



Developing productivity and susceptibility attributes towards a rapid management-risk assessment of seaweed

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ABSTRACT

The challenge of balancing conservation with sustainable use of marine resources faced by fisheries managers is quite often constrained by limited data on key species. This has become particularly true in the case of seaweed, which provide essential habitats for a diverse range of species in marine ecosystems and have long been valued by humans as food or, more recently, for their industrial applications. The expanding seaweed industry relies heavily on harvesting but historical declines in seaweed populations raise concerns over sustainability, leveraged by a general data-poor scenario for these species. To address this, we propose adapting the Productivity and Susceptibility Analysis (PSA) method—traditionally used in fishery assessments—for seaweeds. This novel approach incorporates the unique biology of seaweeds, including growth, reproduction, and susceptibility to environmental changes and harvesting practices, to evaluate their vulnerability. We applied this adapted PSA framework to a case study of seaweed harvesting in the Azores Archipelago, mid-north Atlantic, demonstrating its applicability in future science-based seaweed fisheries management strategies. Among the 18 species studied, we identified five of high vulnerability (*Cystoseira pustulata*, *Fucus spiralis*, *Gongolaria abies-marina*, *Laminaria ochroleuca*, and *Ericaria selaginoides*). Our adapted PSA framework also considers local ecological impacts, stakeholder input, and relevant environmental factors, providing targeted management recommendations. While such a PSA does not replace stock assessments, it serves as a valuable risk assessment tool, identifying species needing greater management attention despite data limitations. Ultimately, this framework supports local, national and international policy and management measures, contributing to the conservation of coastal marine ecosystems.

1. Introduction

Seaweed are main primary producers in rocky reef ecosystems and exhibit a high diversity of species and morphologies, which in turn generates a wide array of habitats, ranging from turf-like formations to large kelp forests. Due to their ability to modify the environment in which they live, they are considered ecosystem engineers and foundation species, supporting high biodiversity, offering shelter, nurseries, and foraging resources for a large variety of organisms, including many of high fisheries and conservation value [1].

The earliest human societies recognized the value of seaweed and used their properties for a wide variety of functions, including as a food resource [2,3]. In recent decades, seaweed have been valued as food supplements and additives due to their unique organoleptic properties and nutritional health benefits [4]. They are also a rich source of bioactive compounds, which have demonstrated a broad range of pharmacological properties, from antidiabetic to antineoplastic [4,5]. Today, these species are emerging as a promising frontier in the search for medical and pharmaceutical solutions, offering a vast repertoire of compounds with therapeutic potential [4,5].

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FAO statistics settle at about 1.09 million tonnes of wet weight from wilding harvest of seaweed worldwide in 2015 [6], while Europe largely depends on direct harvesting from natural environments, representing around 68 % of the total [7]. The management of these fisheries is usually carried out by regional authorities, harvester associations, or harvesting companies [8]. Nevertheless, a decrease in the abundance of some species has already been observed [9–13].

Unfortunately, for many commercially important seaweed species, knowledge about their populations, their ecological interactions, and the impact of harvesting pressure is lacking, hindering effective management. This highlights the critical need for tools to assess and manage harvesting impacts—particularly in data-scarce environments, such as small-scale coastal fisheries that are often closely tied to local communities and traditions [14,15].

For other types of fisheries, primarily those targeting invertebrates and fish, alternative methods have been developed based on species' life history traits. These methods are tailored to specific management regions and are designed to accommodate varying levels of data availability, including complete data absence [16–19].

In this context, the Productivity and Susceptibility Analysis (PSA) has emerged as a widely adopted approach for evaluating the vulnerability of fishery-targeted stocks through semi-quantitative analysis [14,15,17–24].

This assessment method operates on the assumption that the vulnerability of a fishery stock is determined by a combination of 1) its intrinsic productivity, which is a function of the stock's life-history characteristics, with 2) the susceptibility to the impacts of fishing, or the degree to which the fishery can negatively impact the stock [17,22]. Hence, vulnerability is expected to differ among stocks based on these two key elements. A stock with a low level of productivity would be considered vulnerable to fishing only if it is also susceptible to the fishery.

PSA was primarily developed for assessing the relative vulnerability to exploitation of fish and other marine species with well-defined life history traits and ecological interactions within marine ecosystems. However, it is important to highlight the need for ongoing refinement and adaptation of the methodology to address its limitations and provide more comprehensive and accurate assessments of fisheries impacts, particularly across different species with huge disparity of life traits as seaweeds. This diverse group of photosynthetic organisms have gained increasing prominence in recent years due to their multifaceted applications in fields such as biotechnology (e.g. pharmaceuticals, cosmetics), food production (e.g. supplements, fresh/dry), and environmental management (e.g. aquaculture IMTA, bioremediation) [25,26]. Hence, its broader utilization has brought the imperative of systematically assessing and mitigating the associated risks.

Adapting PSA for algae presents unique challenges and considerations that require a careful consideration of the unique biology and ecology of algae, the potential ecological and socio-economic impacts of algal harvesting practices, and the data availability. Additionally, it should incorporate region-specific and stakeholder considerations to make it a practical and effective tool for managing algal resources sustainably.

In response to this emerging challenge, for the first time, a novel and comprehensive risk assessment methodology is presented, specifically tailored to address the unique characteristics and dynamics of macroalgae, enabling cost-effective risk management through the implementation of management actions. To our knowledge, only one report attempted to address this issue for kelps, suggesting an assessment framework [27]. Ultimately, this new approach will support efforts towards meeting the requirements of local, national and international policies and legislation, including the EU Marine Strategy Framework Directive, Habitats Directive and Common Fisheries Policy, as well as align with the United Nations' Sustainable Development Goals, namely SDG14.

The PSA developed is applied to a case study of seaweed in the

oceanic Archipelago of the Azores (mid-north Atlantic). Specifically, this paper aims to (1) develop a PSA framework specifically designed for algae; (2) demonstrate its value in the assessment and management of algae as a fishery resource; (3) evaluate and compare risk outcomes in small-scale fisheries regions such as the Azores; and (4) formulate recommendations for a wider application of this approach to other data-limited, small-scale fisheries regions considering local and regional variations.

2. Material and methods

2.1. Productivity and susceptibility analysis (PSA)

This methodology evaluates the vulnerability of the stock to fishing activity based on two key elements: 1) productivity, a function of the species' intrinsic biological characteristics, and 2) susceptibility, the degree to which fishing can negatively affect the stock [17,21].

PSA is thus based on assigning scores to productivity and susceptibility attributes to estimate relative potential vulnerability. The scoring ranges from 1 to 3 for a standardized set of attributes related to each factor. The overall vulnerability score (v) is calculated as the Euclidean distance from the origin of the x-y scatter plot (i.e., 3.0, 1.0):

$$v = \sqrt{(p - 3)^2 + (s - 1)^2}$$

The development of the PSA began by evaluating the attributes, which were adapted, modified, and validated through expert group discussions. This process assessed whether each attribute met the following criteria: (1) scientific validity for calculating the productivity or susceptibility of a stock, (2) applicability across different scales (e.g., stocks of varying sizes and spatial distributions), and (3) usability for most species, considering data availability.

The following two sections provide descriptions of the productivity and susceptibility attributes, along with explanations of the scoring criteria.

2.1.1. Productivity attributes

Productivity is defined as the recovery ability of a stock when the population is depleted [21], reflecting its life history characteristics. The selection of attributes was based on the methodological work of the Aquaculture Stewardship Council and Marine Stewardship Council [28], which, although incomplete, serves as a starting point for developing the PSA for macroalgae. The selection of attributes was also based on the work of Torres et al. [19], supported by Musick's [29] qualitative risk of extinction assessment and the PSAs of Stobutzki et al. [21], Hobday et al. [16], and Patrick et al. [17,30] for other functional groups.

Productivity data is supported by the best available scientific knowledge for the region [31]. In the absence of information for local populations, digital platforms such as Algaetraits [32], Algaebase [33], and other works [34,35] were used.

Consequently, the productivity attributes used were:

2.1.1.1. Life span. The average lifespan of an individual or a specific population [36]. It has a direct relationship with productivity since species with a short life span (annual or ephemeral) are more productive than perennial species [37].

2.1.1.2. Functional group. Functional groups were created to include different species with similar morphological and anatomical structures that respond similarly to productivity and disturbance potentials [38]. The simpler the structure, the faster the population renewal, and the higher the productivity [39,40].

2.1.1.3. Net primary production (NPP). Primary production is the biomass increase of a photosynthetic organism per unit of time [41]. The standardized average NPP (kg C/m²·year) was used [35]. Species with

higher average NPP are considered more productive.

2.1.1.4. Generation time. The average duration of a life cycle from birth to first reproduction [36].

2.1.1.5. Reproductive frequency. The number of times and duration of the fertile period throughout the year directly affects productivity. The lower the number of times and/or the fertile period, the lower the productivity.

2.1.1.6. Reproduction. Macroalgae have different life cycles depending on the species, including various stages and forms, alternating periods of sexual and asexual reproduction. The more complex the cycle, the less productive the population, with predominantly asexual reproducing algae having higher productivity.

2.1.1.7. Dispersal capacity. The capacity and strategies for dispersion indirectly influence productivity. Characteristics that favour dispersion are used to categorize dispersal ability as low, medium, or high. Species with floating structures (intermediate score 2) have good dispersal ability, while species capable of fragmenting or detaching and drifting have even greater dispersal ability (maximum score 3). Species without characteristics that favour dispersion are scored the lowest (1).

2.1.1.8. Regeneration. The ability of the organism to regenerate after fragmentation (natural or anthropogenic) directly affects its productivity. Species that show very slow regeneration after cutting have a lower productivity value than those with faster regeneration after fragmentation.

2.1.2. Susceptibility attributes

Susceptibility is defined as the potential of a given stock to be impacted by a fishery. The attributes were adapted for macroalgae from recommendations in Patrick et al. [17,30], Hobday et al. [16], and Torres et al. [19]:

2.1.2.1. Commercial importance. Assumes that highly valued stocks are more susceptible to overfishing due to increased effort. The score is based on the three previously determined groups (see species selection section 2.3).

2.1.2.2. Harvest seasonality. Estimated as the number of months the species is targeted for harvesting, assuming that susceptibility is higher the longer the harvesting period.

2.1.2.3. Natural abundance. Assumes that a stock's susceptibility to overfishing is higher if the species has low natural abundance.

2.1.2.4. Stranding probability. Considers that algae with a higher probability of stranding are less susceptible to overfishing due to the reduced harvesting pressure on the still intact and living algae population.

2.1.2.5. Overlap of stock area and harvest area. Refers to the degree of horizontal (area) and vertical (depth) overlap between the known distribution of a stock and the harvest area. Species with greater and better accessibility will be more susceptible.

2.1.2.6. Management measures. A stock's susceptibility to overfishing can largely depend on the effectiveness of fishery management measures. Stocks without catch limits (TAC – Total Allowed Catch) or spatial protection zones, for example, are more susceptible to overfishing. This characteristic was based on local legislation (Decree No. 23/2024 of April 30).

2.1.2.7. Exploitation signs. Based on the stock's exploitation history and recorded landings. A score of 1 indicates no signs of exploitation; a score of 2 indicates some occasional or continuous landings over time, but with little significance; a score of 3 indicates a historically exploited stock, with significant and continuous landings over space and time.

2.1.2.8. Post-harvest mortality. Depends on the harvesting practices applied to different species, affecting the possibility of population recovery (e.g., harvesting the entire organism instead of just a part).

2.1.3. Data quality index

The uncertainty associated with data can lead to errors in ecological risk assessment [42–44]. Applying the precautionary principle, assessments are often assigned a higher risk score in an attempt to avoid mistakenly identifying a high-risk species as low-risk [21,42,45]. In this regard, a data quality index was estimated on a 5-level scale corresponding to the uncertainty of the final vulnerability values for a given species (Table 1). The quality value was calculated for productivity and susceptibility as a weighted average of the quality values of the respective individual attributes, thereby indicating the overall quality of the data. In the absence of data for a given attribute (score of 5), it is not used in the vulnerability estimate, but it is reflected in the overall data quality [17,30]. Thus, the higher the score, the lower the quality of the available information.

2.2. Study area

The Azores Archipelago is composed of nine volcanic islands and several islets, spread across 600 km between latitudes 37° N and 40° N along the Mid-Atlantic Ridge (see Fig. 1). The exclusive economic zone (EEZ) of the Azores covers nearly 1 million km². Due to their volcanic origins, the islands and approximately 400 seamounts feature steep slopes that descend rapidly to the ocean floor [46]. This extensive marine region has an average depth of about 3000 m and is characterized by a rich variety of deep-sea habitats [47,48]. Shallow areas, defined as depths <200 m, make up only 0.2 % of the Azores EEZ, primarily consisting of narrow island shelves and heavily eroded seamount summits. The coastline is mostly exposed to strong oceanic swells, with sheltered areas being limited to a few small bays and artificial harbours [49,50].

Due to their volcanic origin, like other archipelagos with comparable features, the Azores islands have limited suitable habitats for macroalgae. This limitation arises from specific geological and environmental factors. For example, the steep coastal slopes and narrow intertidal zones commonly found on volcanic islands reduce the areas where seaweed can establish and thrive. Furthermore, the composition of volcanic substrates can influence which macroalgae species are able to colonize these habitats [51–53].

In Portugal, seaweeds have been used as fertilizers since the 14th century, collected from the coastal area after storms in the northern region [54]. This knowledge was likely brought to the Azores during colonization [55], followed by the extraction of hydrocolloids in the late 1950s [54,55]. Nowadays, seaweeds are traditionally consumed as food in the archipelago [56] and used as natural fertilizer for agriculture, in

Table 1

Five levels of data quality used in the assessment of algae productivity and susceptibility.

Score	Description
1	data for the species at regional level
2	data for the same species, but from another location
3	data for the genus or family and not the species
4	information based on expert knowledge
5	when no data or expert knowledge is available, the quality of the attribute is assessed with a score of 5. This score is excluded from the estimation of the final 'productivity' or 'susceptibility' values to avoid introducing bias into the index

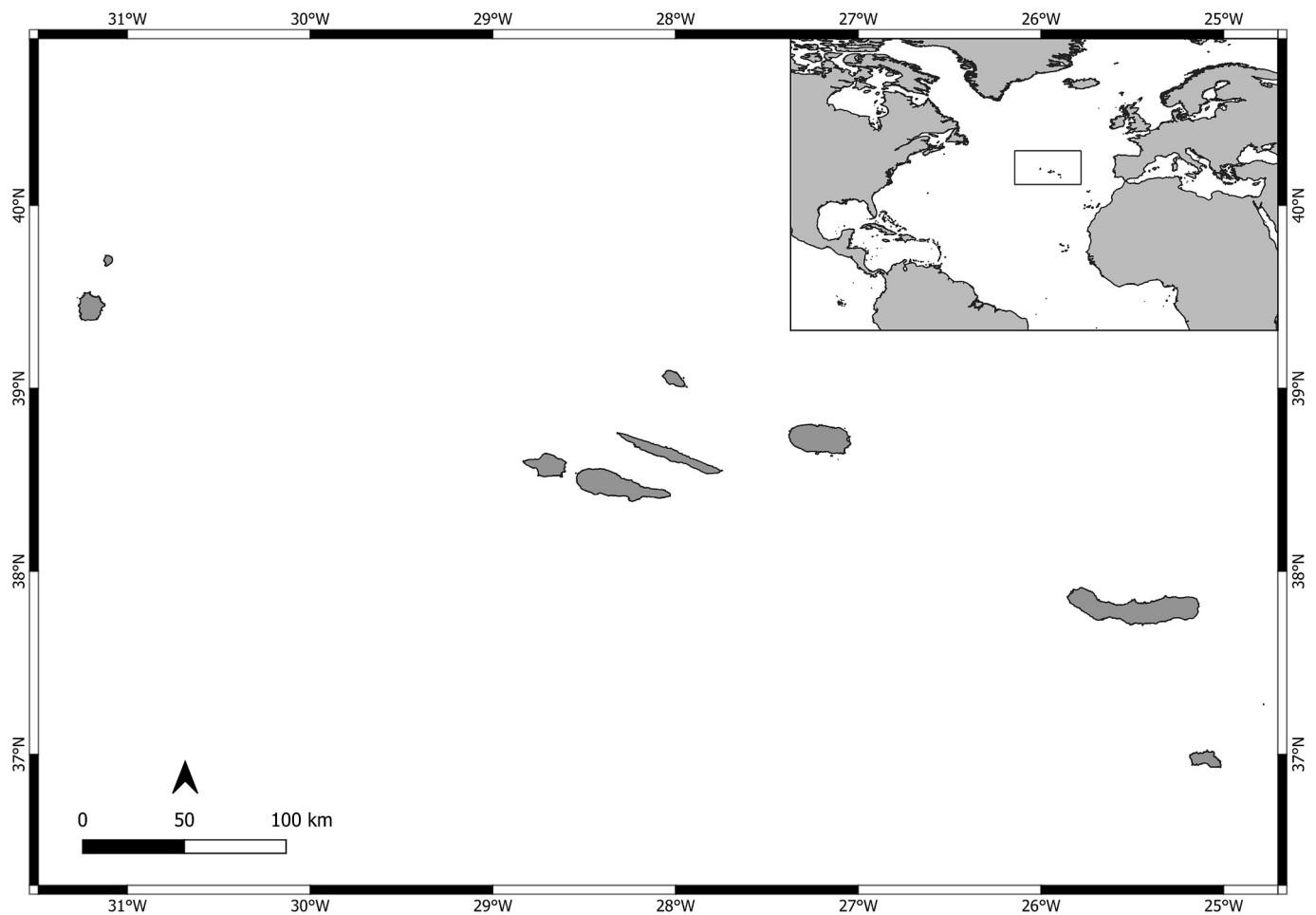


Fig. 1. Location of the Azores Archipelago in the North Atlantic.

this case, without regulation. Since 2014, with the introduction of a new harvesting regulation designed to promote activity by the regional government (Decree No. 1/2014 of January 10), several companies have revived operations, focusing on agar as well as exploring new applications in the pharmaceutical and cosmetic industries. According to our data the industry relies entirely on wild harvesting, with a total catch of approximately 50 t (dry weight) in 2023.

Currently, there are 12 species of seaweeds listed in regional legislation (Decree No. 23/2024 of April 30): five for direct human consumption (*Porphyra* spp., *Ulva intestinalis*, *Ulva rigida*, *Asparagopsis taxiformis*, and *Osmundea pinnatifida*) and seven for other purposes, particularly the cosmetics and pharmaceutical industries (*Pterocladia capillacea*, *Sargassum* spp., *Halopteris scoparia*, *Asparagopsis* spp., *Zonaria tournefortii*, *Cystoseira humilis*, and *Gelidium* spp.). The processing and registration of these species after harvesting goes through a complex and bureaucratic process, depending on whether they are intended for human consumption, and includes three different registrations to be filled out by the harvester.

The Decree also includes a limit on the number of seaweed harvesting licenses per island, regardless of the species, and the designation of harvesting prohibition areas per island, initially established for the management of limpets and, more recently (2014), extended to seaweed, lacking scientific support. Since 1996, the number of harvesting licenses has remained constant, below 50 until 2015, reaching 192 in 2018, followed by a progressive decline to 110 licenses in 2024. The increase from 2015 may be linked to the license renewal criteria established in Legislative Order 64/2013, which does not define or differentiate recreational from commercial fishing and does not present

any specific measures for recreational harvesters.

2.3. Species selection

Commercial algae species were first selected for evaluation based on current industry information and extensive bibliographic research. Out of the 522 algae species recorded for the Azores archipelago [57], 18 species were selected and categorized into three groups according to the following criteria:

- local socioeconomic importance, based on historical exploitation.
- potential socioeconomic importance, based on global exploitation patterns.
- species listing in current local harvesting legislation (Decree No. 23/2024 of April 24).
- protection status (e.g. OSPAR, Habitats Directive (Directive 92/43/CEE)).
- vulnerability indicated by historical population declines.

Group 1 includes five target taxa of established fisheries, i.e., species with significant historical harvest records over multiple consecutive years – *Asparagopsis taxiformis*, *Gelidium microdon*, *Porphyra* spp., *Pterocladia capillacea*, and *Sargassum* spp..

Group 2 includes nine target species of non-established fisheries, i.e., species with sporadic harvest records in small quantities and/or in non-consecutive years – *Asparagopsis armata*, *Halopteris scoparia*, *Cystoseira pustulata*, *Fucus spiralis*, *Osmundea pinnatifida*, *Gongolaria abies-marina*, *Padina pavonica*, *Ulva intestinalis*, and *Zonaria tournefortii*.

Group 3 includes potentially four exploitable species, i.e., species with no harvest records but with potential for industry, and considered as vulnerable species – *Ericaria selaginoides*, *Laminaria ochroleuca*, *Petalonia binghamiae*, and *Ulva rigida*.

The selected species were then analysed and evaluated based on i) available information, ii) biology and ecology, iii) exploitation history in the Azores. Available information for each species was gathered through bibliographic research, including technical reports and scientific articles, and data provided by companies. In the absence of local sources, information from other studies conducted in other geographically related areas (Azores-Macaronesia-Portugal-Atlantic) was compiled. All bibliographic references for the Azores are listed in [31].

3. Results

The development of the PSA resulted in the assessment framework presented in Tables 2 and 3 that combine both productivity and susceptibility attributes for seaweed. Typically, a default weight of 2 is assigned to each attribute, with the option to adjust weights on a scale from 0 to 4 to tailor the analysis to each fishery. When determining the appropriate weighting for each attribute, the focus was on its relevance in describing productivity or susceptibility, rather than the availability of data for that attribute. For instance, attributes with limited data should not automatically be assigned low weights.

It is important to note that not all attributes are equally effective in assessing a stock's vulnerability. Consequently, earlier versions of the PSA employed an attribute weighting system, assigning higher weights to the most significant attributes [18,21,58].

The scoring criteria were grounded in clear, objective rules to minimize subjective interpretation. To reduce scoring bias, the weighting and attribute scores were established through a collaborative process with input from various experts and stakeholders [17,30,59].

3.1. The Azores case study

Out of the 18 species studied, the PSA identified five of high

Table 2
Productivity attributes, ranking and weight.

Productivity Attributes	Ranking			Weight (0–4)
	Low (1)	Moderate (2)	High (3)	
Life span	perennial	annual	ephemeral	4
Functional group	leathery macrophyte, articulated calcareous and crustose	filamentous, (coarsely branched), corticated foliose and corticated macrophytes	foliose	2
Net Primary Production (NPP)	0–0.05	0.05–0.1	>0.1	2
Generation time	> 1 year	3 to 12 months	< 3 months	2
Reproductive frequency	At least one short period/year	at least one long period/year	fertile all over the year	2
Reproduction	sexual reproduction predominant	asexual and sexual reproduction both possible	asexual reproduction predominant	3
Dispersal capacity	Low dispersal capacity	Medium dispersal capacity	High dispersal capacity	2
Regeneration	species with none or low regenerative capacity	species with relatively high regenerative capacity	species with high regenerative capacity	2

Table 3
Susceptibility attributes, rankings and weights.

Susceptibility Attributes	Ranking			Weight 0–4
	Low (1)	Moderate (2)	High (3)	
Commercial importance	spp. group 3	spp. group 2	spp. group 1	3
Harvest seasonality	< 4 months	4–6 months	year-round	2
Natural abundance	abundant (50–100 %)	frequent (15–49 %)	occasional (<15 %)	3
Stranding probability	high	moderate	low	2
Overlap of stock area and harvest area	Low overlap (< 25 % of stock occurs in the area fished)	Moderate (Between 25 % and 50 % of the stock occurs in the area fished)	High (> 50 % of stock occurs in the area fished)	4
Management measures	More than one management measures (spatial and technical measures)	One management measure (spatial or technical)	Absence of management measures	3
Exploitation signs	No or low exploitation	Moderate exploitation	Intense exploitation	4
Post-harvest mortality	When only part of the organism is harvested or if the harvesting practices allow population recovery in a short period of time	When only part of the organism is harvested BUT the harvesting practices do not allow population recovery in a short period of time	When the whole organism is harvested or if the harvesting practices do not allow time/rotation for biomass/population recovery	2

vulnerability ($v \geq 2.0$: *Cystoseira pustulata*, *Fucus spiralis*, *Gongolaria abies-marina*, *Laminaria ochroleuca*, and *Ericaria selaginoides*) and three of moderate vulnerability ($1.8 \leq v < 2.0$: *Halopteris scoparia*, *Pterocliadiella capillacea*, and *Sargassum* spp.) (Table 4 and Fig. 2).

While productivity spreads across a larger range reflecting the different species, only two scored below 2.0 in susceptibility, as the majority lacks efficient monitoring and management measures. Hence, while productivity scores for all species ranged from 1.4 to 2.4, susceptibility scores ranged from 1.9 to 2.5. The generally high-quality ratings assigned to the information used for scoring each attribute, even in data-limited situations, demonstrate its practicality and usefulness. Webb and Hobday [60] proposed categorizing the data quality score into three groups: low (> 3.5), moderate (2.0–3.5), and high (< 2.0). Most species showed moderate quality in productivity data compared to susceptibility data, except for *Asparagopsis armata*, *Padina pavonica*, and *Petalonia binghamiae*. Only three species (*Pterocliadiella capillacea*, *Zonaria tournefortii*, and *Asparagopsis armata*) presented high overall quality, with a value of 2.0. For the remaining species, the overall quality assessment revealed a moderate value, reflecting the lack of some important information about local stocks (Table 4, Fig. 2).

4. Discussion

This study offers the first attempt globally to evaluate the ecological risk to exploitation of different stocks of seaweeds of effective or potential socio-economic interest through a PSA. It offers a specific framework and demonstrates its applicability by identifying five stocks of high risk which are currently not subject to any specific monitoring

Table 4

Final PSA values, productivity, susceptibility, vulnerability and data quality scores. Values considered to be highly vulnerable are marked in bold and values considered to be moderately vulnerable (including species with susceptibility >2.3) in an asterisk (*).

Species	Productivity	Susceptibility	Vulnerability	Productivity Quality	Susceptibility Quality	Data Quality
<i>Fucus spiralis</i>	1.6	2.5*	2.1	2.7	2.2	2.4
<i>Gongolaria abies-marina</i>	1.5	2.5*	2.1	2.9	2.2	2.5
<i>Cystoseira pustulata</i>	1.6	2.4*	2.0	2.6	2.0	2.3
<i>Laminaria ochroleuca</i>	1.4	2.2	2.0	2.7	2.1	2.4
<i>Ericaria selaginoides</i>	1.6	2.4*	2.0	2.3	2.1	2.2
<i>Halopteris scoparia</i>	1.4	2.0	1.9*	3.0	1.8	2.3
<i>Sargassum</i> spp.	1.7	2.3	1.9*	2.7	2.0	2.3
<i>Pterocliadella capillacea</i>	1.7	2.2	1.8*	2.2	1.8	2.0
<i>Osmundea pinnatifida</i>	2.0	2.4*	1.7*	2.0	2.2	2.1
<i>Padina pavonica</i>	1.9	2.2	1.6	1.8	2.0	1.9
<i>Petalonia binghamiae</i>	2.1	2.3	1.6	2.0	2.4	2.3
<i>Asparagopsis taxiformis</i>	2.0	2.3	1.6	2.8	2.0	2.3
<i>Ulva intestinalis</i>	2.1	2.3	1.6	2.4	2.2	2.3
<i>Gelidium microdon</i>	2.2	2.3	1.5	2.5	2.0	2.2
<i>Zonaria tournefortii</i>	1.8	1.9	1.5	2.3	1.8	2.0
<i>Porphyra</i> spp.	2.4	2.3	1.4	2.9	2.2	2.5
<i>Ulva rigida</i>	2.3	2.2	1.4	2.0	2.4	2.3
<i>Asparagopsis armata</i>	2.1	1.9	1.3	2.0	2.0	2.0

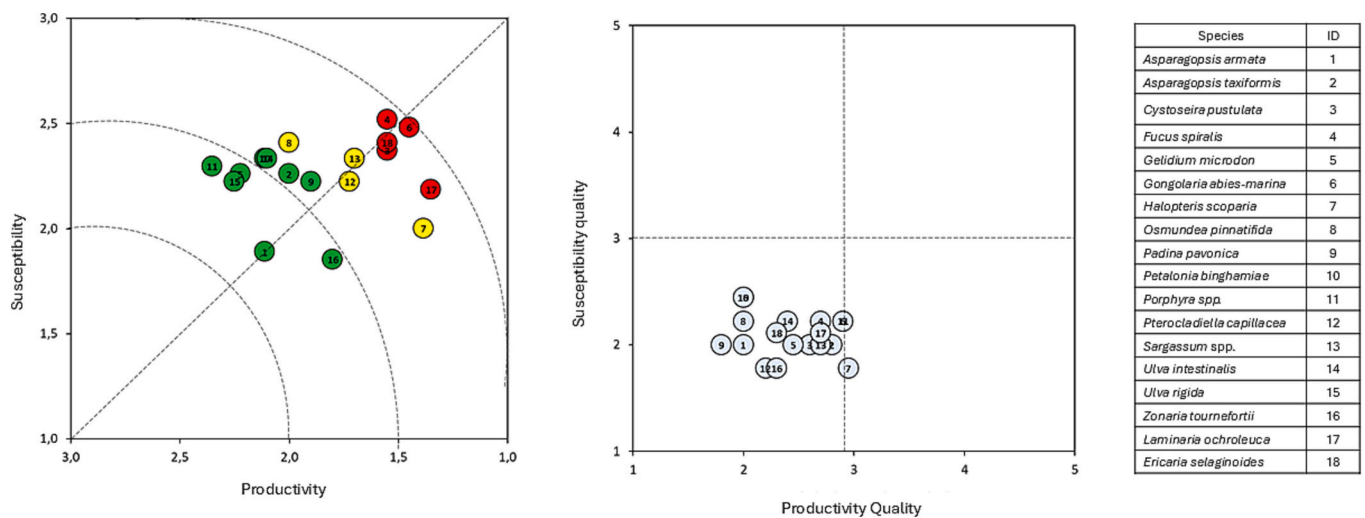


Fig. 2. Productivity and susceptibility scores and quality of attributes for each species/stock assessed (Red: $v \geq 2.0$ high vulnerability; yellow: $1.8 \leq v < 2.0$ moderate vulnerability; green: $v < 1.8$ low vulnerability). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

program or management measures in support of a sustainable management and industry development in the Azores region. This framework can serve as a basis for seaweed PSA assessments in other regions and fisheries.

4.1. Seaweed of higher risk

In this study, five species of seaweed were identified as species of high vulnerability risk, i.e., scoring a vulnerability index equal to or higher than 2.0. In addition to their high vulnerability scores, all these five species have historically been subjected to population declines in other regions, namely *L. ochroleuca* [61], *E. selaginoides* [62], *G. abies-marina* [63], *F. spiralis* [64], and *C. pustulata* [65]. *Fucus spiralis* and *G. abies-marina* deserve special attention, as a population decline of *F. spiralis* was reported during the first decade of the 21st century [64] and a reduction of over 97 % of *G. abies-marina* populations in the last thirty years [63]. Another study conducted in tidal pools in the Canary Islands highlighted the ecological role of *C. pustulata* for the associated epifauna communities [66]. In the Azores, where this habitat is very limited and fragmented, it thus seems particularly important to

implement effective management measures of this resource that may prevent similar declines in the future.

Laminaria ochroleuca also plays a crucial role as primary producer and serves an essential function as habitat builder [67]. *Cystoseira pustulata* (previously divided into two species: *C. humilis* and *C. compressa* [68]) recorded a total of 26.7 kg in 2018, 2019, and 2023. This species has been studied for its fatty acid composition and its potential antioxidant and antibacterial properties [69]. A study conducted in the Azores highlighted the significant potential of *Gongolaria abies-marina* and *Fucus spiralis* for future applications in medicine, food production, or the cosmetic industry [70]. Although their potential is evident, records of these species are limited: *G. abies-marina* with 56.9 kg between 2018, 2021, 2022, and 2023, and *F. spiralis* with 5 kg in 2021 and 1 kg in 2022. However, despite these small quantities, it is known that these species have traditionally been harvested in the Azores as food [56,71]. Therefore, it is possible that they are being collected even if no official records exist, especially considering the inefficient system in place.

The algae included in this group (*L. ochroleuca*, *E. selaginoides*, *G. abies-marina*, *F. spiralis*, and *C. pustulata*) share common characteristics such as low productivity, rarity, high ecological significance, and

documented population declines in regions where their population dynamics have been studied. Therefore, it is recommended that the exploitation of these species be treated under a precautionary approach, and algae such as *G. abies-marina*, *F. spiralis*, and *C. pustulata* be excluded from the current harvesting Ordinance in the Azores until new monitoring data provide sufficient grounds to revise these criteria.

4.2. Seaweed of medium risk

This group includes three species of $1.8 \leq v < 2.0$ (*Pterocladia capillacea*, *Sargassum* spp. and *Halopteris scoparia*, Table 4 and Fig. 2). However, we followed Patrick et al. [17] suggestion, in that he considers that stocks of high susceptibility values (i.e. > 2.3) should also be a cause for concern, regardless of their final vulnerability value, thus resulting in the addition of *Osmundea pinnatifida* to this group of medium vulnerability species. These species offer very different situations regarding their use and commercialization.

Pterocladia capillacea played a key role in the development of the agarophyte industry in Portugal, particularly in the Azores, following the rise in demand after World War II. The agar industry, based on a hydrophilic colloid from Rhodophyceae algae, became crucial in several sectors due to its gelling properties [72]. This demand led to the expansion of agar production, with *Gelidium corneum* utilized on the mainland and *Pterocladia capillacea* in the Azores [54,73,74], establishing Portugal as the fifth-largest agar producer by the 1980s [75]. *Pterocladia capillacea* produces high-quality bacteriological agar and agarose [76–78]. As a result, populations of this species face intense exploitation, as all raw material is harvested from wild algae stocks [75], potentially leading to stock overexploitation [76–78].

In the late 1950s, agar production began in the Azores, with estimates suggesting a harvest potential of 5000 tons annually. Two factories were built, and harvests grew to 1800 tons by 1980, generating €1.1 million and employing 210 workers [55]. A Maximum Sustainable Yield (MSY) of 2000 tons/year was estimated, although more was needed for optimal operation [73]. By 1990, however, the industry declined due to labour shortages and reduced market value [54,79].

In 2014, a new local regulation (Decree No. 1/2014 of January 10) aimed at reviving the seaweed harvesting and industry [75], resulted in harvests increases of *P. capillacea* between 2013 and 2017, though still below historical levels. The stagnation that followed in recent years is attributable to a reduction in effort. Fralick's MSY and a legal limit of 150 harvesters suggest that, if maximum daily quotas were to be reached, then sustainability would be at risk. Additionally, in islands where algae harvesting currently occurs (São Miguel, Faial, Terceira, and Graciosa), some areas overlap with designated MPAs, particularly in Terceira and São Miguel, which can potentially hamper broader conservation efforts in the region [31].

The genus *Sargassum* is recognized for its diverse health benefits, with various species exhibiting bioactive properties. Research has linked *Sargassum* to cancer prevention, angiogenesis inhibition, and antimicrobial, antioxidant, and anti-inflammatory effects [80–82]. Studies also suggest its potential in fighting bacterial, viral and parasitic infections, [83–85]. Recent findings further highlight its role as an antioxidant, antidiabetic, and anti-inflammatory agent [86].

This genus still presents some complexity regarding taxonomic classification, with considerable controversy in species differentiation (morphological versus genetic studies) [87–89]. Three species have been previously reported for the Azores (*Sargassum cymosum*, *Sargassum desfontainesii*, and *S. vulgare*), collectively referred to as *Sargassum* spp. or “sargaço,” as commonly noted in the region and in the legislation (Decrees and Legislative Order).

Local *Sargassum* catches have been modest but stable between 2014 and 2023, primarily in the central island group with quantities close to 80 kg in dry weight during 2018, 2022, and 2023. However, local auctions recorded a significant increase between 2014 and 2017, peaking at approximately 10.5 tons in dry weight on Terceira Island.

This amount is clearly overestimated due to the inability to distinguish species at auction, where all material is classified as “sargaço” in doubt, even when other species are involved.

For *Halopteris scoparia*, this low-productivity alga (scored 1.4) has been harvested since 2016. Although the total catch quantity is not very high, a significant increase was observed in the last two years, reaching a maximum of 215 kg in wet weight in 2023. There is limited information on the productivity of this species, leading to the exclusion of many attributes and resulting in a high data quality value (3.0). Therefore, it is crucial to expand knowledge of its biology and implement monitoring and precautionary management measures to ensure the sustainability of this stock.

Finally, *Osmundea pinnatifida* has shown significant potential for future applications in medicine, food production, and the cosmetic industry, as highlighted by a study conducted in the Azores [70]. However, only 3 kg were officially recorded in 2022. Nevertheless, this species has historically been harvested in the Azores for food [56,71], though its collection has largely gone undocumented in official records.

Regarding specific regulatory measures, it is proposed to maintain, in the short term, the current regulations in place for species at moderate or low risk, considering there is no evidence of stock depletion. However, a more species-specific approach will be necessary in the future to account for their individual features. It is also recommended the re-evaluation of the number of licenses per island/species and the allowable quantities (both for food and non-food purposes), given that harvesting is currently limited to a few islands (except for agarophytes). Hence, a monitoring plan should be developed to assess the impact of harvesting on the most vulnerable stocks in the region.

4.3. Approach: Limitations and applicability

The scoring of susceptibility attributes presented some difficulty in their selection, especially the attributes of stock area vs. harvest area overlap, stranding probability, and post-harvest mortality. In most cases, these attributes were discussed and assigned based on expert knowledge. Maintaining consistency in scoring these attributes, especially when there are multiple evaluators, was a significant challenge and required special attention during the application of the PSA.

The data quality assessment was useful for identifying discrepancies in the availability of information. One of the main advantages of the PSA is its ability to assess populations even when the available information is very limited. In this sense, most species showed moderate overall quality data, better for susceptibility scores, reflecting the knowledge gap for local populations and the inevitability of using expert advice in some attributes.

Other important attributes of potential interest for a seaweed PSA, such as fecundity [17,30] and IUU (illegal, unreported, and unregulated fishing) [19] were not considered in this PSA due to a lack of information on the target stocks but could be so in the future may this knowledge gap be bridged. For example, informal information available suggests a high percentage of unregistered harvesting across all stocks. Productivity scores are intrinsic to the species, so even with improvements in data quality, it is unlikely they will change significantly. Therefore, any reduction in vulnerability must always be achieved through management focused on reducing the stock's susceptibility.

Vulnerability scores are useful for quickly determining priority stocks that require scientific attention and better management. On the other hand, data quality ratings identify stocks for which it is urgent to improve and increase the available information. Productivity and susceptibility scores can also provide additional information that allows establishing catch levels in data-limited situations [90] or for prioritizing resources for stock assessments. Additionally, the PSA can be used to identify species that are not currently targeted by fisheries but that may be highly vulnerable to overfishing while bearing high ecological importance, such as *Laminaria ochroleuca* or *Ericaria selaginoides* [67,91].

5. Conclusions

The Productivity/Susceptibility Analysis identified nine species at higher risk (*Cystoseira pustulata*, *Fucus spiralis*, *Gongolaria abies-marina*, *Laminaria ochroleuca*, *Ericaria selaginoides*, *Halopteris scoparia*, *Pterocladia capillacea*, *Sargassum* spp., and *Osmundea pinnatifida*), with the first five classified as high risk. These species were deemed high priority, with a precautionary approach recommended for their management, particularly in the absence of more formal quantitative assessments. It also highlighted significant gaps in knowledge regarding ecology, biology, and vulnerability of algae to exploitation. For instance, there is limited information on recruitment and the trophic dependencies of invertebrate and vertebrate biodiversity associated with these algae.

Despite all the legislation and regulations, there are still clear inconsistencies. Harvesting efforts continue to lack adequate monitoring, both in commercial and recreational fishing, which requires stronger regulation and enforcement. Additionally, the established limits (quantities and number of licenses) appear to lack a scientific basis, particularly for the most vulnerable species. There is also a significant gap in official records, both in harvest logs and at auction sites, due to technical and logistical challenges.

The PSA provides a tool for assessing risk within a management framework, providing an initial filter to detect target species potentially affected and more vulnerable. While the results are not intended to replace proper stock assessment, vulnerability benchmarks can and should signal stocks that require greater management attention, despite possible data limitations.

The evaluation results for each species should be interpreted with caution, as we used a modified subset of the attributes used in other studies [17,30,92]. However, this approach can be considered a first step in a continuous evaluation and management process. Therefore, we recommend that the PSA developed here be used dynamically, expanding and modifying the list of attributes and data quality whenever scientifically advisable.

This PSA intended to evaluate the vulnerability of seaweeds specifically affected by fisheries. Nevertheless, additional potential effects caused by other environmental factors such as habitat degradation, invasive species (e.g., *Rugulopteryx okamurae*) and climate change, should be considered towards a more global comprehensive management of these coastal resources.

CRedit authorship contribution statement

D. Milla-Figueras: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **P. Torres:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **A.Z. Botelho:** Writing – review & editing, Methodology, Data curation. **A. Larrea:** Writing – review & editing, Data curation. **M.I. Parente:** Writing – review & editing, Methodology, Data curation. **P. Afonso:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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