016). While some models link its distribution to non-climatic factors like wave exposure and substrate availability (Martinez et al., 2012), local extinctions, such as on Berlengas Island in Portugal, are possibly caused from sea surface temperature warming (Neiva et al., 2016).



Figure 4: Canopy formed by *Pelvetia canaliculata* in Viana do Castelo. Copyright: Óscar Babé

1.2 Threats and decline of brown macroalgae

In the last decades, canopy-forming seaweeds have experienced declines in different regions around the globe, due mainly to the synergistic negative effect of climate change and local anthropogenic stressors (Araújo et al., 2016; Duarte et al., 2013).

Climate change and the increasing frequency of extreme events is a major threat to fucoïd forests. Rising sea temperatures, changes in ocean currents, ocean acidification, and alterations in weather patterns (e.g., storms, floods, heat waves, etc.) can disrupt the delicate balance necessary for their growth and survival (Vásquez et al., 2006; Koch et al., 2013). Brown macroalgae species are highly sensitive to the warm and nutrient-poor water conditions associated to the climate change (Pereira et al., 2015; Schiel & Foster, 2015), threatening the stability of populations, and influencing their distribution (Wernberg et al., 2010; Filbee-Dexter et al., 2016; Franco et al., 2018), often resulting in massive mortality events (Johnson et al., 2011). Furthermore, heat waves can pose even greater threat to populations at lower latitudes, which live at the limit of their distribution range, than those within midlatitude temperate regions. In fact, southerly distributed populations in Spain and Portugal are living at their thermal limit, which means that their resistance and resilience to disturbances may be compromised by the already highly stressful local conditions (Fernandez, 2011; Tuya et al., 2012; Voerman et al., 2013).

Climate change impacts are also expected due to sea level rise, affecting low-lying coastlines through increasing inundation of the intertidal zone. Intertidal habitats are particularly at risk when they are constrained and unable to move landward, due to unsuitable conditions, e.g. urban or otherwise occupied areas (Schaefer et al., 2020).

Besides climate change and extreme weather events, brown macroalgae are sensitive to a variety of local anthropogenic stressors. Pollution, including coastal runoff, industrial discharge, and nutrient inputs, can have detrimental effects on the survival of these species (Connell et al., 2008). Excess nutrients can lead to eutrophication, promoting the growth of algae (e.g., ephemeral turfing algae) that compete with brown macroalgae for space and resources (Moy & Christie, 2012). Pollution can also impair their ability to photosynthesize and reproduce, weakening their overall health and resilience.

Habitat destruction and coastal development pose further threats to these ecosystems. Construction of coastal infrastructure, such as marinas and seawalls, can alter water flow patterns, disrupt nutrient cycling, and physically damage the seaweeds. Increased

sedimentation from coastal erosion or land-based activities can also smother them and impede their growth (Airoldi & Beck, 2007; Araujo et al., 2012).

Another significant threat is the introduction of invasive species, which can outcompete native species for space and resources, disrupting the balance of the ecosystem. Invasive species can alter the physical structure of canopies, reducing biodiversity and changing the dynamics of the community (Britton-Simmons, 2004; Casas et al., 2004).

Overfishing and destructive fishing practices pose a threat to brown macroalgae. Removal of predators can lead to an overabundance of herbivores that consume these seaweeds, such as sea urchins, resulting in the dense canopies shifting to barren grounds (Steneck et al., 2002; fig.7). Additionally, bottom trawling and other destructive fishing practices can damage the physical structure of these habitats, leading to their decline (Žuljević et al., 2016).



Figure 5: Effect of grazers (left) and excessive sedimentation (right) on Fucus spp. canopies
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To protect these brown seaweed ecosystems, it is essential to address these threats through conservation and management strategies. This includes implementing sustainable fishing practices, monitoring and controlling the spread of invasive species, reducing pollution inputs, and minimizing coastal development impacts. Additionally, establishing marine protected areas can provide refuge and promote the recovery of damaged or degraded kelp ecosystems.

1.3 Using remote sensing to monitor intertidal seaweeds

Seaweed communities living inhabiting intertidal environments are subjected to variable and physiologically stressful conditions, with their structure and dynamics changing significantly over small spatial scales due to the mosaic of habitats shaped by both biotic and abiotic factors (Airoldi, 2003). Monitoring of these communities traditionally involved several methods, such as quadrats, transects, and collecting data on composition, distribution and abundance of the species (Murfitt et al., 2017). However, these methods come with several constraints, being labour-intensive and time-consuming, covering relatively small areas, and often being restricted by tidal cycles and weather conditions, thus limiting the frequency of observations and making difficult to assess large-scale patterns (Bórges et al., 2023). Recently, remote sensing technologies, including satellite imagery, and aerial photography from airplanes and UAVs (Unoccupied Aerial Vehicles), or drones, have been used to provide large-scale, non-invasive monitoring with greater spatial and temporal coverage. Remote sensing minimizes human error, allows for rapid detection of changes, and reduces ecological disturbance (e.g., trampling, Araújo et al., 2009). However, it faces challenges such as limited resolution for small patches or species-level identification (fig.6), the need for technical expertise, and high costs depending on the survey platform. Remote sensing also struggles with weather and tidal constraints, which can affect data quality (Anderson & Gaston, 2013; tab.1).

Table 1: Summary of the characteristics of different remote sensing techniques

Attribute	Satellites	Airplanes	Drones (UAVs)
Spatial Coverage	Global to regional	Regional to local	Local, site-specific
Resolution	Moderate to low (10m – 30m for recent free imagery, decimetres for commercial/payed imagery)	High (centimeters to meters)	Very high (sub-centimeters to a few centimeters)
Temporal Coverage	Frequent, regular intervals; variable, occasional for commercial surveys	Variable, campaign-based	On-demand, highly flexible
Cost	Free to expensive (depends on provider)	Expensive (due to logistics)	Moderate (after initial investment)
Environmental Constraints	Affected by cloud cover, weather	Affected by weather, cloud cover, regulations	Affected by wind, weather, regulations

Attribute	Satellites	Airplanes	Drones (UAVs)
Applications	Large-scale monitoring, long-term trends	Medium to large-scale, high-resolution surveys	Site-specific studies, detailed assessments
Flexibility	Low (fixed orbit paths) to moderate (commercial, planned focussed surveys)	Moderate (customizable flight plans)	High (can be deployed quickly)
Data Processing	Complex for high-resolution imagery	Moderately complex	Typically simpler but requires flight planning



Figure 6: Difference in resolution among remote sensing techniques: left, Google satellite (pixel size: 0.9 m); centre, airplane (Vexcel UltraCAM, pixel size: 0.125 m); right: drone (pixel size: 0.015 m)

By integrating remote sensing with traditional field-based approaches and *in-situ* monitoring, researchers can leverage the strengths of both methods: remote sensing for extensive, repeated observations and traditional methods for in-depth, accurate species-level assessments and providing ground truth for remote-sensing output calibration. This combined approach can potentially improve the overall effectiveness of monitoring intertidal

seaweeds, allowing for a more complete and deeper understanding of their distribution, status, and ecological dynamics.

1.4 Aim of the thesis

The main objective of this research is to map intertidal fucoid-dominated marine forests and to assess their vulnerability of along the northern coast of Portugal, focusing on the impact of climate change variables such as sea-level rise. To achieve this, we employed geospatial mapping tools and ecological models to evaluate the current and projected habitat suitability for three key seaweed taxa: *Fucus* spp., *Ascophyllum nodosum*, and *Pelvetia caniculata*. The “habitat suitability” is defined as the habitat potential to support a particular species (Kellner et al., 1992). Thus, the first step of the process was to generate detailed information on present habitat conditions by identifying key environmental variables (e.g., type of substrate, elevation, orientation, roughness, etc.) . Subsequently, we modeled how these seaweed assemblages are likely to respond to future climate change scenarios, providing information about the vulnerability of the target species to changes in local environmental conditions. The “vulnerability” is defined as the probability that a species will be exposed to a stressor to which it is sensitive. According to Zacharias & Gregr (2005), vulnerability is the likelihood of exposure to a relevant external stress factor, combined with the exposure (duration, magnitude, rate of change) to that stress. The anticipated results of our analysis are expected to provide essential insights into the current and future vulnerability of intertidal marine forests under environmental change, enhancing our understanding of how marine ecosystem dynamics are affected by ongoing climate shifts, and their broader implications for biodiversity and ecosystem services. Additionally, this study will provide valuable guidance for the sustainable management of marine resources, contributing with new data and methodologies to the scientific community.

2. Materials and methods

2.1 Characterization of the study area

The study area encompasses about 60 km of the northern coast of Portugal, from the northernmost point in Viana do Castelo (41.183 N, -8.67977 W) south to Matosinhos (41.7470185 N, -8,8768017 W) (fig.7). The coastal landscape is characterized by a mix of soft and hard substrates, with estuaries fragmenting the shoreline and creating a patchwork of both substrate types. The coastline is exposed to significant wave action, with the

dominant swell coming from the west and northwest. Wave heights typically range between 1.5 and 2 meters, but can reach up to 7 meters during the winter months. The tidal regime is semidiurnal, with the highest spring tides ranging from 3.5 to 4.0 meters (Araújo et al., 2005). The area experiences seasonal upwelling during the spring and summer, with cold deep waters which supplies nutrients crucial for primary producers (Lemos & Pires, 2004).

As outlined by classical zonation schemes such as in Pérès & Picard (1964), and Seoane-Camba (1969), the rocky intertidal ecosystems of northern Portugal are divided into three major zones. The uppermost zone is dominated by encrusting lichens along with the gastropod *Melaraphe neritoides* (Linneus, 1758), but during colder seasons, can be also be colonized by the seaweed *Porphyra linearis* Greville, 1830. The mid-littoral zone of exposed shores is prevalently occupied by filter feeders such as *Patella* spp., *Chthamalus* spp., *Mytilus* spp., and *Sabellaria alveolata* (Linneus, 1767). However, in more sheltered areas, brown algae including *Fucus spiralis*, *Fucus vesiculosus*, *Ascophyllum nodosum*, and *Pelvetia canaliculata* dominate the mid-shore, while *F. serratus* primarily occupies mid-low levels. The lower littoral zone is characterized by a rich diversity of turf-forming algae and big canopy-forming species, such as *Saccorhiza polyschides* (Lightfoot) Batters, 1902, *Laminaria ochroleuca* Bachelot de la Pylaie, 1824, *Laminaria hyperborea* (Gunnerus) Foslie, 1884, *Bifurcaria bifurcata* R.Ross, 1958.

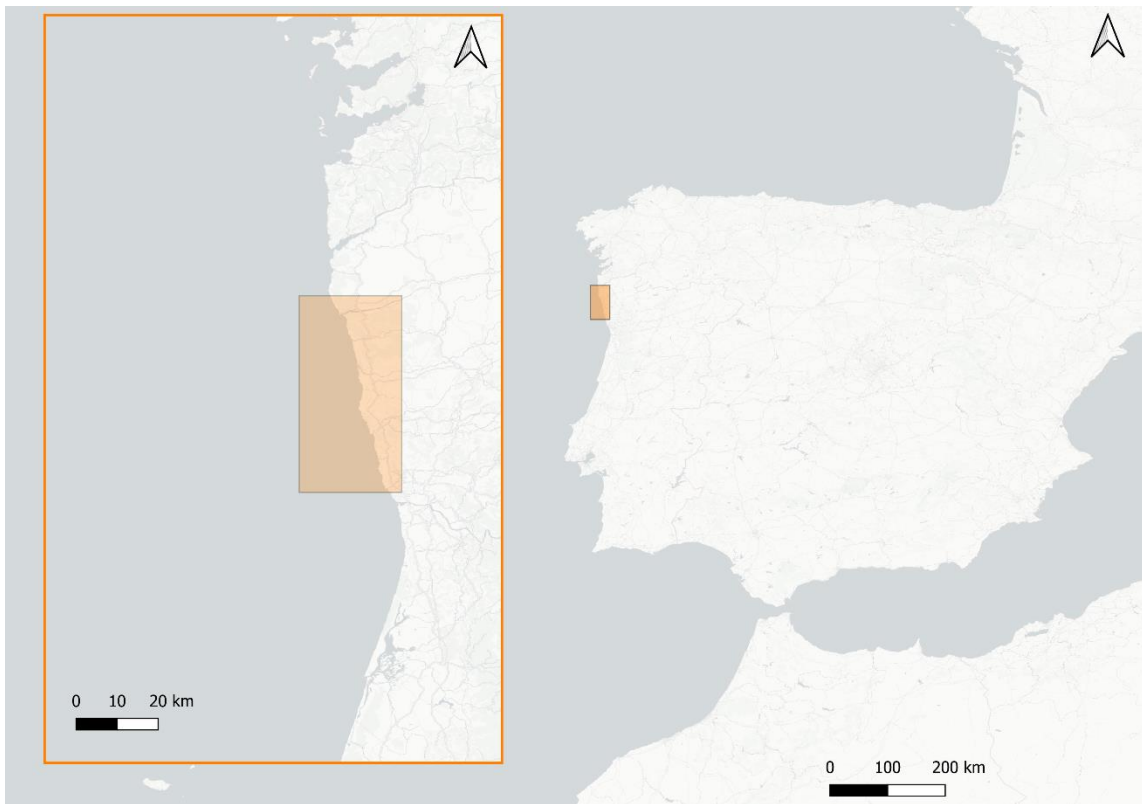


Figure 7: Location of the study area (shaded in orange) on the northern-Portuguese Atlantic coast

2.2 Spatial predictors for the Habitat Suitability model

To assess habitat suitability for brown macroalgae along the northern Portuguese coast, we used habitat suitability models (HSMs), which allow us to evaluate the influence of various environmental and substrate-related factors on the distribution of these species. HSMs are a widely-used tool in ecological research, providing insights into how species respond to their environment by identifying the factors they either select for or avoid. These models generate an index of suitability based on the availability of key factors across a given landscape.

In this study, we identified several local environmental variables as key factors influencing habitat suitability, building raster data layers to map the selected environmental categories, including elevation, width of the rocky platform, orientation, type of substrate and roughness. These variables were, then, integrated into the models to predict areas of potential habitat for brown macroalgae.

With the results of HSM, we used a geographic information system to map the obtained suitability indices. This allowed us to spatially represent potential habitats, thereby providing a clear overview of areas along the coast where the environmental conditions are favourable for brown macroalgal growth.

All the statistical analyses were carried out using the software R (R Core Team 2024), while the geographic information system used was QGIS software ver. 3.30.0.

2.2.1 Digital Elevation Model and topo-bathymetric model

Aerial photos from previous surveys were used to create ortho-mosaics and Digital Elevation Models (DEMs) for the study area (Bio et al., 2022). The photos were captured along a 90 km stretch of coastline between Espinho (41.0072° N, 8.6410° W) and Caminha (41.8385° N, 8.8142° W) in a single row, with 80% overlap between consecutive images. The high-resolution images were captured using a digital photogrammetric camera mounted on a manned aircraft, and georeferenced using an onboard GNSS/INS (Global Navigation Satellite Systems/ inertial navigation system) system. For post-processing, GNSS relative positioning was applied, obtaining the camera's position and attitudinal angles for each image. A boresight alignment with ground control points corrected minor systematic effects (around 0.02°) and *in-situ* measurements in urban areas were used for calibration. 1-meter

resolution DEMs were created using stereo-matching via Agisoft software. Final DEM accuracy was approximately 10 cm, closely matching the image resolution.

Topo-bathymetric information was obtained from a CIIMAR/FCUP high-resolution aerial topographic survey, carried out on 2019. These data cover the dry coast (up to about 1 km distance from shore) and the intertidal area up to about 1 m below mean sea level. Subtidal nearshore bathymetries were extracted from the Digital Terrain Model (DTM) from a national survey with LIDAR carried out in 2011, the only high-resolution near-shore bathymetry available for the study area (information provided by the Direção-Geral do Território), and ocean bathymetry from the EMODnet 2020 DTM (EMODnet, 2020). Data were aggregated prioritizing higher-resolution data in overlapping areas, i.e., using the DEM from the aerial survey where available, followed by the LIDAR-based DTM and by the EMODnet bathymetries.

Table 2. Characteristics of the aerial survey used to build the DEM and topo-bathymetric model

Date	20 February 2019
Camera	Vexcel UltraCAM
Bands	Red, green, blue, near infrared
Resolution	9420×14430 pixels
Flight details	Airplane, flying at 1600 m altitude, during spring low tide conditions
Pixel on the ground	12.5 cm

The DEM was used to extract several environmental variables (e.g., platform width, orientation, elevation above mean sea level, shade and slope) used as inputs in the habitat suitability model to evaluate their influence on seaweed distribution. Slope refers to the steepness or gradient of the terrain, influencing water retention, wave exposure, and substrate stability in intertidal zones. Shade represents the degree of sunlight obstruction based on the terrain's orientation and elevation, affecting the microclimatic conditions experienced by intertidal species. Both variables were extracted using QGIS tools: slope was calculated by measuring the maximum rate of elevation change between neighboring cells, and shade was derived using the hillshade function, simulating the sun's position to model shadowing effects. The orientation represents the direction that each slope faces, providing insight into how environmental factors such as sunlight and wave exposure vary

along the coast. Using the aspect tool in GIS, the orientation of each pixel in the DEM was calculated, yielding the direction in degrees relative to north. We then categorized the orientation into four groups to facilitate the association of orientation with each pixel in the map: North (0°-90°), East (90°-180°), South (180°-270°), and West (270°-360°).

The width of the rocky platform was also calculated from DEM. We defined a fringe between -2 and -3 meters below the lower limit of the tidal range, representing the zone where waves typically break. Using GIS, the proximity tool was employed to calculate the distance of each pixel from this defined fringe, effectively measuring the width of the rocky platform at each point.

2.2.2 Land Cover supervised classification

To evaluate the habitat suitability for brown seaweeds, the first step was to carry out a Land Cover classification using a supervised classification method (fig.8). Semi-automatic or supervised classification is an image processing technique that allows for the identification of materials or substrates in an image, according to their spectral signatures (Merry et al., 2023). In this research, we followed the same workflow as in Meyer et al. (2024). The multispectral images were classified through a supervised classification with the random forest algorithm, using the four image bands red, green, blue and near-infrared. The number and type of cover classes was determined by the visual identification of the most representative coverages in the images. 30 Regions of Interest (ROIs) of 20 × 20 cm² were selected for each class for the training of the classification, resulting in approximately 13,000 pixels.

The output of the Land Cover classification was also used to build the occurrence map for intertidal brown seaweeds.

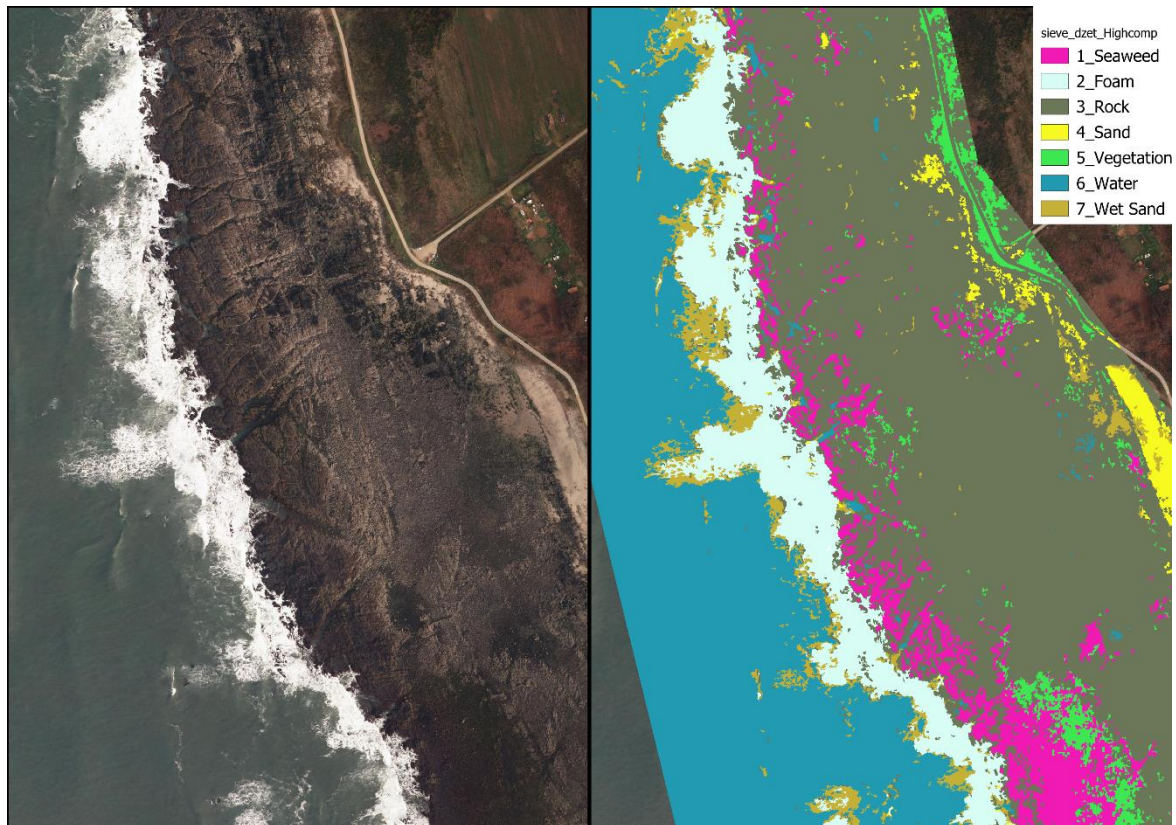


Figure 8: Semi-automatic classification to assess Land Cover. On the left, the ortho-mosaic built from the RGB images; on the right, the semi-automatic classification result based on the 4 bands of the multispectral images. Different colours identify different types of cover

2.2.3 Terrain ruggedness index

The Terrain Ruggedness Index (TRI) is a quantitative measure that captures the amount of elevation change between adjacent cells in a DEM, representing the terrain's "roughness" by analysing how much the elevation varies over a local neighbourhood. TRI is computed by summing up the elevation differences between a central cell in the DEM and its neighbouring cells (usually the eight adjacent cells in a 3x3 window). The mathematical equation is described as follows:

$$TRI = \sqrt{\sum (z_i - z_{center})^2}$$

We used the DEM described in chapter 2.2.1 to obtain the TRI for the study area and used the results to feed the Habitat Suitability model.

2.3. Habitat suitability

2.3.1 Model development - Presence determination and filtering occurrence records

To build the presence map and feed the model, 30 occurrence points for each target taxa were recorded in the intertidal along the study area, for a total number of 120 points. For each point, geographical position and elevation were noted, to identify the vertical range (i.e., maximum and minimum elevation with respect to mean tidal range) that these species occupy in the intertidal. These areas with known species cover and precise location were also used as training and validation areas for the supervised cover classification. Additionally, each of the 120 seaweed presence points was associated with one of the categorized orientations in 2.2.1, allowing us to analyze how the direction of the slope influenced seaweed distribution across the study area.

2.3.2 Linear Model to predict Habitat Suitability

To assess the habitat suitability for brown seaweed based on environmental variables, a linear model (LM) was employed using the `lm()` function of the Stats package in the R software (R Core Team, 2024). The response variable was the presence of brown seaweed, while the predictor variables included elevation, shade, platform width, orientation, slope, and terrain ruggedness index (TRI), which were extracted from spatial data layers. Before running the linear model, we verified that the predictor variables were not highly correlated ($r > 0.7$) by calculating pairwise correlation coefficients. The final model was expressed as:

$$lm(\textit{Presence} \sim \textit{orientation} + \textit{width} + \textit{shade} + \textit{slope} + \textit{TRI} + \textit{elevation})$$

2.4. Habitat vulnerability

To evaluate the potential impact of climate change on intertidal brown seaweed habitats, we calculated the potential available habitat area, considering only the rocky shore regions within the elevation range that is suitable for our target species, as identified from the vertical distribution of the species. This analysis was conducted for the current conditions and projected across three sea-level rise (SLR) scenarios developed by NASA, as outlined in the Sea Level Projection Tool (NASA, 2023). These scenarios allow for projections of habitat shifts based on varying levels of sea-level rise (SLR) under different global temperature increases and emissions pathways. The scenarios selected for this research included:

- *Low Scenario*, with a 0.5 m SLR by 2100
- *Intermediate Scenario*, with a 1 m SLR by 2100

- *High Scenario*, with a 1.5 m SLR by 2100

The vulnerability of the brown seaweeds was assessed by overlaying future SLR projections onto current habitat maps, generating spatial outputs of habitat loss or gain under different climate futures. These outputs indicated the degree to which the species' optimal habitat range is expected to shift or diminish, providing insight into the vulnerability of these intertidal assemblages under varying levels of climate change.

3. Results

3.1 Land Cover classification

From the analysis of Land Cover classification 7 classes were identified, namely “Seaweeds”, “Bare rock”, “Sand”, “Wet sand”, “Vegetation”, “Water” and “Foam” (fig.9). The class “Seaweeds” occupied the smallest area with 0.85 km², including not only our target species but also low-intertidal red algae and kelps.

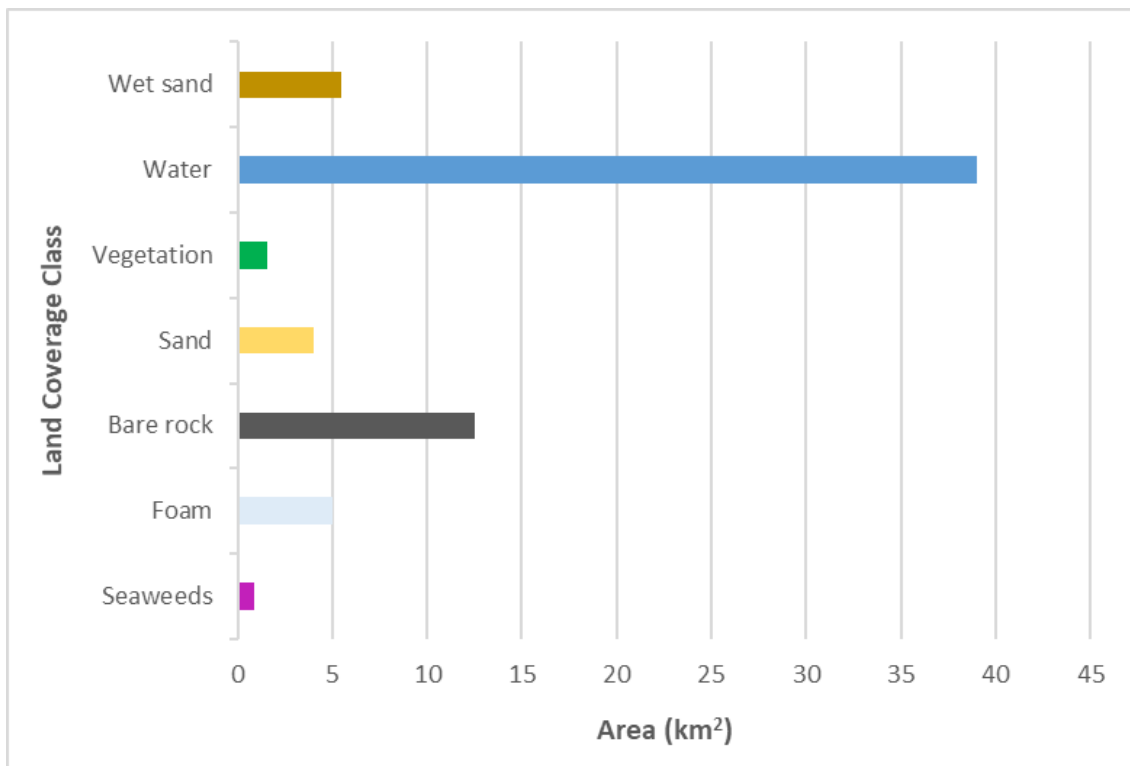


Figure 9: Area occupied by each Land Coverage class

3.2 Brown seaweed occurrence map

An elevation cut-off was done after establishing the occurrence range of the target species, to avoid areas that were unlikely to support the presence of the target species (fig.10). From the first evaluation, these species occurred from 1.65 m above the mean tidal range (*P. caniculata*) to 0.72 m below the mean tidal range (*F. serratus*). However, since the vertical distribution of *F. serratus* also overlapped with the one of red algal species and kelps, potentially affecting the results of the statistical model, we decided to exclude it. We therefore considered an occurrence interval between 0 (corresponding to the value of mean tidal range) and 1.7 m above it.

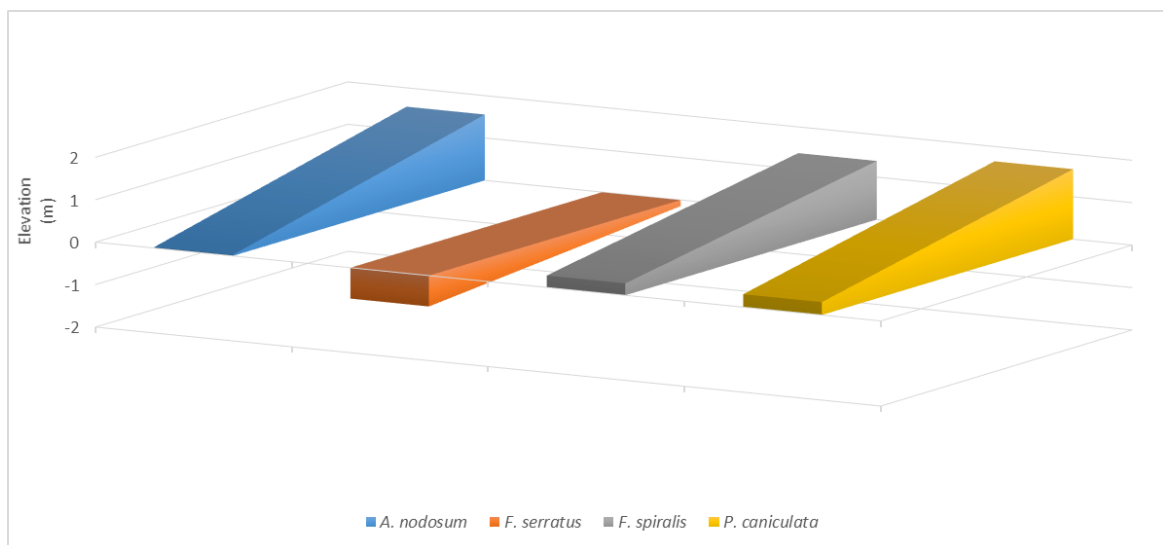


Figure 10: Vertical distributional range of the target species, identified by maximum and minimum elevation

The elevation cut-off was applied to the Land Cover map selecting just the “seaweed” class, in order to visually represent the occurrence of intertidal brown seaweed and calculate the occupied area (fig.11). From our analysis, the area covered by our target species was 0.095 km².



Figure 11: On the left, the map resulting from the initial Land Cover classification, on the right the brown seaweed occurrence map obtaining after the elevation cut-off

3.3 Habitat suitability

The linear model yielded a significant overall fit, with an R^2 value of 0.6644 ($p < 0.001$), indicating that 66.44% of the variance in brown seaweed presence can be explained by the included environmental variables (tab. 3).

Among the considered predictors, platform width had a significant positive effect on the presence of brown seaweed ($p < 0.001$), indicating that wider platforms are associated with higher presence of brown seaweed. The orientation also significantly influenced the presence of brown seaweeds ($p < 0.01$), with a negative coefficient indicating that as the orientation shifts clockwise from North to South and West, the likelihood of seaweed presence decreases. This trend is supported by the distribution of seaweed presence points, where North-facing slopes had the highest number of seaweed occurrences (38 out of 120), while South-facing slopes had the fewest (21 out of 122). Elevation also

demonstrated a significant positive effect on brown seaweed presence ($p < 0.001$), indicating that higher elevation is associated with increased presence of the target species.

In contrast, other variables such as shade, slope, and TRI did not show significant effects ($p > 0.05$).

Table 3: Summary of the results of the habitat suitability linear model. Significant differences are indicated by * ($p \leq 0.05$); ** ($p \leq 0.01$); *** ($p \leq 0.001$)

Model: lm (Presence ~ orientation + width + shade + slope + TRI + elevation, data=dataset)					
Residuals:	Min	1Q	Median	3Q	Max
	-0.9303	-0.16502	-0.01862	0.17441	0.85342
Coefficients:					
	Estimate	Error	t value	Pr(> t)	
	Std.				
(Intercept)	3.68E-02	2.47E-01	0.149	0.881493	
Orientation	-5.92E-04	1.99E-04	-2.972	0.003271	**
Width	4.72E-03	2.52E-04	18.726	2.00E-16	***
Shade	4.14E-04	1.29E-03	0.321	0.748479	
Slope	8.47E-05	4.23E-03	0.02	0.984045	
TRI	-1.33E-01	1.83E-01	-0.727	0.468209	
Elevation	8.25E-02	2.31E-02	3.571	0.000432	***
Residual standard error: 0.2939 on 235 degrees of freedom					
Multiple R-squared: 0.6644, Adjusted R-squared: 0.6558					
F-statistic: 77.53 on 6 and 235 DF, p-value: < 2.2e-16					

The graphical output of the habitat suitability model, which classified the study area into four probability categories (0-25%, 25-50%, 50-75%, and 75-100%, fig.12), reveals that the vast majority of the study area, approximately 19.5 km², fell within the lowest probability category (0-25%), indicating limited suitability for brown seaweed growth across much of the region. In contrast, the higher probability categories are limited to much smaller areas, with only 1.11 km² falling within the 25-50% range, 0.31 km² within the 50-75% range, and just 0.06 km² in the highest suitability range (75-100%).

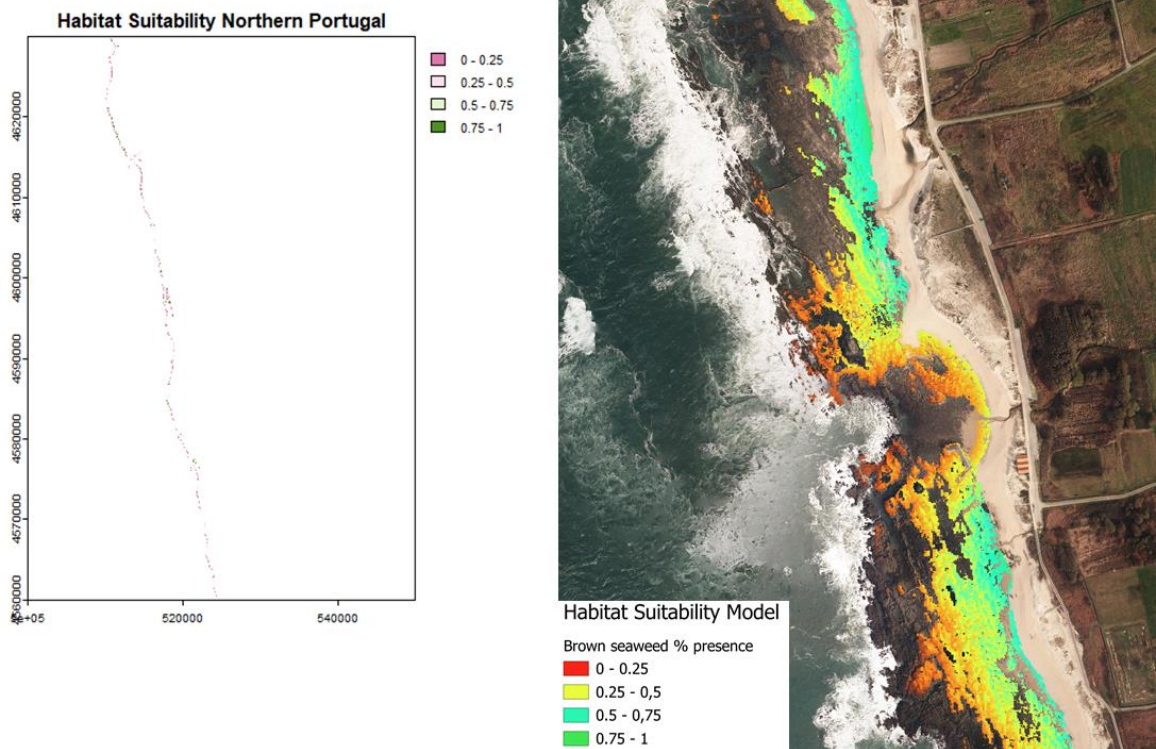


Figure 12: Graphical outputs of the Habitat Suitability model. On the left, the output from R software; on the right, the map obtained with QGIS software

3.4 Habitat vulnerability

Applying future SLR projections onto current habitat maps, we generated three distinct spatial outputs illustrating habitat changes under varying climate futures (Fig. 13). Our assessment revealed significant impacts on the availability of potential habitat for brown seaweeds, which currently occupies a total area of 2.13 km² of rocky shores. Under the Low Scenario (0.5 m rise), we projected a habitat loss of approximately 25%, indicating already a substantial reduction in the area suitable for brown seaweed growth (1.60 km², fig.14). The Intermediate Scenario (1 m rise) showed a habitat loss of about 42%, highlighting a critical decline in available habitat with a potential area of 1.23 km² (fig.14). The most severe impact was observed in the High Scenario (1.5 m rise), where the projected habitat loss reached 52% (potential available area: 1.02 km², fig.14).

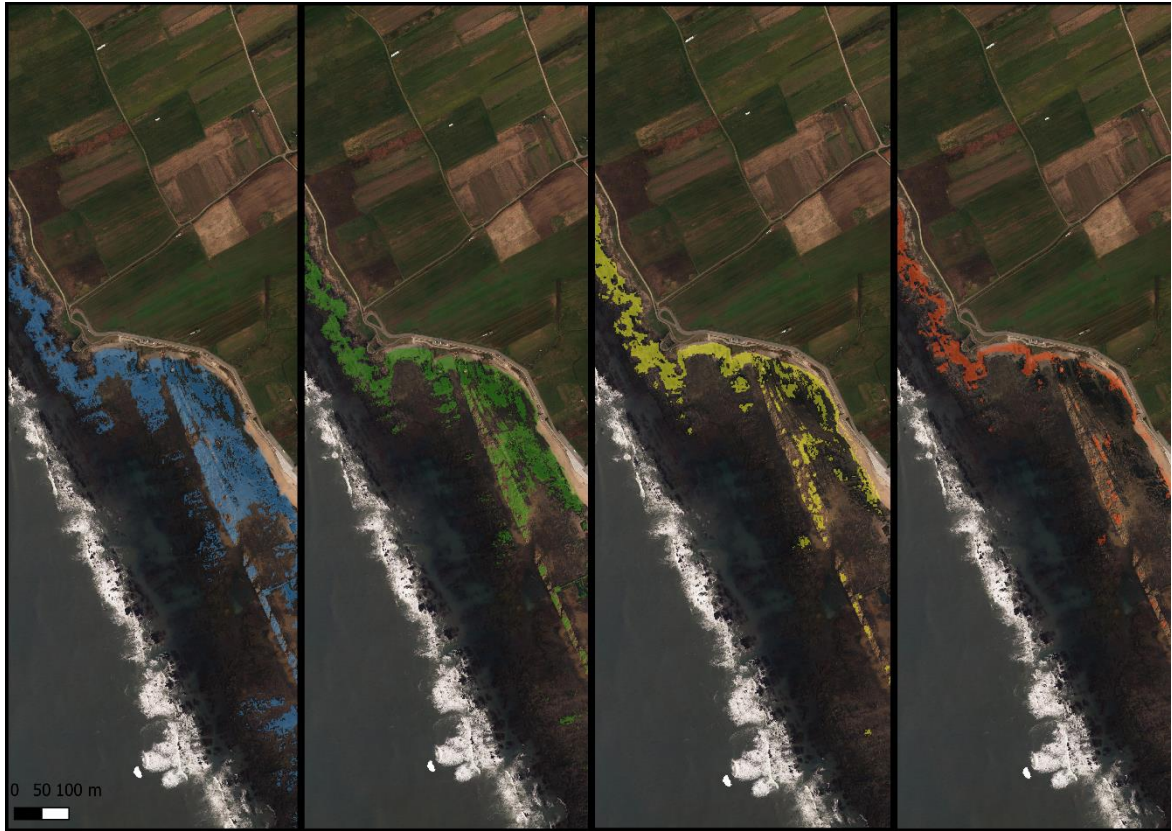


Figure 13: Maps of the potential habitat for intertidal brown seaweeds under different SLR scenarios: blue: current potential habitat, green: potential habitat under the Low scenario (0.5m SLR); yellow: potential habitat under the Intermediate scenario (1m SLR); red: potential habitat under the High scenario (1.5m SLR)

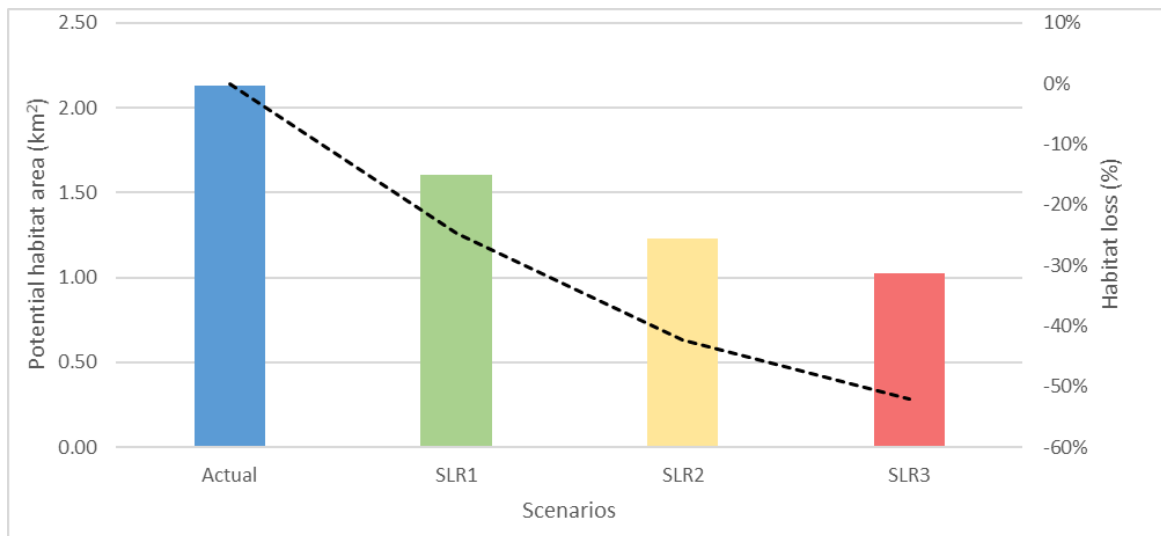


Figure 14: Potential habitat area for each scenario: blue: current situation; green) SRL1; yellow: SLR2, red: SLR3. On the second axis the percentage of habitat loss under each scenario is shown

4. Discussions

The primary goal of this study was to evaluate the habitat suitability and assess the vulnerability of intertidal brown seaweed habitats along the northern Portuguese coast in relation to the impacts of climate change, through a multidisciplinary approach including the use of remote sensing techniques, ecological modelling and integration of projections of future climatic conditions.

Traditionally, intertidal communities have been monitored primarily through visual census, with previous studies in Portugal focusing on small spatial scales (Borges et al., 2020; Melo et al., 2021). However, remote sensing has increasingly been adopted as a tool for continuous, large-scale monitoring of intertidal habitats (Collin et al., 2019; Rossiter et al., 2020). Understanding the dynamics and studying spatio-temporal changes in seaweed communities is fundamental for predicting shifts in ecosystem structure, biodiversity, and productivity, especially in response to climate change and other stressors (Brodie et al., 2018). Remote sensing offers a powerful means to capture these changes over time, particularly in environments that are difficult to access regularly due to tidal cycles or harsh weather conditions, enabling more effective management and conservation efforts (Brodie et al., 2018; Konar et al., 2018).

In our study, remote sensing techniques played a crucial role by providing high-resolution spatial data for habitat mapping and monitoring of intertidal macroalgal assemblages. However, the remote estimation of intertidal seaweed biomass presents several challenges, and errors in substrate classification are possible. On rocky shores, this task is particularly difficult due to various sources of noise in the reflectance spectra, including sun glint from rock pool surfaces, shade caused by microtopography, and the angle of incident sunlight (Borges et al., 2023).

The brown seaweed presence map generated through GIS tools using remote sensing techniques, estimated a seaweed coverage of 0.09 km², provides a useful comparison with the results of the habitat suitability model. The habitat suitability model identified a highly restricted area of optimal habitat for brown seaweeds, with only 0.06 km² classified in the highest probability range (75-100%). This close alignment between the areas identified by remote sensing and the model's prediction of highly suitable habitat suggests a strong concordance between observed seaweed presence and model outputs, both being close to the actual size of our intertidal furoid forests. The observed presence map, while showing a slightly larger coverage, may reflect areas where seaweeds have already established, possibly influenced by microhabitat factors or transient conditions not fully captured by the model. However, both methods indicate that brown seaweed presence is concentrated in small, localized areas within the study region, especially in the area located further north, between Viana do Castelo and Carreço. Here, the actual seaweed coverage detected through remote sensing largely overlaps with the high-suitability zones predicted by the model, reinforcing the validity of the model's output in identifying key areas where environmental conditions are favourable for seaweed growth. This concordance highlights the importance of the habitat suitability model as a predictive tool for identifying areas with potential for seaweed establishment, even in regions where direct observational data may be limited (Silva et al., 2008). However, it is worth noting that the habitat suitability model also identified some areas with moderate probability (50-75%, 0.31 km²), which could represent potential zones for future seaweed establishment under changing environmental conditions.

The similarity in coverage highlights that both remote sensing and habitat suitability modelling are valuable and complementary tools in monitoring and managing intertidal seaweed populations and, when feasible, the optimal approach would be to combine both tools. The ability to use GIS and remote sensing technologies to assess habitat suitability and predict future changes under various sea-level rise scenarios represents a powerful tool for conservation and management efforts.

Research in modelling literature has indicated that numerous factors beyond climate can significantly influence species' geographical distributions, especially at fine spatial resolutions (Heikkinen et al., 2006; Austin & Van Niel, 2011). For example, previous habitat distribution models for intertidal seaweeds in the Iberian Peninsula revealed that the presence of *A. nodosum* and *P. canaliculata* was associated with a limited range of non-climatic environmental factors and particular locations. These habitats may offer favourable microclimatic conditions or serve as refuges from competitors and natural enemies, or potentially both, resulting in local climate refugia at the southern distribution limits of these species (Martinez et al., 2012). Our regional to local scale habitat suitability model confirmed that platform width, elevation, and orientation significantly influenced the presence of our target brown seaweeds, with platform width emerging as the most important factor. These findings align with previous studies showing that larger platforms provide greater space for attachment and protection from wave action, supporting species resilience and resistance to stressors. Availability of space, in fact, is a fundamental factor in shaping intertidal seaweed assemblages, as colonization of seaweeds largely depends from the availability of hard substrates for attachment (Lüning, 1990; Vadas et al., 1992). Besides supporting denser populations and a wider distribution of intertidal seaweeds, larger rocky areas also reduce inter- and intra-specific competition, both among seaweed species and between seaweeds and other organisms, such as barnacles or mussels, that also depend on hard substrates for attachment (Edwards & Connell, 2012). Intertidal seaweeds are also subjected to highly variable environmental conditions, such as variation in light, salinity, temperature, and hydrodynamics (Lalegerie et al., 2020), and larger rocky platforms can create microhabitats that provide refuges from environmental stressors, such as wave action, desiccation, and predation (Bauer et al., 2024).

Elevation also played a crucial role, as higher elevations may limit exposure to wave energy and grazing, providing more stable conditions for seaweed growth (Burel et al., 2020). Low shore communities, in fact, bear rougher wave height conditions, which can lead to increased physical stress and reduce the likelihood of successful seaweed establishment (Gaylord, 1999).

The results of the linear model also revealed a significant influence of orientation on the presence of brown seaweeds, with a negative coefficient indicating that as orientation shifts from North to South and West, the likelihood of seaweed presence decreases. The association of seaweed presence points with specific orientations further elucidates this trend, as the highest number of presence points was observed on North-facing slopes (0°-90°), while South-facing slopes (180°-270°) exhibited the lowest presence. This pattern suggests that North-facing slopes could provide more favourable conditions for brown

seaweed growth, likely due to reduced direct sunlight exposure and decreased desiccation stress during low tides, maintaining more stable and cooler conditions. In contrast, South-facing slopes may experience harsher environmental conditions, including increased sunlight radiation causing potential heat stress, which can limit the establishment and persistence of seaweed populations (Amstutz, 2020).

Topography of substrate is usually important in shaping intertidal communities, forming microhabitats with peculiar environmental condition and acting as a key modulator of abiotic stressors and biotic pressures (Bauer et al., 2024). However, in our study the TRI which measure the complexity of a landscape based on its elevation, was not a significant factor in explaining the presence of brown seaweeds. While TRI can give a general overview of ruggedness across a larger area, it may overlook smaller variations in substrate characteristics that can be crucial for understanding how specific communities develop. Fine-scale heterogeneity, in fact, can include variations in texture, grain size, and small features of the substrate that influence local ecological interactions that TRI failed to capture, potentially limiting its effectiveness as an indicator of habitat suitability for brown seaweeds

The graphical output from the habitat suitability model also showed that the majority of the study area, approximately 19.5 km², falls within the lowest probability class (0-25%), indicating that a substantial portion of the intertidal zone is characterized by conditions that are largely unsuitable for the target species. This may be due to environmental factors such as suboptimal platform width, excessive slope, or insufficient wave exposure, which restrict the ability of brown seaweeds to establish and thrive. In contrast, the higher suitability categories represent much smaller areas. Only 1.47 km² is classified in the 25-100% range, suggesting that moderately suitable habitat is scarce and spatially confined. The limited availability of high-probability habitats (75-100%) is particularly significant, highlighting the vulnerability of brown seaweed populations in the region. Given that only 0.06 km² of the study area offers the most favourable conditions, even small-scale environmental disturbances (such as changes in wave dynamics, sediment deposition, or human activity) could disproportionately impact these critical habitats. Furthermore, the limited availability of suitable areas may reduce the resilience of brown seaweed populations to environmental changes, particularly under future scenarios of climate change and sea-level rise, underscoring the precarious position of intertidal seaweed populations even under current conditions (Vaselli et al., 2008).

In this context, the habitat vulnerability assessment projects a clear trajectory of habitat loss under each successive SLR scenario, with even a moderate rise in sea levels (0.5 m)

resulting in a substantial reduction of suitable areas and a loss of about the 25% of available habitat. Given that the habitat suitability model has already highlighted the restricted availability of high-probability areas, the added pressure from sea-level rise is likely to exacerbate habitat degradation. The areas currently classified as highly suitable (50-100%) are the most at risk, as these habitats, often located in lower elevation zones, will likely be submerged or exposed to increased wave action and erosion. This combination of limited suitable habitat and projected habitat loss under SLR suggests a significant threat to the survival and distribution of brown seaweeds in the region. The loss of critical habitats, as shown by the vulnerability assessment, could lead to population declines and shifts in community structure, as species struggle to adapt to rapidly changing environmental conditions (Rilov et al., 2021). Moreover, the small, fragmented patches of high-suitability habitat could become even more isolated, reducing connectivity between populations and hindering the ability of brown seaweeds to recover in response to environmental changes or other stressors such as grazing (Reeves et al., 2022).

Together, these findings emphasize the urgent need for targeted conservation and management strategies. Protecting the remaining areas of high suitability, which are already scarce, should be a priority, especially considering their heightened vulnerability to SLR. Restoration efforts in moderately suitable areas (25-50%) could also help enhance habitat resilience and provide refuges for brown seaweeds as sea levels continue to rise. Furthermore, integrating SLR projections into habitat suitability models can provide a more dynamic understanding of how climate change will reshape coastal ecosystems, offering a clearer roadmap for adaptive management strategies. These findings suggest that conservation and management efforts should focus on protecting and possibly restoring the few areas identified as highly suitable for brown seaweeds. Targeted actions, such as establishing marine protected areas (MPAs) or enhancing the resilience of marginal habitats through active restoration, could help safeguard these ecosystems (Gianni et al., 2013; Eger et al., 2022). Moreover, understanding the specific environmental factors that define these high-probability areas can provide valuable insights into the conditions necessary for the persistence of brown seaweeds, informing broader conservation strategies across similar intertidal zones.

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