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Canopy – forming macroalgae Distribution, Ecological Status and Threats in the Iberian Peninsula and Islands

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Esther Domínguez Crisóstomo,

Barcelona, 28th of September 2023

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ABSTRACT

Coastal marine ecosystems are crucial habitats worldwide, rivalling terrestrial forests in providing diverse organisms and essential ecosystem services. These underwater marine forests face a critical threat from human activities and climate change, leading to their decline. Canopy-forming macroalgae, particularly prevalent on temperate rocky coasts, function as ecological engineers, sustaining a plethora of organisms and contributing to CO2 sequestration, nutrient cycling, and coastal protection. This study focuses on the Iberian Peninsula, strategically located amidst the Atlantic Ocean, Mediterranean Sea, and Cantabrian Sea, creating a biodiversity hotspot with unique oceanographic conditions influencing brown canopy-forming algae distributions.

The aim is to capitalize on available published information and provide an overarching perspective on the ecological status and stress factors affecting canopy-forming macroalgae of the Fucales, Laminariales, and Tilopteridales orders along the coasts of the Iberian Peninsula, encompassing the Balearic and Canary Islands. Additionally, we have provided an updated and quantitative map of canopy-forming macroalgae distribution to assess their ecological status, analyse and identify potential threats and their consequences. This is in pursuit of promoting further research, advocating for environmental protection, and prioritising local conservation efforts.

Our meticulous analysis of the most recent data reveals preliminary results about trends and disparities in research endeavors. While the Mediterranean and Atlantic coasts receive considerable attention, other areas remain inadequately studied. Ecological state records, primarily categorized as positive, display a nuanced trend, with a notable inclination towards a moderate to poor rating and a paucity of data, emphasizing the urgent need for comprehensive ecosystem health improvement. The primary stress factors contributing to population decline differ by geographic region. Water quality issues are confined to specific regions like the Mediterranean and Balearic Islands, whereas habitat destruction and global warming extend along the coasts of the Iberian Peninsula. Herbivory prevails along both the Atlantic and Mediterranean coast. This suggest a regionalization of the impacts or a limited bias in the investigation.

This compilation of information highlights the critical importance of preserving canopy-forming species and the ecosystems they create. To ensure the effective management of kelp and fucoid forests, it is imperative to undertake targeted actions tailored to the unique characteristics of each region and the specific threats they face. Additionally, addressing knowledge gaps and rectifying research imbalances is crucial in order to prevent the decline of biodiversity and the depletion of essential ecosystem services. The spatial distribution of the data obtained is invaluable in helping stakeholders and managers make informed decisions.

KEY-WORDS: Canopy-forming; Conservation; Ecological Status; Iberian Peninsula; macroalgae; Threats.

SUMÁRIO

Os ecossistemas costeiros marinhos são habitats excecionais que sustentam uma diversidade de organismos em todo o mundo, oferecendo uma variedade de bens e serviços ecossistêmicos. semelhantes aos fornecidos pelas florestas terrestres e mantendo simultaneamente a biodiversidade e a produtividade. No entanto, os efeitos combinados das atividades humanas e das alterações climáticas têm tido um impacto negativo nas florestas marinhas subaquáticas, levando à sua diminuição e perda, com provável impacto na diversidade de fauna associada e nas interações tróficas.

As macroalgas formadoras de dosséis, particularmente dominantes nas costas rochosas temperadas, desempenham papéis cruciais como engenheiras ecossistêmicas., oferecendo alimentos, abrigo e zonas de reprodução a várias espécies, ao mesmo tempo que contribuem para a sequestração de CO2, ciclo de nutrientes e proteção costeira. Estas algas também atuam como indicadores sensíveis da saúde dos ecossistemas costeiros.

Este estudo concentra-se na Península Ibérica, localizada estrategicamente entre o Oceano Atlântico, o Mar Mediterrâneo e o Mar Cantábrico e o Mar de Alborão, criando um ponto quente de biodiversidade. As condições oceanográficas, como temperatura, influxo de nutrientes e salinidade, afetam substancialmente a distribuição de macroalgas formadoras de dossel, como Laminariales, Tilopteridales e Fucales. O estudo faz distinção entre kelps e fucoides, destacando suas diferenças biológicas, especialmente em relação ao potencial de dispersão, o que afeta significativamente a dinâmica de recuperação das populações.

Apesar da sua importância ecológica, as algas de dosséis enfrentaram graves declínios e desaparecimentos devido a fatores de stress antropogénicos, como urbanização, poluição, fragmentação de habitats e aumento da temperatura do mar. Mudanças nas espécies em resposta ao aquecimento têm perturbado os equilíbrios ecológicos ao longo da costa atlântica da Península Ibérica e em águas do Mediterrâneo. Consequentemente, a perda de algas fucoódeas formadoras de dosséis tem permitido a invasão de habitats menos complexos por espécies não nativas, com implicações ecológicas, sociais e económicas de longo alcance.

Preservar espécies formadoras de habitats é crucial, exigindo estratégias eficazes de gestão ambiental que considerem fatores ambientais e interações intraespecíficas. A primeira etapa na preservação ecológica envolve a utilização de informações para orientar a tomada de decisões, incluindo a compreensão da distribuição temporal das espécies, a avaliação da saúde das populações e a identificação de fatores de stress.

Uma revisão sistemática da literatura foi realizada, coletando dados de 67 artigos e extraindo 1166 pontos de dados. Foram obtidas informações sobre o título, o autor, as coordenadas dos pontos de amostragem, as espécies, o estado ecológico e as ameaças. Ao examinar a cronologia de publicação dos artigos analisados, observou-se um aumento gradual, sendo ligeiramente superior nos anos mais recentes. A identificação de espécies de macroalgas formadoras de dossel não se distribuiu uniformemente nos artigos analisados, revelando uma notável disparidade em sua presença e frequência.

Nos artigos revisados, foram identificadas 18 espécies pertencentes ao grupo *Cystoseira sensu lato*, representando aproximadamente 50% dos dados. Entre elas, *Cystoseira compressa, Ericaria selaginoides e Gongolaria baccata* se destacaram como as espécies mais frequentemente identificadas. No entanto, *Laminaria ochroleuca*, pertencente à ordem Laminariales, resultou ser a espécie mais frequentemente identificada em várias publicações, seguida *de Sacchorhiza polyschides*, que foi identificada em 14 e 12 publicações, respetivamente. Relativamente à dinâmica da abundância das populações de algas formadoras de copas, observam-se tendências contrastantes em diferentes regiões.

No norte da Península Ibérica, abrangendo o Mar Cantábrico, foi documentado um declínio significativo das populações de macroalgas formadoras de dossel. Por outro lado, quando nos voltamos para as regiões costeiras do Mediterrâneo, surge um padrão diferente. Aqui, as populações de macroalgas formadoras de dossel parecem mostrar uma relativa estabilidade ao longo do tempo.

Nos registros de estado ecológico, os pontos foram classificados como "bom", "moderado" ou "pobre", e muitas regiões mostraram uma predominância de dados insuficientes, mais concretamente, o norte da Península Ibérica é o Mar de Alborão. Os resultados na maioria das regiões, embora predominantemente categorizados como positivos, mostram uma tendência matizada, com uma notável inclinação para uma classificação de moderada a pobre, e há poucos dados disponíveis, o que destaca a urgente necessidade de melhorar a saúde dos ecossistemas.

Os principais fatores de estresse que provocam o declínio das populações variam de acordo com a região geográfica. Os problemas de qualidade da água estão circunscritos a regiões específicas, como o Mar Mediterrâneo e as Ilhas Baleares, enquanto a destruição do habitat se estende ao longo das costas da Península Ibérica. O aquecimento global mostra impactos variados, com uma tendência de temperaturas marinhas mais altas ao longo de toda a península, mas com especial atenção no noroeste peninsular. A herbivoria, impulsionada principalmente por ouriços-do-mar, espáridos e peixes herbívoros, prevalece ao longo das costas atlânticas e mediterrâneas. No que respeita às causas naturais, elas não apresentaram uma zonagem evidente, distribuindo-se ao longo da costa noroeste atlântica e sobrepõem-se frequentemente aos pontos críticos do aquecimento global, em especial na região noroeste de Espanha. Finalmente, observou-se uma aparente zonagem para as populações que não sofriam nenhuma ameaça, limitando-se à região das Ilhas Baleares.

Este estudo tem como objetivo fornecer um mapa quantitativo atualizado e abrangente da distribuição das macroalgas formadoras de dossel, avaliar o estado ecológico, analisar e identificar as possíveis causas da situação observada e suas consequências em escala ibérica. O principal objetivo deste estudo é capitalizar as informações publicadas disponíveis sobre o estado ecológico e os fatores de estresse que afetam as macroalgas formadoras de dossel das ordens Fucales, Laminariales e Tilopteridales ao longo das costas da Península Ibérica, incluindo as Ilhas Baleares e Canárias, a fim de oferecer uma visão geral das regiões que sofrem maiores impactos e quais carecem de informações relevantes. Isso visa promover novas pesquisas, instigar a proteção do meio ambiente e priorizar os esforços de conservação.

Esta compilação de informações destaca a importância crítica de preservar espécies formadoras de dossel e os ecossistemas que elas criam. Para garantir a gestão eficaz das florestas de algas castanhas e fucoides, é imperativo empreender ações direcionadas adaptadas às características únicas de cada região e às ameaças específicas que enfrentam. Além disso, abordar lacunas de conhecimento e corrigir desequilíbrios na pesquisa é crucial para evitar a redução da biodiversidade e o esgotamento dos serviços

ecossistêmicos essenciais. A distribuição espacial dos dados obtidos é inestimável para ajudar partes interessadas e gestores a tomar decisões informadas.

PALAVRAS-CHAVE: Ameaças; Conservação; Estado ecológico; Formação do dossel; macroalgas; Península Ibérica.

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INTRODUCTION

Coastal marine ecosystems are exceptional habitats that support a diverse arrange of organisms around the world (Capdevila et al., 2018; Fragkopoulou et al., 2022), offering a variety of ecosystem goods and services akin to those provided by terrestrial forests (Schiel & Foster, 2006; Steneck et al., 2002), and whilst maintaining biodiversity and productivity (Gray, 1997). However, the combined effects of human activities and climate change have collectively taken a toll on underwater marine forests ultimately causing their decline and loss (Alberto et al., 2010; Cheminée et al., 2013; Coleman & Wernberg, 2017; de Caralt et al., 2020), is likely to have an impact for associated fauna diversity and trophic interactions (Wahl et al., 2015).

Canopy-forming macroalgae dominate temperate rocky coasts (Orlando-Bonaca et al., 2021). Characterised by high productivity (Bernal-Ibáñez et al., 2021; Casado-Amezúa et al., 2019) and ecosystem engineers (Fernández et al., 2022; Smale et al., 2020), a wide variety of animals, including ecologically and economically important species, depend on them for food, shelter, protection from predators and nursery grounds (Dayton, 1975; Fraschetti et al., 2011; Smale et al., 2013). Moreover, canopy seaweeds not only play an important role in CO_2 sequestration, nutrient cycling, and coastal protection (Filbee-Dexter & Wernberg, 2018; Krause-Jensen & Duarte, 2016), they are also valuable ecological indicators of the health of coastal environments, as most of them are highly sensitive to anthropogenic disturbances (Bernal-Ibáñez et al., 2022; García et al., 2020)

The Iberian Peninsula hosts a diverse array of coastal ecosystems due to its strategic location among the Atlantic Ocean, Mediterranean Sea, and Cantabrian Sea (Muguerza, Arriaga, et al., 2022). This unique geographical situation makes it a biodiversity hotspot (Durrieu de Madron et al., 2011; Garrabou et al., 2019; Monteiro et al., 2022). The oceanographic conditions inherent of these water bodies such as water temperature, nutrients upwelling and salinity are crucial for the distribution patterns of brown canopy-forming algae like those belonging to the orders Laminariales, Tilopteridales, and Fucales (Coll et al., 2010; Muguerza, Arriaga, et al., 2022; Ramos et al., 2020). In these coastal waters, kelps (Laminariales, Tilopteridales) and fucoids (Fucales) are abundant and inhabit intertidal regions to the photic limit (Duarte et al., 2022). Despite similarities, these orders differ biologically and ecologically, notably in dispersal potential (Schiel & Foster, 2006). Kelps can disperse hundreds of meters due to their smaller spores

(Wernberg et al., 2019), while fucoids characterized by slow growth, with larger, sinking propagules, have limited dispersal within a few meters.

Over the last decades, severe declines and even the disappearance of canopy algae have been reported on both the Atlantic ocean (Bernal-Ibáñez et al., 2021) and Mediterranean sea (Thibaut et al., 2005, 2015; Verdura et al., 2018) mainly due to anthropogenic stressors such as urbanization, pollution, habitat fragmentation and elevate levels of sea water temperature (Fabbrizzi et al., 2020; Schiel et al., 2004; Soltan et al., 2001; Thibaut et al., 2015; Verdura et al., 2021). Many species have shifted their geographical distributions in response to warming along the Atlantic coast of Iberian peninsula, particularly for *Laminaria ochroleuca*, *Saccorhiza polyschides,* or *Fucus serratus,* seriously compromising the ecological balance (Casado-Amezúa et al., 2019; Fernández, 2011; Wahl et al., 2015). Simultaneously, brown seaweeds in the Mediterranean Sea typically dominated by the *Cystoseira* genus are likewise affected by the pronounced impacts of warming, water quality, and overgrazing (Garrabou et al., 2019; Ling et al., 2015; Sales et al., 2011). Therefore, the loss or extinction of fucalean canopy-forming algae stimulate the invasion of algal turf, opportunistic seaweed or non – native species, as is the case of *Rugulopteryx okamurae* or *Caulerpa cylindracea,* which prevent algal recruitment and promotes less complex habitats (Benedetti-Cecchi et al., 2001; García-Gómez et al., 2020; Piazzi et al., 2016). Consequently, these reconfigurations in species distributions are expected to have profound ecological, social, and economic implications (Wernberg et al., 2016).

Thus, conserving habitat-forming species is a critical goal for ecologists and environmental managers. Achieving this necessitates effective environmental management and protective strategies for algal forests, considering both environmental factors and intraspecific interactions (Liu & Gaines, 2022; Valdazo et al., 2020). The Mediterranean and Atlantic coasts are both currently facing a decline in species and habitats (Freitas et al., 2019; Thibaut et al., 2014). To tackle these challenges, recent legislative measures have been implemented, such as The Water Framework Directive (WFD), the Marine Strategy Framework Directive (MSFD) are the European umbrella regulations for water systems, the Barcelona Convention (Annex II) (United Nations Environment Programme/Mediterranean Action Plan [UNEP/MAP], 2018) or the methodology CARtography of LIToral and upper-sublittoral rocky-shore communities

(CARLIT), that uses macroalgae abundance to assess the ecological status of coastal waters (Ballesteros et al., 2007). These initiatives aim to ensure the sustainability of marine waters, habitats, and coastal resources. Recently, local restoration initiatives have brought a glimmer of hope to the future of canopy-forming macroalgal ecosystems. However, the outcomes of species restoration remain quite limited, indicating that prioritizing stressor mitigation and preservation efforts may be the most effective strategy for safeguarding these habitats (Garcia et al., 2020).

The initial phase of ecological preservation involves utilizing information to guide stakeholders and managers in decision-making. This encompasses comprehending the temporal distribution of macroalgal species, evaluating population health across different scales, and identifying stressors. This strategic approach is crucial for tailoring conservation, mitigation, and restoration plans to the unique environmental characteristics of each region.

In light of the current circumstances, the main objective of this study is to capitalize on the available information on the ecological status and stress factors influencing macroalgae populations in the waters surrounding the Iberian Peninsula. The intention is to provide a holistic perspective of existing knowledge in this area. This valuable information will serve as a fundamental resource for regional management, strategic planning, and identification of key areas for conservation and restoration efforts, tailoring the approach to address specific threats in each unique area.

The aim of this study were i) to provide an up-to-date and exhaustive semi-quantitative map of the distribution of each taxon, ii) to assess the status of the taxa: stable, in decline, functionally extinct or possibly locally extinct and iii) to analyse and identify the possible causes of the observed situation and its consequences at Iberian scale.

METHODS

Search Strategy

The bibliographic search was performed in four databases/platforms: (a) Web of Science – Core Collection, (b) Scopus, and (c) ScienceDirect, by applying a combination of keywords adapted accordingly for each database using Boolean operators to meet its search specifications **(Table 1.1)**. The search was supplemented with projects in grey literature (e.g., technical reports), sourced through a Google Scholar search.

Web of Science and Scopus enable users to access multiple databases and search for articles using parameters such as article title, abstract, and keywords. In contrast, ScienceDirect provides access solely to the Elsevier database but offers a more extensive search capability, allowing users to search for articles using article title, abstract, keywords, and full text.

From all databases, the total of the documents retrieved by the search was limited to peer-reviewed articles published between January 2013 and May 2023. In the web-based search via the Google Scholar database, the first 200 hits were considered (Haddaway et al., 2015). The inclusion of the start date was deliberate, as the study aimed to evaluate the current ecological state and threats of macroalgae. To avoid outdated data, older publications were excluded from the search.

The choice of a broad search query is intended to incorporate articles with general, yet useful information for our intent. However, this may lead to the inclusion of articles without relevant data, which extends the selection process due to the need for more time.

After applying the search query to Web of Science, Scopus, ScienceDirect and Google Scholar, search results were combined. Duplicates were removed manually and with the aid of EndNote software. After excluding duplicates, the search returned a total of 684 articles.

Table 1.1 Details of Systematic Review search strategy per database, i.e., name of database, date of search, search query, and results (as the number of documents returned by the search).

Database 1:	**Scopus**
Date of search:	May 3rd, 2023
Query:	TITLE-ABS-KEY (laminaria* OR fucal* OR tilopteridal* OR kelp OR Cystoseira OR saccorhiza OR macroalga*) AND (“canopy forming”) AND (“Iberian Peninsula” OR “Canary Islands” OR “Balearic Islands” OR “Mediterranean” OR “Atlantic coast” OR “Cantabrian sea” OR Spain OR Portugal OR “Spanish coast” OR “Portuguese coast”)
Results:	563 documents
Database 2:	**Web of Science – Core Collection**
Date of search:	May 3rd, 2023
Query:	TS= (laminari* OR fuca* OR fucoid* OR kelp* OR Cystoseira OR tilopteridal* OR saccorhiza OR macroalga*)) AND TS=((“canopy-forming”))) AND TS= ((“Iberian peninsula” OR “Balearic Islands” OR “Canary Islands” OR Portugal OR Spain OR “Portuguese coast” OR “Spanish coast” OR “Atlantic coast” OR “Mediterranean” OR “Cantabrian Sea”)
Results 1:	75 documents
Database 3	**ScienceDirect**
Date of search:	May 3rd, 2023
Query	TITLE-ABS-KEY-TEXT (laminaria OR fucus OR kelp OR Cystoseira OR tilopteridal) AND (“canopy-forming”) AND (“Iberian peninsula” OR “Balearic Islands” OR “Canary Islands”)
Results:	52 documents
Database 4	**Scholar Google**
Date of search:	May 3rd, 2023

Query	laminari* OR fuca* OR fucoid* OR kelp* OR Cystoseira OR tilopteridal* OR saccorhiza OR macroalga*) AND (“canopy-forming”) AND (“Iberian peninsula” OR “Balearic Islands” OR “Canary Islands” OR Portugal OR Spain OR “Portuguese coast” OR “Spanish coast” OR “Atlantic coast” OR “Mediterranean”
Results:	869 documents (only the first 200 hits were considered)

Eligibility evaluation

Studies obtained through online search engines on canopy-forming macroalgae in the Iberian Peninsula were systematically reviewed to assess their suitability for data extraction. To determine the eligibility of the data included in this review, a structured selection process was carried out.

Predefined inclusion and exclusion criteria were applied to filter relevant studies. Inclusion criteria considered location, start date of the study, presence of canopy – forming macroalgae of the orders Fucales, Laminariales and Tilopteridales and other relevant aspects can be seen in **Table 2.1**. Studies that met these criteria were subjected to a methodological quality assessment. The process of evaluating eligibility involved an initial screening of the title and abstract by two reviewers to conduct a preliminary assessment. Subsequently, if the outcome was favourable, a more comprehensive examination of the methods, results, and discussion sections was undertaken. All the studies without georeferenced data were not further examinated and were excluded from the review.

The details of the selection and assessment process were transparently documented in a flow chart following the PRISMA guidelines. The documentation includes the number of studies retrieved, excluded, and finally included, with the exclusion reasons at each stage **(Supplementary Figure 2.6).**

Table 2.1. Inclusion and exclusion criteria for the Systematic Review in correspondence with the "Participants, Concept and Context, PCC" mnemonic and evidence types and sources.

	Inclusion criteria	Exclusion criteria
PARTICIPANTS *Macroalgae canopy-forming*	Studies on canopy - forming macroalgae order Laminariales, Fucales and Tilopteridales.	Studies on non-canopy-forming macroalgae. Studies on macroalgae other than canopy-forming macroalgae of the order Fucales, Laminariales, and Tilopteridales.
CONCEPT *Description of the variables considered.*	All studies specifically including ecological status, threats impacting populations, geographical information, species identified, abundance dynamics and year of sampling or observation.	Studies in which the authors used the same sampling data to conduct different investigations and publish more than one paper ("*re-cycling*" *of published data*)
CONTEXT *Marine realm*	Studies in: • Iberian Peninsula, Spain, Portugal, Balearic Islands, Canary Islands. • Marine realm.	No specific geographical information on macroalgae communities was provided. Studies without a marine component.

EVIDENCE TYPES & SOURCES	- peer-review literature - grey literature - publication years from 2013-2023 - all publication stages, subject areas, and source types - experimental and observational studies - case studies, reviews, framework/synthesis - studies published in languages competent to the researchers' team (e.g., English, Spanish and Portuguese according to the team's language competency)	---

Data extraction

The purpose of data extraction was determined by the stated research objective. Six main variables were considered: (1) geographical information: precise information on the occurrence of macroalgae of the orders of interest. Usually described as geographic coordinates, site names or maps, (2) ecological status: data on the ecological status of the canopy-forming macroalgae populations were extracted. In some cases, these data were numerical and in others categorical, (3) stressors: the role of multiple stressors, both abiotic and biotic, impacting the populations of the macroalgae of interest (4) dynamics of the abundances: study of the increase, stable or decreasing abundances of the populations (5) species: identified (6) year of sampling: when the observation or sampling took place.

Regarding geographical information, coordinates using the Decimal, Minutes, and Seconds (DMS) system were converted to Decimal Degree coordinates, location names were searched in online websites such as Google Earth or regional mapping providers (Información xeográfica de Galicia: xeoportal/ infraestrutura de Datos Espaciais de Galicia, Registro Nacional de dados Geográficos SGIG) and maps were georeferenced using the QGIS 3.32.2-Lima software, which allowed the extraction of coordinates with the same program.

In terms of ecological status descriptions, categorical data exhibited notable diversity. Sites categorized as "forest," "continuous belts," or "dominant" were deemed to possess *Good* ecological status. "Patchy" descriptions indicated *Moderate* status, whereas "scattered individuals," "barren," or "absent" corresponded to *Poor* status. Conversely, numerical data utilized different measurements such as wet weight, thalli count, or percentage cover. For each metric, different thresholds were used to assign the data to the study's ecological status.

The data were classified into three categories describing ecological status as *Poor*, *Moderate,* or *Good*, as outlined in **Tables 3.1** and **3.2**. For the Fucales order, the classification was based on the methodology described by Fraschetti et al., (2022) with some minor changes, such as adding the descriptive measure. Subsequently, a similar methodology was applied to the Laminariales and Tilopteridales orders, based on information extracted from various articles. For instance, a study conducted by Barrientos et al. (2023), showed a density increase of 16.6 ± 3.78 individuals per 0.25 m^2 of *Laminaria ochroleuca*, coinciding with an approximate percentage cover of 60. These findings resulted in a classification as a *good* ecological status.

In cases where parameters were not clearly described and/or there was uncertainty in the interpretation of these data, they were discussed and interpreted in consultation with other contributors.

As the taxonomy of some species is subject to constant changes during the last years, most of the species names used in the reviewed publications are no longer accepted, as is the case for Cystoseira s. l. These names were changed to the latest accepted taxonomy.

Table 3.1 Criteria used to classify the different data within the three ecological states of Fucales established in this study: Poor, Moderate, and Good (obtained through Fraschetti et al., 2022).

	Ecological status		
Measure	**Poor**	**Moderate**	**Good**
% cover	0-10	10-50	50-100
Wet weight (g/m^2)	0-100	100-500	≥ 500
Density (Individuals/m^2)	0-1	2-3	≥ 4
Descriptive	"Scattered individuals" "Absent" "Barren ground"	"Patches"	"Forest" "Continuous belts" "Dominant"

Table 3.2. Criteria used to classify the different data obtained through different variables within the three ecological states of Laminariales and Tilopteridales established in this study: Poor, Moderate, and Good.

	Ecological status		
Measure	**Poor**	**Moderate**	**Good**
% cover	0-30	30-60	60-100
Wet weight (g/m^2)	0-250	250-600	≥ 1000
Density (Individuals/m^2)	0-4	5-9	≥ 10
Descriptive	"Scattered individuals" "Absent" "Barren ground"	"Patches"	"Forest" "Continuous belts" "Dominant"

Data Analysis

The resulting database was composed of georeferenced points presenting various categories. These points were mapped using Geographic Information System (GIS) software, specifically QGIS 3.32.2-Lima. The coordinate reference system used was WGS 84 (EPSG: 4326), and a satellite image from the National Aerial Orthophotography Plan (PNOA) was chosen as the background map for the visualization of the data.

In order to identify geographical differences at regional level, the Iberian Peninsula was divided into six sub-regions, as proposed in the OSPAR Commission (2010) with some changes. The sub-regions of the Iberian Peninsula used in this study can be seen in **Figure 1.1**

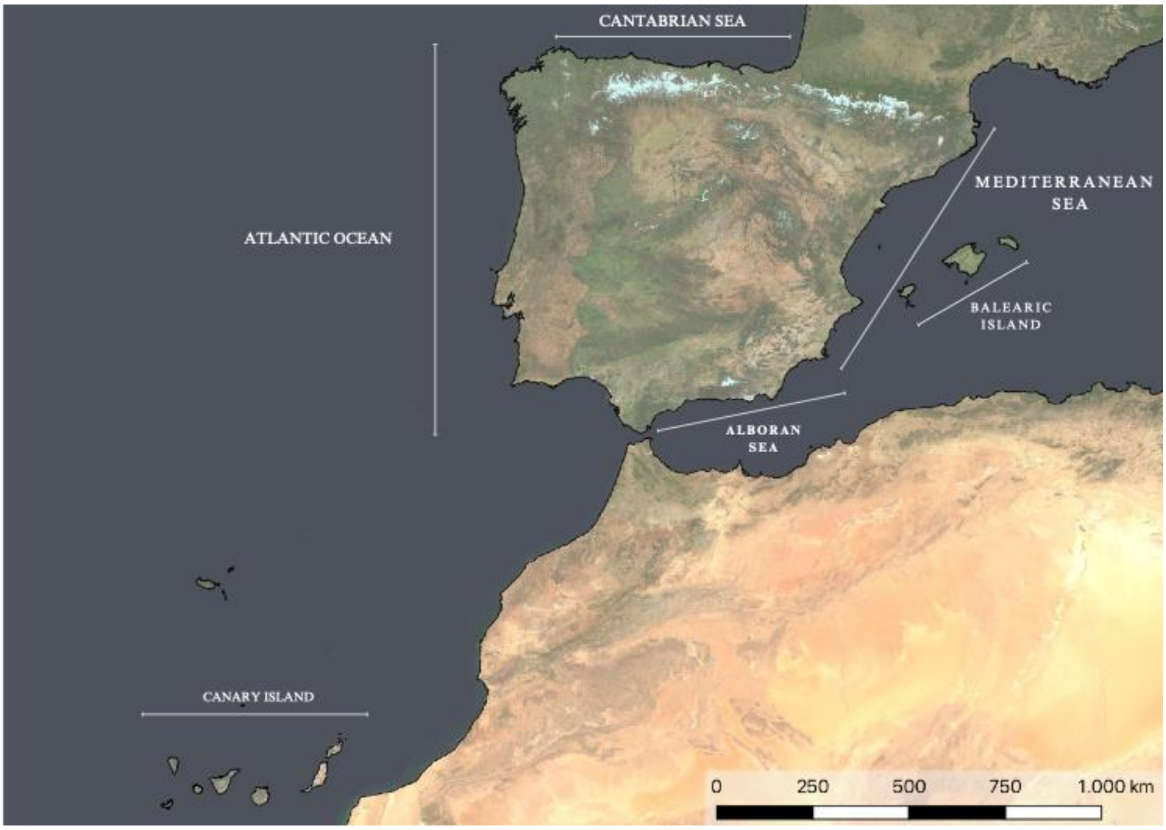

Figure 1.1. Map of Iberian sub-regions (modified from OSPAR Commission 2010. Atlantic Ocean, Cantabrian Sea, Mediterranean Sea, Alboran Sea, Balearic Islands and Canary Islands)

To assess whether certain geographical regions received more research attention than others, a count of the points located within each sub-basin was conducted -given that the presence of macroalgae is primarily concentrated in coastal areas-, the number of points counted in each sub-region was standardized by dividing it by the length of the corresponding coastal line. The total length of the coastal line for each sub-region was determined using a linear layer provided by OpenStreetMaps, which is generated from aerial imagery and is freely accessible online (https://osmdata.openstreetmap.de/data/coastlines.html)

It is crucial to address the Coastline Paradox, also known as the Richardson Effect as this concept underscores that the length of a coastline is not a fixed quantity but rather varies depending on the level of measurement detail. In essence, as we meticulously map intricate coastal features such as bays, coves, and peninsulas, the measured coastline length increases exponentially, theoretically approaching infinity. Our choice of employing a layer (Reference to layer name) with a high degree of precision yielded coastline measurements that reflected significant values for each region, consistent with this paradoxical phenomenon.

To illustrate trends in research on the subject, we conducted an analysis of the years of publication of the articles reviewed, as shown in the figure. In addition, we quantified the number of articles identifying each species within the orders Fucales, Laminariales and Tilopteridales, in order to assess possible research biases in relation to these species, as shown in another figure. Subspecies, variants, and forms were not taken into account, and the classification of species was done at the species level.

In addition, we examined whether stress factors affecting macroalgal populations in the Iberian Peninsula, the Canary Islands and the Balearic Islands showed spatial patterns in the Atlantic Ocean, the Cantabrian Sea, the Alboran and Mediterranean Sea. We projected data points for the stressors and created layers of distinct points for each stressor to determine whether certain regions were more affected by specific stressors than others.

The "Standard Distance" is then used as a fundamental tool to assess the spatial dispersion of our set of data points. The "Standard Distance" calculates the mean centre (X, Y) of the sampling points and then determines the mean distance of each point from this mean centre, similar to the calculation of a standard deviation. This process culminates in the generation of a circle with the mean coordinates at its centre and the mean distance as radius. This analysis is crucial to identify patterns of clustering or dispersion that may be of relevance.

Ethic and Sustainability Criteria

All the articles reviewed in this study were legally accessed, prioritizing the use of Open-Access journals. However, when access was limited, the credentials provided by the Algarve University Library were used.

The majority of authors in the reviewed articles acknowledged the absence of conflicts of interest in their publications. In the case of sampling within Marine Protected Areas, it should be noted that the authors had obtained prior approval and meticulously adhered to the guidelines mandated by the competent authorities.

RESULTS

Research Trends

The data screening yielded a total of 67 articles subject to review, from which a total of 1166 data points were extracted. The number of points obtained for each article showed considerable variability, ranging from 1 to 279 points. A full catalogue of the articles submitted for analysis is included in **Supplementary Table 5.6**. Each data record is completed with information regarding geographical coordinates, title and author, date of publication, year of sample collection where available, a specification of ecological status and stressors that were sampled.

By examining the chronology of publication of the articles under review, a gradual increase is observed, being slightly higher in the most recent years, with 2023 being an exception as it only considered until March, as illustrated in **Figure 1.2**. 2020 stands out as the year with the highest number of selected publications, with 14 articles under review, while 2013 is the least represented, without any selected articles.

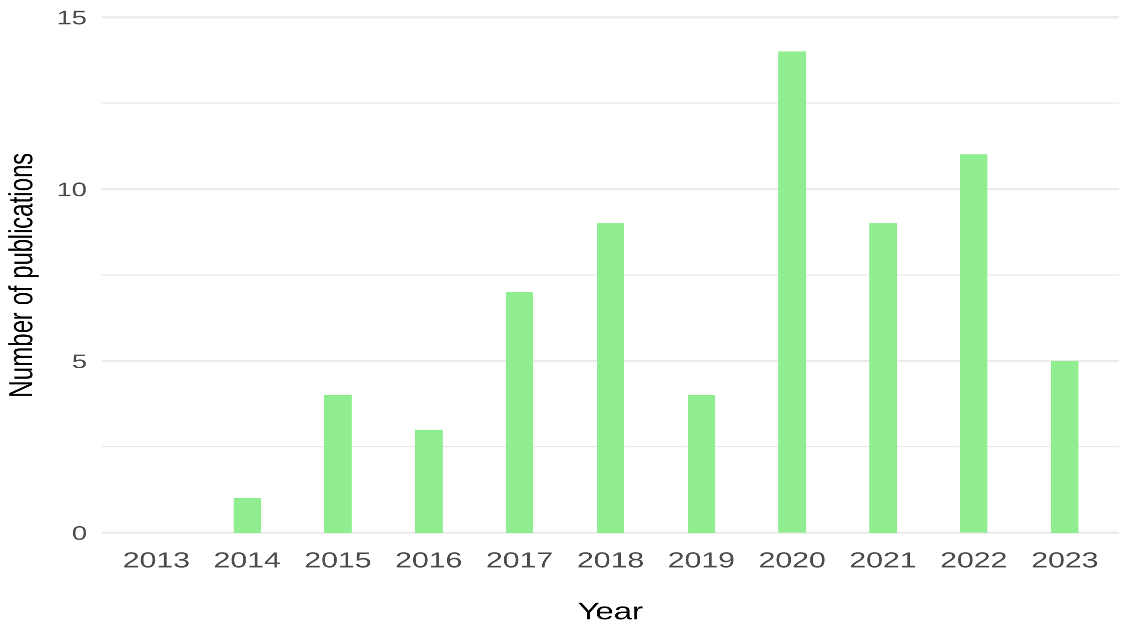

Figure 1.2. Number per year of scientific papers reporting spatial data on canopy – forming macroalgae of the order Fucales, Laminariales and Tilopteridales in the Iberian peninsula, Balearic and Canary Islands.

The identification of canopy-forming macroalgae species was not evenly distributed in the articles analysed, revealing a remarkable disparity in their presence and frequency **(Figure 1.3)**. In the totality of the articles reviewed, we identify a set of 18 species belonging to the *Cystoseira sensu lato* group, which represent approximately 50% of the dataset. Among these, *Cystoseira compressa*, *Ericaria selaginoides*, and *Gongolaria baccata* stood out as the most frequently identified species. However, *Laminaria ochroleuca*, belonging to the order Laminariales, was found to be the species with the highest frequency of identification in multiple publications, followed by *Sacchorhiza polyschides*, which was identified in 14 publications and 12 publications respectively. In contrast, *Alaria esculenta, Fucus spiralis, Halidrys siliquosa* and *Sargassum natans* were the least frequently identified species, with only one occurrence each in the entire literature review. This information is mainly available for the shallow rocky infralittoral habitat, where many ecological studies and systematic monitoring have been carried out, thus representing a biased scenario of macroalgal occurrence. Furthermore, although most studies provided information at the species level, a total of 72 records were mapped at the genus level as *Cystoseira spp* in the order Fucales.

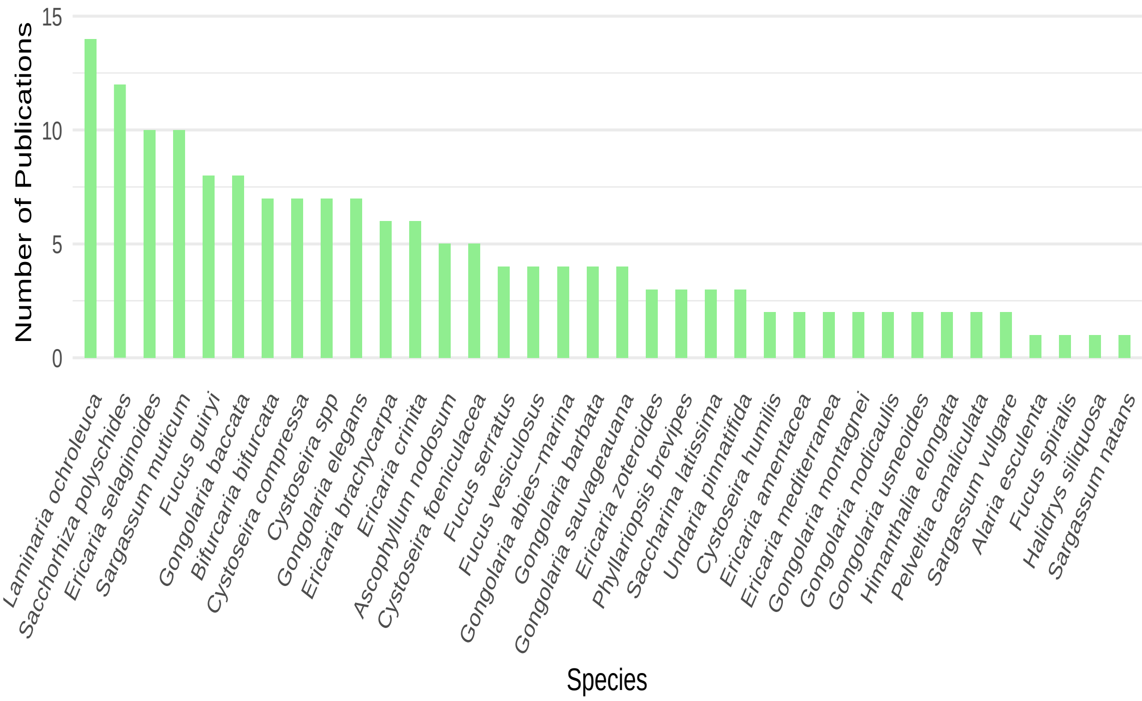

Figure 1.3. Data availability. Number of articles reviewed identifying different canopy – forming macroalgae of the order Fucales, Laminariales, and Tilopteridales.

The currently known distribution, obtained by points of occurrence, represents the areas where canopy – forming macroalgae of the orders Fucales, Laminariales, and Tilopteridales are known to be present **(Figure 1.4)**. The distribution of sampling points across the Iberian Peninsula and its islands is not uniform, with the south-eastern part notably underrepresented. In the Mediterranean Sea, in particular, there is a marked scarcity of sampling points along the Costa Blanca and Costa de Azahar, as well as in the Gulf of Cadiz, as shown in the **Figure 1.5**. On the other hand, some subregions, such as the Cantabrian Sea and the northwest of the Peninsula, stand out for having a notable density of sampling points.

However, it is important to note that, since canopy – algae are predominantly found in the intertidal zone (Schiel & Foster, 2006; Steneck et al., 2002) sampling point density should not be used as an indicator, despite it being an intuitive interpretation. Instead, to compare subregions, it is recommended to use the density of sampling points per unit length of coastline, as shown in the accompanying **Table 4.1**. The mentioned table provides an overview of the total coastline lengths for each sub-region. Given the considerable variation in coastline lengths among these sub-regions, we standardized the data by calculating the number of sampling points per 1,000 km of coastline.

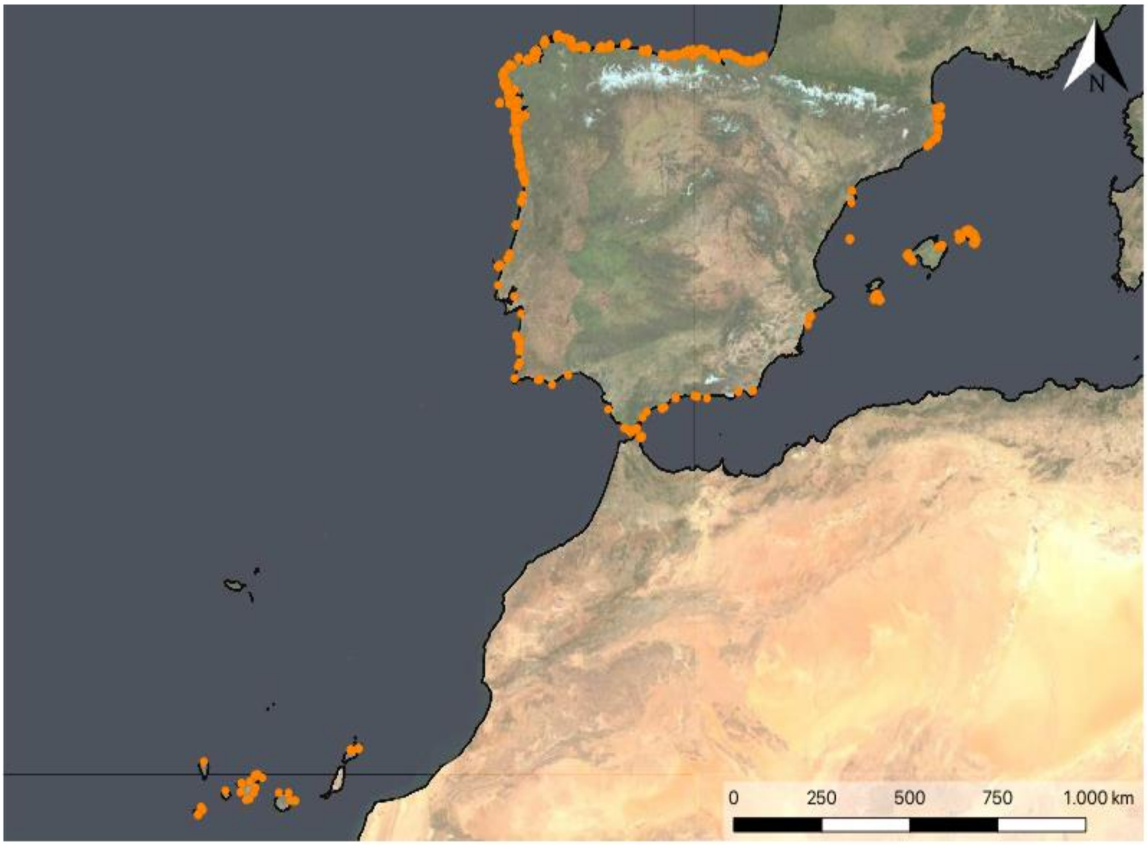

Figure 1.4. Map of sampling points obtained in the data extraction process, represented on a base map showing the Iberian Peninsula and the sub-regions defined in this study (Balearic and Canary Islands).

Table 4.1. Sampling points by Iberian Peninsula and Islands regions. Coastline lengths used to standardize data, and the values obtained after the standardization are also displayed.

Regions	Sampling Points	Km of coastline	Sampling points/ 1000km
Cantabrian Sea	137	1,602	85,51
Atlantic ocean	750	6,271	119,59
Mediterranean Sea	258	3,466	74,43
Alboran Sea	21	1,095	19,17
Balearic Islands	129	1,490	86,57
Canary Islands	36	1,857	19,38

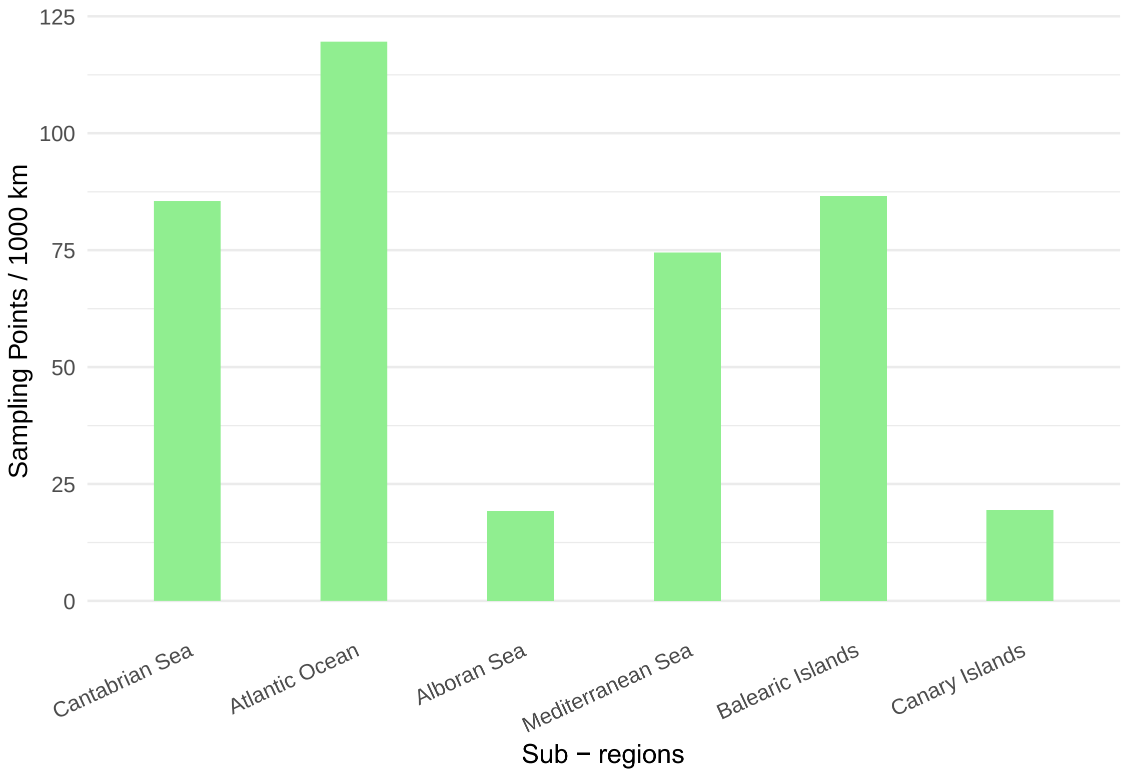

Figure 1.5. Sampling points of each sub-region, standardized by coastline length (Cantabrian Sea, Atlantic Ocean, Alboran Sea, Mediterranean Sea, Balearic Islands and Canary Islands).

Ecological Status Assessment

A comprehensive assessment of canopy seaweed population's ecological status was conducted. This assessment involved assigning labels representing three fundamental categories: 'Good,' 'Moderate,' or 'Poor.' It is pertinent to note that the 'Unknown' category was applied to those sampling points where sufficient information to allow a precise evaluation of ecological status was unavailable.

Out of an initial set of 1166 sampling points, information related to ecological status was obtained for a total of 609 points. Among these, 229 were identified as having an ecological status categorized as 'Good,' indicating a favourable level of health and conservation. In contrast, 156 points were labelled as 'Moderate,' suggesting an acceptable ecological status, albeit with detectable concerns. Lastly, 224 points were identified with a 'Poor' ecological status, signifying a notable degradation in the ecological conditions of these areas.

The representation of the ecological status data shows an intricate spatial distribution, lacking any discernible apparent pattern (see **Figure 1.6 and 1.7)**.

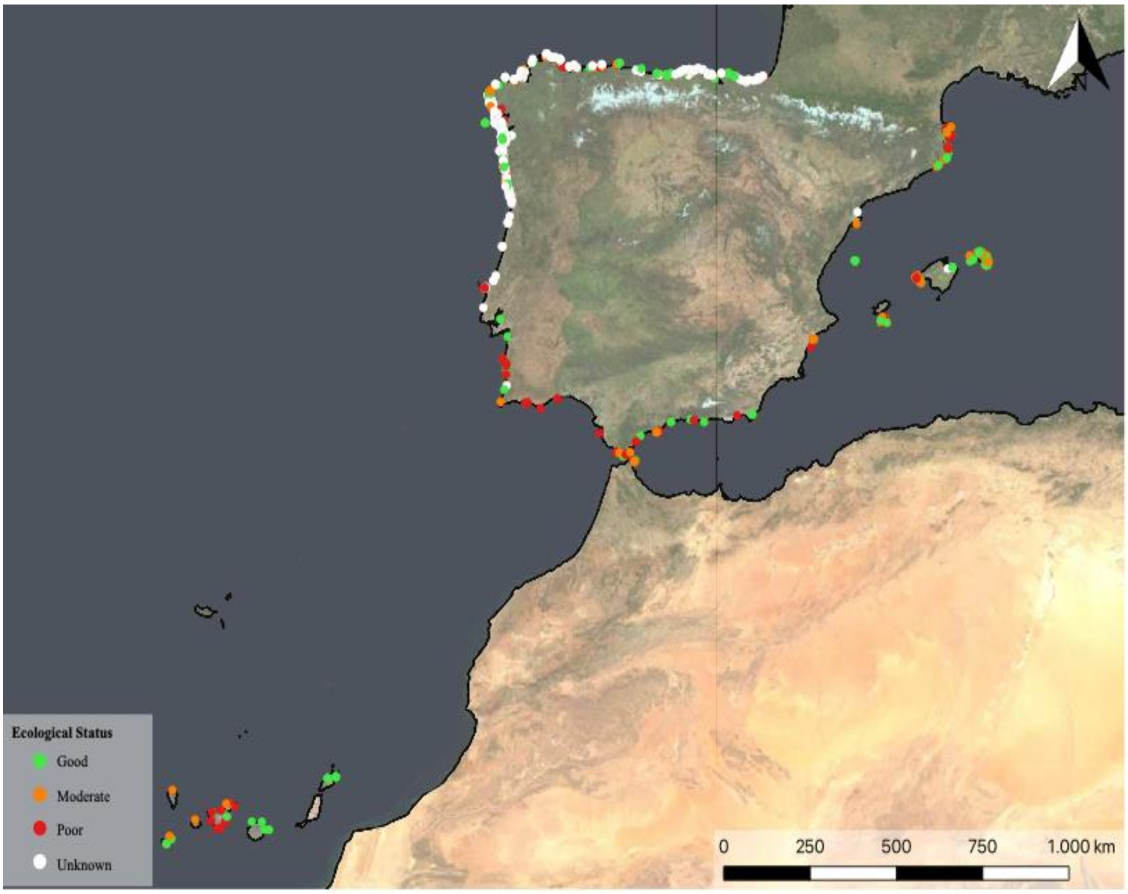

Figure 1.6. Map of ecological status of canopy - forming populations along the Iberian Peninsula and Balearic Island.

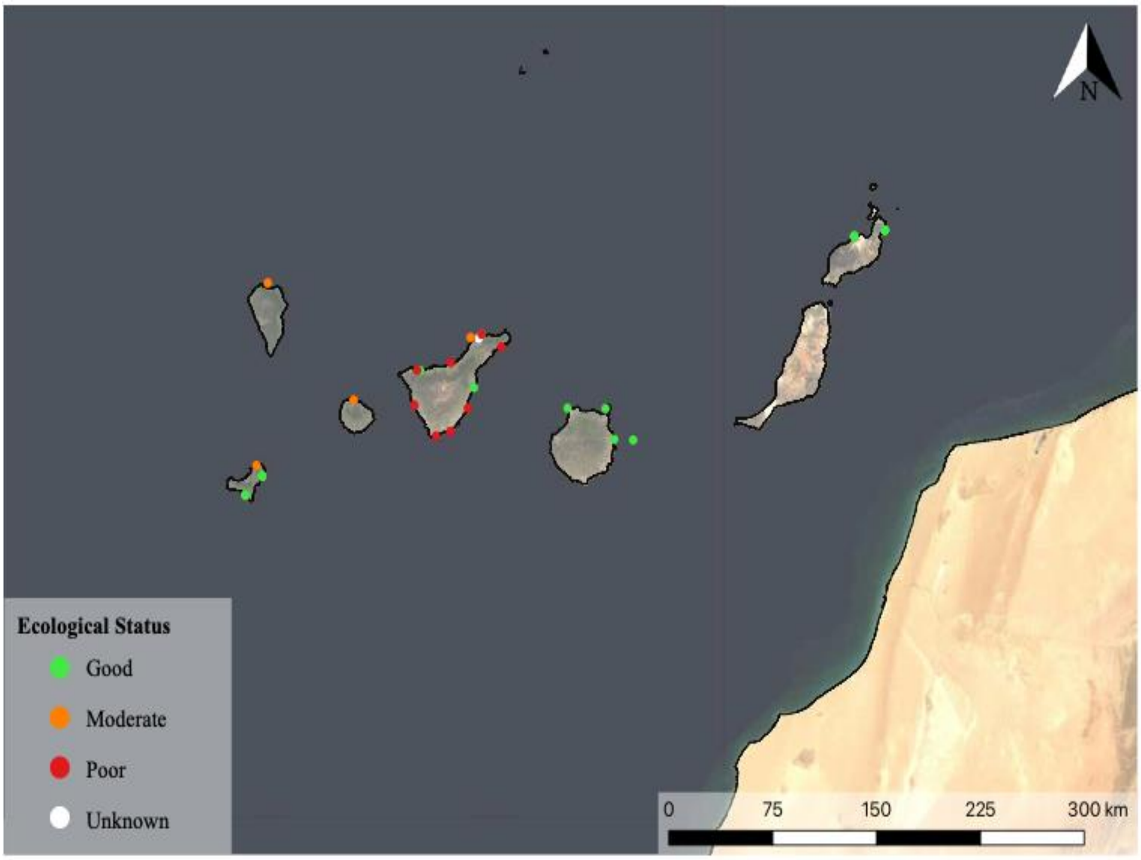

Figure 1.7. Map of ecological status of canopy - forming populations along Canary Islands.

Broadly speaking, there is no pronounced predominance of sites with favourable ecological status across the study area. Instead, there is a preponderance of sampling points with insufficient data, showing a certain tendency towards spatial zonation, mainly concentrated in the northern reaches of the Atlantic region, and extending along the Cantabrian Sea. In addition, other regions seem to show a mixed presence of different ecological states.

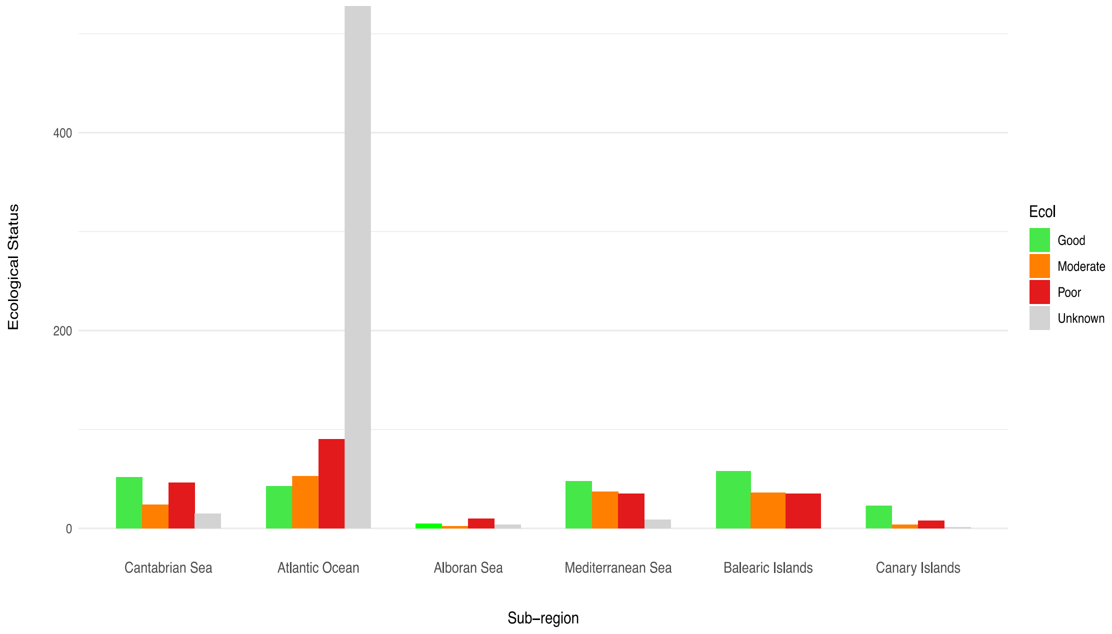

Figure 1.8. The presence of different ecological status points found (Green = Good, Orange = Moderate, Red = Poor) at each sub-region (Cantabrian Sea, Atlantic Ocean, Alboran Sea, Mediterranean Sea, Balearic Islands, Canary Islands).

However, a more nuanced perspective emerges when the data are examined according to sub-regions. This refined view reveals the presence of areas characterized by a markedly impoverished ecological state, exemplified by segments of the Atlantic Ocean and regions of Portugal **(Figure 1.8)**. Specifically, an interesting dynamic was observed in macroalgae populations in the Cantabrian Sea, Mediterranean Sea, and in both islands. These areas exhibited more apparent evidence of a favourable ecological status compared to the analysis of the map alone, characterized by a higher number of observations classified as 'good.' However, it is essential to note that ecological status records, primarily categorized as 'good,' exhibit a notable inclination towards a rating of 'moderate' or 'poor', showing a slight difference in ecological status conditions. Concerning the Alboran Sea, the dataset is very limited.

Abundance Dynamics

When examining population abundance dynamics, only 309 observations were obtained out of a set of 1166. In this case, the focus was specifically on whether these populations had increased, decreased, or remained stable over time.

Stressors Affecting Canopy – Forming Macroalgae

A total of 406 sampling points from published studies and technical reports provided information on target seaweed declines associated with various threats. Although this dataset was less abundant compared to the information collected on ecological status, specific stressors were identified. Interestingly, some stressors were repeated at several sampling points.

The prevalence of stressor data in the dataset may have been relatively low, but it undeniably provides valuable information on the multifaceted challenges faced by canopy-forming macroalgal populations. These stressors were systematically classified into seven distinct groups, as indicated in **Table 5.1.**

Table 5.1. Stressor categories defined on this study, with the number of sampling points obtained for each category.

Categories	Description	Sampling Points
Water quality	Sewage outfall/chemical pollution, water turbidity, sedimentation, eutrophication (e.g., aquaculture farming or mariculture), freshwater inputs, agriculture, eutrophication etc.	22
Habitat destruction	Habitat loss, harbour facilities, urbanisation, trawling, anthropization	131
Global warming	Seawater warming, marine heatwaves, acidification, and/or storms	193
Overgrazing	Herbivorous pressure from autochthonous fish or sea urchin	30
Natural causes	Including hydrodynamics, strong winds, hydrothermal activity etc.	23
None	Absence of stressors confirmed	17
Unknown/Not reported	Stressor either not reported in the study or unknown	750

In **Table 5.1** it can be seen that some stressors have much greater presence than other. Climate change was considered the most relevant stressor. However, other factors, such as habitat destruction and increased frequency of storm surges, and non-climatic factors such as overgrazing, were also identified as relevant.

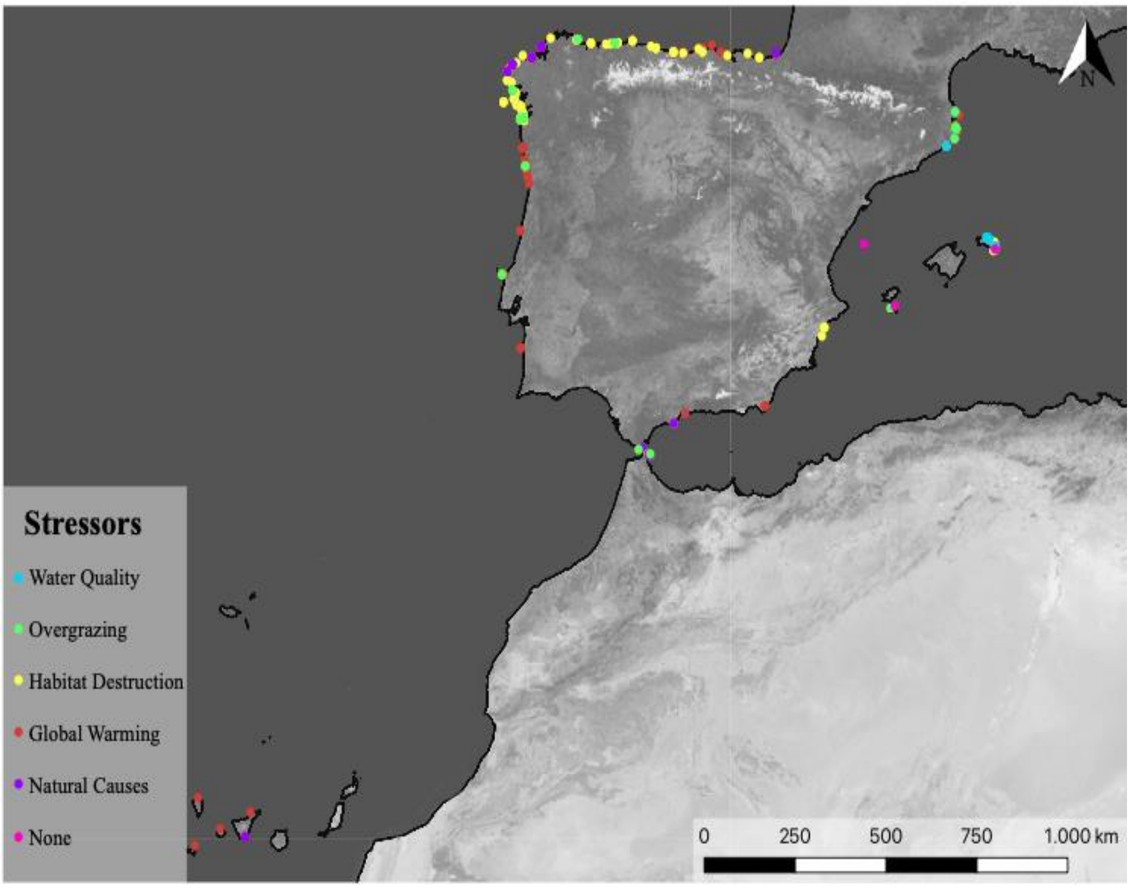

Figure 1.9. Map of stressors impacting canopy – forming populations along the Iberian Peninsula, Balearic Islands and Canary Islands.

The general distribution of data points containing information on threats to canopy-forming macroalgae populations is visually represented in **Figure 1.9**. In particular, subtle patterns in the distribution of stress factors affecting our target algae populations have been identified. Looking at the map, it is evident that water quality exhibits a more pronounced presence in the coastal regions of the northern Mediterranean, extending to some points along the Balearic coast. Conversely, threats such as habitat destruction and global warming are easily discernible along the coasts of the Iberian Peninsula, including the Canary Islands, with both threats showing a higher frequency of occurrence. Conversely, certain threats appear to be more dispersed, such as natural phenomena or overgrazing, which seem not to follow any zonation along the peninsula.

It is also worth noting that there are very few points where macroalgae populations were recognized not to be impacted by any stressor, limiting its presence to Mediterranean areas.

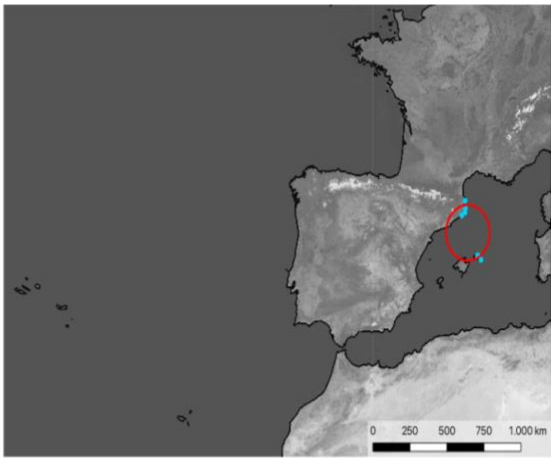

Figure 2.0. Locations impacted by Water Quality

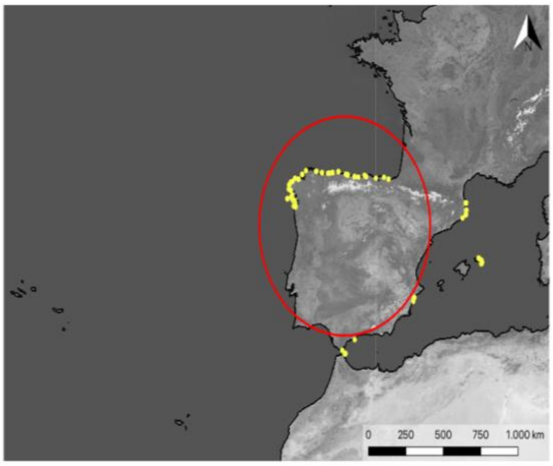

Figure 2.1. Locations impacted by Habitat Destruction

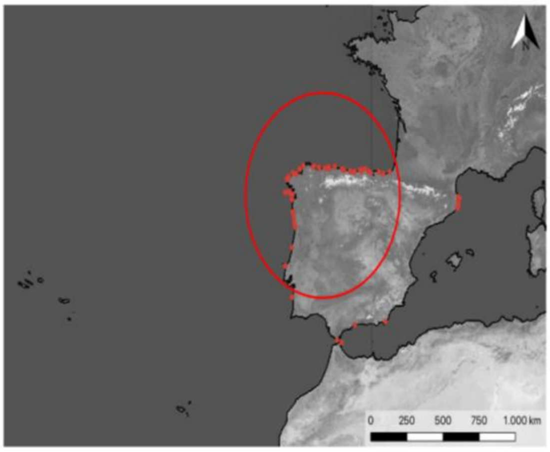

Figure 2.2. Locations impacted by Global Warming

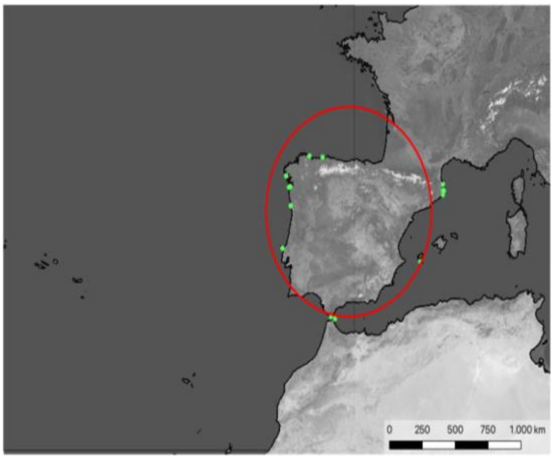

Figure 2.3. Locations impacted by Overgrazing

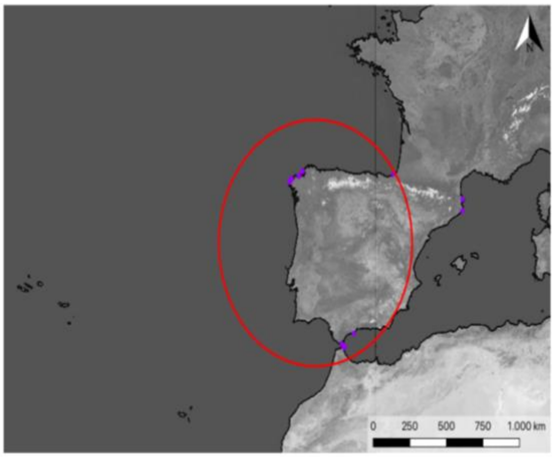

Figure 2.4. Locations impacted by Natural Causes

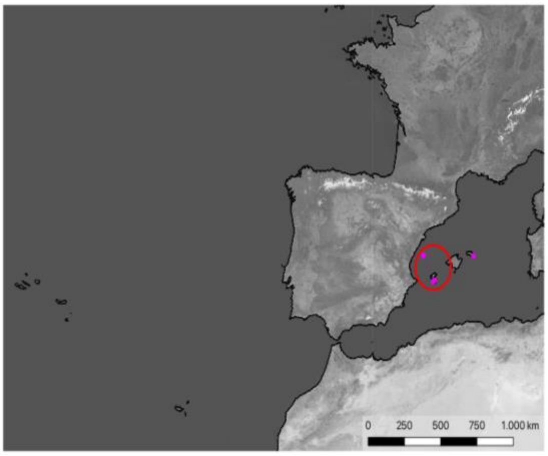

Figure 2.5. Locations not impacted by any stressor

Figures 2.0-2.5. Maps of geographical distribution of the different stressors. The sampling points of the different stressor categories are mapped individually. Standard Distance (SD) is represented as a red circle.

When looking at the geographical distribution of the stressors reveals significant variations in their dispersion and location across the Iberian Peninsula (**Figures 2.0-2.5)**. The calculation of the Standard Distance (SD) Index provides valuable insights into the spatial distribution of these threats and highlights their distinctive patterns. Stressors in the Canary Islands were so poorly represented in the overall data that it was decided not to analyse them further.

The lowest SD is observed in the categories of 'Water Quality' (**Figure 2.0**) and ' locations non impacted by any stressor' (**Figure 2.5**), indicating a notable concentration of points within the standard distance (SD) circle. This suggests low point dispersion and clear zoning in of threats and locations without any recorded disturbance, uniformly distributed within the Mediterranean Sea.

In contrast, the spatial patterns of 'Global Warming' and 'Destruction of Habitat' (**Figure 2.2, 2.3**) exhibit a higher SD, implying that the points are more distant from each other. Both patterns encompass a significant portion of the north-western Iberian Peninsula and display scattered points in the Mediterranean region, indicating a lack of clear zoning. The lack of zoning is more pronounced in the case of 'Habitat Destruction' **(Figure 2.3)**, the SD circle is centrally positioned on the map, with a substantial proportion of points lying outside the circle. These points on both sides may be compensating for each other. For the 'Global Warming' **(Figure 2.2)**, although some distant localities may influence the position of the SD circle, the SD indicated a higher concentration of points on the western part of the Iberian Peninsula.

Regarding 'Overgrazing' (**Figure 2.1**), also shows a high SD, it appears to be distributed more sparsely having a presence in most of the regions. This lack of zonation is more evident since the SD circle occupies a centred position on the map, and some proportions of the points are outside the circle, especially on the east of the SD zone. Finally, in the case of populations impacted by 'Natural Causes' (**Figure 2.4**), their highest incidence is along the northwest coast of the peninsula, with scattered points in the eastern part of Spain.
It is noteworthy to observe how the majority of information on stressors is concentrated in Spanish locations, with limited presence in the coastal areas of Portugal.

DISCUSSION

This study, compiled the most recent information on the ecological status and stress factors affecting canopy-forming macroalgae of conspicuous orders along the coasts of the Iberian Peninsula, including the Balearic and Canary Islands. By reviewing data published in the last decade, I provide a first picture of the geographical distribution of key ecological information crucial for the conservation of these canopy-forming algae. However, substantial variability exists among geographical regions. Many areas, such as the Alboran Sea and the central coastal region of Portugal, have received limited research attention. Notably, extensive efforts have been directed towards the North Atlantic coast and Mediterranean Sea. Although, data concerning the Atlantic coast often lack comprehensive ecological information and primarily document species presence.

In line with the aforementioned, when we examine the research trend on this subject, there is an evident growing interest over the years. However, it is noteworthy that this continuously evolving research predominantly focuses on regions where robust information is readily available. While certain areas are still underexplored concerning their canopy-forming macroalgae populations and ecological status.

Another remarkable aspect of this study pertains to the dissimilar proportions in which various species have been studied across the Iberian Peninsula and its surrounding islands. Despite the predominance of species belonging to the orders Laminariales and Tilopteridales, most of the reported research efforts have been primarily dedicated to species within the *Cystoseira sensu lato* group, which currently encompasses three genera: *Cystoseira, Ericaria, and Gongolaria* (Sargassaceae, Fucales). This is reflected in approximately 50% of the reported identifications. Meanwhile, there still exists a significant knowledge gap regarding the biology and ecology of several species in this group (Hereu et al., 2008)

This observation may be attributed to several factors. Firstly, the wide distribution of many *Cystoseira sensu lato* species along the entire coast of the Iberian Peninsula and its surrounding islands could have led to a higher frequency of research efforts focused on them, (Bermejo et al., 2018; García-Fernández & Criado, 2016; Jódar-Pérez et al., 2020; Martín García et al., 2022). Secondly, numerous *Cystoseira* species tend to thrive in shallow waters within protected coves and bays (Sales & Ballesteros, 2009). The composition, structure, and geographical distribution of deep-water assemblages can pose challenges for research due to difficulties in sampling these less accessible areas (Hereu et al., 2008; Juanes et al., 2008).

Understanding the ecological status of macroalgae populations in the Iberian Peninsula and Spanish islands, plays an essential role in addressing conservation and management challenges in this marine environment, characterized by its diversity and dynamism. In this regard, our meticulous analysis of available information reveals significant trends and disparities in ecological status records across the entire coastal region.

Notably, areas such as the Mediterranean coast and the Balearic and Canary Islands have provided comprehensive data on ecological status, providing detailed information on the ecological status of species. In contrast, the dataset does not reveal clear spatial patterns at large scales, suggesting that the complex interplay of local dynamics exerts a more pronounced influence. A salient observation emerges when we turn our attention to the western regions of the peninsula, where a prevalence of moderate to poor ecological status is evident compared to other regions. This consistent trend aligns well with findings from local and regional studies in the north-western peninsula, as documented by and (Krumhansl et al., 2016), which consistently report a continued decline of marine ecosystems and populations coping with cumulative impacts. Furthermore, it is noteworthy that most of the regions analysed present a mosaic of ecological status records, ranging from poor, moderate and good. This suggests that in areas where apparent ecological health prevails, there may be underlying challenges that require attention, in particular the local threats. Redirecting our attention to regions such as the Canary and Balearic Islands reveals a relatively brighter ecological picture. Emphasis on addressing local threats has proven to be a more effective approach than global-scale management strategies. However, it is plausible that the comparatively better ecological status of these areas is due, in part, to a narrower spectrum of research efforts.

This finding is consistent with previous studies that have reported on the current status of marine ecosystems. According to assessments done by Airoldi & Beck, (2007), less than 15% of the European coastline is considered to be in a "good" state. These figures underscore the need to address and improve the health of marine ecosystems in the Iberian

Peninsula, especially in regions where ecological status records are less encouraging. In particular, addressing local threats is a more effective approach than global-scale management strategies.

Stressors affecting canopy-forming macroalgae populations displayed geographical variations as Casado-Amezúa et al., (2019) mentioned, and global declines (Strain et al., 2014). Direct anthropogenic pressures, such as water quality, exhibited high zonation and were confined to relatively small areas. High incidences of water pollution were observed in the Mediterranean Sea, often coinciding with habitat destruction in this region. Habitat loss, a stressor displaying considerable dispersion, was widespread along the Northwest Atlantic. This suggests that inefficiencies in regulating coastal activities may be common among regions. In this context, organizations such as the European Union, the OSPAR commission (2010), the Barcelona Convention Water and Marine Strategy Framework Directives (WFD and MSFD) could play a crucial role in promoting the protection and conservation of these marine ecosystems, by detecting these local threats.

On the other hand, herbivory was significantly widespread throughout the Iberian Peninsula, affecting kelp populations along the Atlantic coast and, in the case of the Mediterranean Sea, affected *Cystoseira* species, with a more pronounced impact in the northern areas. The primary categories of herbivores involved in these processes include sea urchins, sparid fish in the Mediterranean, due to overfishing, and native or invasive herbivorous fish (Barrientos et al., 2022; Gianni et al., 2017; Sala et al., 1998; Vergés et al., 2014). Both sea urchins and fish are responsible for persistent damage and loss of various species in the Mediterranean Sea (Guidetti & Dulcić, 2007; Nikolaou et al., 2023) and in the Atlantic Ocean (Barrientos et al., 2023; Wernberg et al., 2019). Increasing abundances of grazers that feed on macroalgae can lead to the loss of dominant habitat-forming species. This decline could result in the proliferation of less complex and smaller species of turf-forming algae, ephemeral filamentous algae, or opportunistic species (Perkol-Finkel & Airoldi, 2010; Tait & Schiel, 2011; Thibaut et al., 2015). In this sense we propose that a standardized monitoring to establish the critical thresholds of grazers abundances that can lead to canopy forming decrease, may help to identify areas where grazers management is needed.

Global warming exhibits a significant variability in its impact. A notable incidence of rising temperatures is observed in the northwest region of the Iberian Peninsula, coinciding with the presence of natural threats whose distribution overlaps with that of global warming. These findings support prior research, such as Wahl et al., (2015) studies which has emphasized the sensitivity of algae to temperature variations. This increase in sea temperatures reduces the resilience of algae species, rendering them more susceptible to other threats and consequently leading to shifts in their distribution. This response is unsurprising, given the evident rise in sea surface temperatures (SST) impacting the distribution of numerous species along Atlantic coasts, including Spain (Díez et al., 2012; Fernández, 2011), Portugal (Tuya et al., 2012), Canary Islands (Álvarez-Canali et al., 2019) as well as the Mediterranean area (Marbà et al., 2015). Currently, a growing number of studies focus on the effects of increasing SST and the risk that these expansive brown algae forests, which play a fundamental role in the marine ecosystem and provide multiple benefits to coastal communities, may lose their positions at the southern boundaries of their distribution areas (Díez et al., 2012; Muguerza et al., 2017; Voerman et al., 2013). As illustrated in **Figure 2.2** related to global warming, research is expanding to address the consequences of this phenomenon in both the enclosed Mediterranean basin and the open waters of the Atlantic Ocean.

The patterns identified in our systematic review represent preliminary findings with respect to the studied species and areas. For instance, the geographical variation in stressors such as water quality or habitat destruction may primarily arise from regionalized impacts, limited available information, or research bias that focuses exclusively on these aspects, as is also the case with ecological status.

The patterns observed in our systematic review provide insight into a rapidly changing world and should serve as clear evidence that different stressors have the potential to disrupt ecosystem functioning through subtle effects on habitat-forming species. This review represent preliminary findings respect to the studied species and areas. The geographical variation in stressors such as water quality or habitat destruction may primarily arise from regionalized impacts, limited available information, or research bias that focuses exclusively on these aspects, as is also the case with ecological status. Consequently, prioritizing the preservation of canopy-forming species becomes a fundamental aspect of coastal ecosystem management, as their loss could trigger a cascade of biodiversity decline and a reduction in ecosystem services (Filbee-Dexter & Wernberg, 2018; Muguerza, Díez, et al., 2022). It is essential to bear in mind that species conservation is not only determined by global laws, but also by local actions. The next step is to gather information not considered in the present work, such are technical reports, cartographies available from the administration and also expert judgment, which are essential to have a complete and realistic view of the actual scenario of macroalgae forest ecosystem trends in the Spanish and Portuguese coast.

CONCLUSION

This study provides a comprehensive overview of the ecological status and stress factors affecting canopy-forming macroalgae throughout the Iberian Peninsula and its surrounding islands, including the Balearic and Canary Islands. It reveals disparities in research efforts, with certain regions, such as the Alboran Sea and the central coast of Portugal, receiving limited attention compared to the well-documented Atlantic coast and the Mediterranean Sea. In particular, the group *Cystoseira sensu lato* has garnered significant attention, while many other species remain relatively understudied. Our analysis identifies trends and disparities in ecological status records across the entire region. Most areas reported slightly equal conditions, showing a lack of macroalgae populations in good ecological status. These areas are also heavily impacted by various stressors, emphasizing the need to prioritize local conservation efforts in these regions. We also observe a general knowledge gap on the subject. The available data only contain partial geographical information and are limited to specific areas, particular species, and a common stressor. The first step towards a better understanding of the dynamics of these ecosystems will be to identify and assess local threats to improve disturbed areas. This will subsequently enhance the management and conservation of canopy-forming algae forests on a larger scale.

In conclusion, this study provides a preliminary framework for the ecological status and threats to canopy-forming algae populations across the Iberian Peninsula, including the Balearic and Canary Islands. Prioritizing the conservation of these species is imperative to prevent biodiversity decline and reduce the depletion of ecosystem services. Therefore, the spatial distribution of the obtained data is a first attempt to provide the needed information to assist stakeholders and managers in prioritizing decision-making processes.

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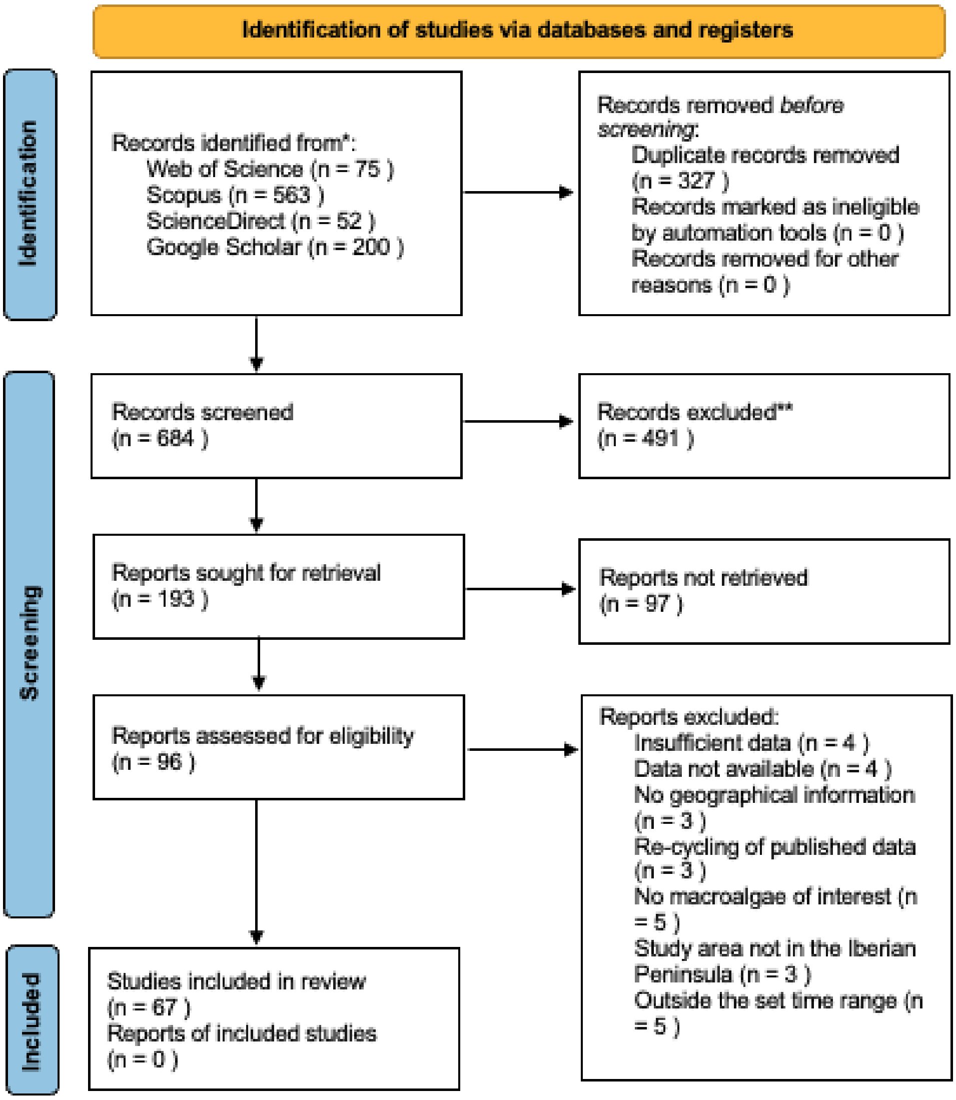
APPENDIX

Supplementary Figure 2.6. PRISMA diagram of the flow of information through the different phases of a systematic review to identify the literature used.



Supplementary Table 5.2. List of articles reviewed in this study. Information availability of Ecological Status and Stressors at each article is also included.

ID	References	Title	Journal	Ecological Status	Stressors
1	Álvarez-Canali et al., 2020	Local variations in environmental parameters govern 50 years of the decline of *Fucus guiryi*populations in the Canary Islands (eastern Atlantic)	Journal of Sea Research	Yes	Yes
2	Sánchez de Pedro et al., 2022	Seasonal and ontogenetic variability in the photosynthetic thermal tolerance of early life- stages of Fucus guiryi (Phaeophyceae, Fucales)	International Phycological Society	No	No
3	Sánchez de Pedro et al., 2023	Temporal and spatial variability in population traits of an intertidal fucoid reveals local-scale climatic refugia	Marine Environmental Research	Yes	Yes
4	Sánchez de Pedro et al., 2022	Parental environment modulates offspring thermal tolerance in a foundational intertidal seaweed	European Journal of Phycology	Yes	Yes
5	Serebryakova et al., 2018	Summer shifts of bacterial communities associated with the invasive brown seaweed Sargassum muticum are location and tissue dependent	PLOS ONE	No	No
6	Valdazo et al., 2020	Seasonality in the canopy structure of the endangered brown	European Journal of Phycology	Yes	Yes

		macroalga Cystoseira abies-marina at Gran Canaria Island (Canary Islands, eastern Atlantic)			
7	Verdura et al., 2018	Restoration of a Canopy-Forming Alga Based on Recruitment Enhancement: Methods and Long-Term Success Assessment	Frontiers in Plant Science	Yes	Yes
8	Verdura et al., 2020	Local-scale climatic refugia offer sactuary for a habitat-forming species during a marine heatwave	Journal of Ecology	Yes	Yes
9	Pereira et al., 2022	Fine-scale abundance of rocky shore macroalgae species with distribution limits in NW Iberia in 2020/2021	Biodiversity Data Journal	No	No
10	Piñeiro-Corbeira et al., 2021	Structure and Trophic Niches in Mobile Epifauna Assemblages Associated With Seaweeds and Habitats of Syngnathid Fishes in Cíes Archipelago (Atlantic Islands Marine National Park, North West Iberia)	Frontiers in Marine Science	Yes	No
11	Fernandes et al., 2022	Developing kelp reforestation methods	Repositorio Universidade de Oporto	No	No
12	Muguerza 2020	Assessment of climate change impact on Southern	Repositorio Universidade País Vasco	Yes	Yes

		European macroalgal assemblages			
13	Bertocci et al., 2014	Effects of loss of algal canopies along temperature and irradiation gradients in continental Portugal and the Canary Islands	Marine Ecology Progress Series	Yes	No
14	Bermejo et al., 2018	Marine forests of the Mediterranean-Atlantic Cystoseira tamariscifolia complex show a southern Iberian genetic hotspot and no reproductive isolation in parapatry	Nature	No	Yes
15	Muguerza et al., 2017	Structural impoverishment of the subtidal vegetation of southeastern Bay of Biscay from 1991 to 2013 in the context of climate change	Elsevier	Yes	Yes
16	Medrano et al., 2020	Ecological traits, genetic diversity and regional distribution of the macroalga Treptacantha elegans along the Catalan coast (NW Mediterranean Sea)	Nature research	Yes	Yes
17	Ramos et al., 2020	Changes in the distribution of intertidal macroalgae along a longitudinal gradient in the northern coast of Spain	Marine Environmental Reseach	No	Yes

18	Rodil et al., 2015	Disentangling the effects of solar radiation, wrack macroalgae and beach macrofauna on associated bacterial assemblages	Marine Environmental Research	No	No
19	Rodil et al., 2015	Alteration of Macroalgal Subsidies by Climate-Associated Stressors Affects Behavior of Wrack-Reliant Beach Consumers	Ecosystems	No	No
20	Rodríguez-Expósito et al., 2023	Gongolarones as antiamoeboid chemical scaffold	Biomedicine & Pharmacotherapy	No	No
21	Roman et al., 2020	Heatwaves during low tide are critical for the physiological performance of intertidal macroalgae under global warming scenarios	Sientific Reports	Yes	No
22	Ruiz-Medina et al., 2023	Desiccation and thermo-tolerance of Fucus guiryi (Phaeophyceae) from its southernmost populations (Canary Islands, Eastern Atlantic)	Botanica marina	Yes	Yes
23	Saada et al., 2016	Taking the heat: distinct vulnerability to thermal stress of central and threatened peripheral lineages of a marine macroalga	Diversity and Distributions	Yes	No
24	Provera et al., 2021	Species identity matters: Functional responses to warming in congeneric turfs differ from those	Estuarine, Coastal and Shelf Science	Yes	No

		of a canopy algae but are species-specific			
25	Pons-Fita et al., 2021	Co-occurrence of a reef-building coral and canopy-forming macroalgae in the Mediterranean Sea.	Mediterranean Marine Science	Yes	Yes
26	Bertocci et al., 2015	Spatial and temporal variation of kelp forests and associated macroalgal assemblages along the Portuguese coast	Marine and Freshwater Research	Yes	No
27	Olabarria et al., 2018	Physiological responses to variations in grazing and light conditions in native and invasive fucoids	Marine Environmental Research	No	No
28	Orfanidis et al., 2021	Effects of Natural and Anthropogenic stressors on fucalean brown seaweeds across different spatial scales in the Mediterranean Sea	Frontiers in Marine Science	Yes	Yes
29	Pacheco et al., 2021	Portuguese Kelps: Feedstock Assessment for the Food Industry	MDPI - Applied Sciences	No	No
30	Piazzi et al., 2018	Biodiversity in canopy-forming algae: Structure and spatial variability of the Mediterranean Cystoseira assemblages	Estuarine, Coastal and Shelf Science	Yes	No
31	Medrano et al., 2020	From marine deserts to algal beds: Treptacantha elegans revegetation to reverse stable degraded ecosystems	Restoration Ecology	Yes	Yes

		inside and outside a No-Take marine reserve			
32	Melero-Jiménez et al., 2017	North Atlantic Oscillation drives the annual occurrence of an isolated, peripheral population of the brown seaweed Fucus guiryi in the Western Mediterranean Sea	Peer J.	Yes	No
33	Muguerza et al., 2022	A spatially-modelled snapshot of future marine macroalgal assemblages in southern Europe: Towards a broader Mediterranean region?	Marine Environmental Research	Yes	Yes
34	Neiva et al., 2015	Genes Left Behind: Climate Change Threatens Cryptic Genetic Diversity in the Canopy-Forming Seaweed Bifurcaria bifurcata	PLoS One	No	No
35	Flores-Moya et al., 2021	Seaweeds and Seagrasses: The Marine Forests from the Alboran Sea	Ecosystems and Marine Resourcesand Marine Resources	Yes	No
36	Franco et al., 2017	Modulation of different kelp life stages by herbivory: compensatory growth versus population decimation	Marine Biology	Yes	Yes
37	Hernández et al., 2022	Range-edge populations of seaweeds show niche unfilling and Bad adaptation to	Journal of Biogeography	Yes	Yes

		increased temperatures.			
38	Martín García et al., 2022	Environmental and human factors drive the subtropical marine forests of Gongolaria abies-marina to extinction	Marine Environmental Research	Yes	Yes
39	Martins et al., 2021	Fucoid Macroalgae Have Distinct Physiological Mechanisms to Face Emersion and Submersion Periods in Their Southern Limit of Distribution	Plants	No	Yes
40	Lourenço et al., 2016	Upwelling areas as climate change refugia for the distribution and genetic diversity of a marine macroalga	Journal of Biogeography	Yes	No
41	Lalegerie & Stengel., 2022	Concise review of the macroalgal species Pelvetia canaliculata (Linnaeus) Decaisne & Thuret	Journal of Applied Phycology	No	No
42	Mariani et al., 2019	Past and present of Fucales from shallow and sheltered shores in Catalonia	Elesevier	Yes	No
43	Fernandez et al., 2022	Could the annual Saccorhiza polyschides replace a sympatric perennial kelp (Laminaria ochroleuca) when it comes to supporting the holdfast-associated fauna?	Marine Environmental Research	Yes	No
44	Fernandes et al., 2016	The pigments of kelps (Ochrophyta) as part of the flexible	Journal of Applied Phycology	No	No

		response to highly variable marine environments			
45	de Caralt et al., 2020	Differential effects of pollution on adult and recruits of a canopy-forming alga: implications for population viability under low pollutant levels	Scientific reports	No	No
46	Engelen et al., 2017	A population genetics toolbox for the threatened canopy-forming brown seaweeds Cystoseira tamariscifolia and C. amentacea (Fucales, Sargassaceae)	Journal of Applied Phycology	No	No
47	Jonas de Azevedo et al., 2023	Rapid tropicalization evidence of subtidal seaweed assemblages along a coastal transitional zone	Research Square	Yes	Yes
48	Duarte et al., 2018	Environmental and phenotypic heterogeneity of populations at the trailing range-edge of the habitat-forming macroalga Fucus serratus	Marine Environmental Research	Yes	No
49	Aires et al., 2022	Regional microbiome differentiation of the invasive Sargassum muticum (Fucales, Phaeophyceae) follows the generalist host hypothesis across the North East Atlantic	European Journal of Phycology	No	No

50	Álvarez-Losada., 2020	A regime shift in intertidal assemblages triggered by loss of algal canopies: A multidecadal survey	Marine Environmental Research	Yes	Yes
51	Balado et al.., 2021	Semantic segmentation of major macroalgae in coastal environments using high-resolution ground imagery and deep learning	International Journal of Remote Sensing	No	No
52	Bianchelli & Danovaro., 2020	Impairment of microbial and meiofaunal ecosystem functions linked to algal forest loss	Nature	No	Yes
53	Blanco et al., 2021	Spotting intruders: Species distribution models for managing invasive intertidal macroalgae	Journal of Environmental Management 281	No	No
54	Bustamante et al., 2017	The potential role of habitat-forming seaweeds in modeling benthic ecosystem properties	Journal of Sea Research 130	No	No
55	Capdevila et al., 2018	Effective dispersal and density-dependence inmesophotic macroalgal forests: Insights from the Mediterranean species Cystoseira zosteroides	PLOS ONE	Yes	Yes
56	Cardoso et al., 2020	Sea urchin grazing preferences on native and non-native macroalgae	Ecological Indicators 111	No	No
57	Celis-Plá et al., 2017	Ecophysiological responses to elevated CO2	Climatic Change	No	Yes

		and temperature in Cystoseira ta mariscifolia (Phaeophyceae)			
58	Celis-Plá et al., 2017	Photoprotective responses in a brown macroalgae Cystoseira tamariscifolia to increases in CO2 and temperature	Marine Environmental Research	No	No
59	Chabrerie & Francisco Arenas., 2022	What if the upwelling weakens? Effects of rising temperature and nutrient depletion on coastal assemblages	Research square	No	No
60	Fernández de la Hoz et al., 2019	Climate change induced range shifts in seaweeds distributions in Europe	Marine Environmental Research	No	No
61	Barriento et al., 2022	Paradoxical failure of Laminaria ochroleuca (Laminariales, Phaeophyceae) to consolidate a kelp forest inside a Marine National Park	European Journal of Phycology	Yes	Yes
62	Jódar-Pérez et al., 2020	Multidisciplinary Analysis of Cystoseira sensu lato (SE Spain) Suggest a Complex Colonization of the Mediterranean	Marine Science and Engineering	Yes	No
63	Pons-Fita et al., 2020	Coexistence of the reef-building coral Cladocora caespitosa and the canopy-forming alga Treptacantha ballesterosii:	Scientia Marina	Yes	Yes

		Description of a new Mediterranean habitat			
64	Sempere-Valverde et al., 2018	Substratum type affects recruitment and development of marine assemblages over artificial substrata: A case study in the Alboran Sea	Elesevier	Yes	No
65	Hinz et al., 2019	Fish nursery value of algae habitats in temperate coastal reefs	Peer J.	Yes	No
66	Giakoumi et al., 2018	Exploring the relationships between marine protected areas and invasive fish in the world's most invaded sea	Ecological Society of America	Yes	No
67	Frabbrizzi et al., 2020	Modeling Macroalgal Forest Distribution at Mediterranean Scale: Present Status, Drivers of Changes and Insights for Conservation and Management	Frontiers in Marine Science	Yes	No