

Review

Ecosystem Services Provided by Kelp Forests of the Humboldt Current System: A Comprehensive Review

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Abstract: Marine ecosystems such as kelp are gaining recognition for providing ecosystem services (ES) along the coastal regions worldwide. Here, we synthesize information from the last four decades of research on the structure, functioning and threats of kelp forests, and the ES they provide in the Humboldt Current System (HCS) where information is scarce. The SALSA (Search, Appraisal, Synthesis and Analysis) framework was used for the literature survey and review. From 86 selected articles, only 4 directly discussed kelp ES in Chile. Supporting services-related articles were the most prevalent ($n = 59$), followed by provisioning ($n = 19$), regulating ($n = 3$) and cultural services ($n = 1$). ES-related research was mostly conducted in Chile ($n = 77$). Studies in Peru ($n = 5$), and in Chile and Peru at same time ($n = 4$) were scarce. Our search also showed that *Lessonia trabeculata* presented the highest number of associated taxa ($n = 213$), followed closely by *M. pyrifera* ($n = 210$). However, the number of phyla reported was higher in *M. pyrifera* ($n = 17$) than in the *Lessonia* species ($n = 7$ – 13). Natural and anthropic impacts on the biodiversity of kelp forests using novel technologies would facilitate the quantitative study and economic valuations of the services provided by these ecosystems at the Humboldt Current System.

Keywords: biodiversity; Chile; *Lessonia*; *Macrocystis*; Peru; seaweeds; threats



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1. Introduction

Ecosystem services (ES) are defined as the benefits that humans obtain from ecological systems. These include services such as food and fresh water and climate regulation, among others that make human life possible [1]. This concept is established as a “policy advocacy tool” since it helps with management practices [2]. Consequently, in recent decades, these ES have been categorized by governmental organizations and research bodies globally as supporting, regulating, provisioning and cultural services [3,4].

At a global scale, the study of ES is prioritized under their economic value [5,6]. This helps the valuation of each service provided and facilitates the development of strategies through the management and protection of ecosystems [7,8]. Since the beginning of the Anthropocene, ecosystems worldwide have been rapidly degrading, causing their services to change and/or be lost. In this context, addressing the ES approach has emerged as a priority for blue growth worldwide [9,10].

Coastal ecosystems, including wetlands [11], seagrasses [12], coral reefs [13,14] and kelp forests [15–17] support human activities along coastal regions at a global scale. These are highly efficient at providing bioresources, in nutrient cycling and as climate regulators. Considering that a major portion of the human population has been associated with coastal ecosystems, estimating the value of their benefits has gained relevance in the past decades. However, the estimation of the value of ES and studying the ES represents a challenge for

researchers and policy makers internationally [18]. The productivity of coastal systems globally approximately provides ES valued at ~USD 19,000 per hectare (ha) each year [19]. However, this could fluctuate due to variations between habitats, their benefits and the way their values are estimated, by using up-to-date and more accurate information in relation to their geographical distribution [20]. Economic valuation is a useful tool for the preservation, protection and sustainable management of kelp forests. It shows the benefits kelp provides to stakeholders, decision makers and all of the society, allowing the identification and planning of the integrative management of the kelp ecosystem [21,22].

The term “kelp” has historically been used to refer to almost any large brown marine macroalgae, with some common characteristics that can be reduced to i) being part of the Laminariales order and ii) structuring the habitat for other species, forming the so-called marine forests as a foundation species [17,23]. Kelp forests are mostly composed of mixed assemblages, which can be found globally within temperate, sub-tropical and sub-polar regions [24]. As bioresources, kelp species present a wide array of uses, representing the raw material for different industries, such as pharmaceuticals, cosmetics, fertilizers, textiles, medicine and culinary arts. Additionally, due to their bio-adsorption capacity they have been proposed as a promising alternative for bioremediation. In past decades, some studies have highlighted the potential of certain kelp species as biofuel sources, granting them visibility by the energy industry [25,26].

Besides presenting a great diversity of bioactive components [27], kelp species fix large amounts of inorganic carbon from the atmosphere and the water column [28,29]. The omission of kelp forests from blue carbon assessments significantly underestimates the carbon storage and sequestration potential from vegetated coastal ecosystems globally [30]. They support one of the highest productivity rates via photosynthesis, and greatly influence the physical environment in which they live, due to their three-dimensional structure. This magnifies secondary productivity through habitat forming. The alteration of the environment by kelp biomass has been described in reference to water flow [31,32], physical disturbance [33], sedimentation rates [34] and outwelling [35]. A forest can improve the habitability of the benthos and the water column, generating habitats for a biodiverse microbiome as well as breeding areas for other macrophytes, and both sessile and motile animal species. Many of these organisms are of socioeconomic relevance or are critically endangered [36–39]. Kelp forests are also susceptible to physical, chemical and biological changes in the marine environment, such as heatwaves, pollution and even disease [40–43].

Extended along the coasts of Chile and Peru, the Humboldt Current System (HCS) is one of the most productive marine ecosystems worldwide. This macro-ecosystem, encompassing most of the west coast of South America, is mainly influenced by the Humboldt Current, which is characterized by a predominant northward flow of surface waters of subantarctic origin (~42° S), and by a strong upwelling of cool nutrient-rich subsurface waters of equatorial origin [44].

The economic value of kelp forests in Chile and Peru, where this resource is socially and economically relevant, may change according to new findings, emerging industries and potentially better recognition of kelp’s ecological threats and social role by coastal communities [22,45]. Previous reviews have addressed the importance of kelp forests in other geographical regions [17,29]. Thus, this review is the first that summarizes the state of knowledge of ES provided by the kelp forests of the HCS, focusing on four kelp species: *Lessonia berteroana* Montagne, *L. spicata* (Suhr) Santelices, *L. trabeculata* Villouta and Santelices and *Macrocystis pyrifera* (Linnaeus) C. Agardh. Peer-reviewed papers from both Chile and Peru were used to (1) summarize existing knowledge (Research Articles) on the structure and functioning of kelp forests and the ES they provide in the HCS; (2) identify research trends regarding the ES of kelp forests along the HCS; and (3) highlight knowledge gaps and research priorities that will lead to a better understanding of the current and future role of kelp habitats within the HCS. The information collected will help decision makers, scientists and society establish proper policies, research and management tools related to kelp forests.

2. Materials and Methods

The research area covered the Humboldt Current System in the eastern Pacific between central Chile and north Peru, which is located between $\sim 42^\circ$ S and the equator. In order to locate and synthesize the existing literature on kelp forests along the HCS, the meta-synthesis method [46] was applied using the Search, Appraisal, Synthesis and Analysis (SALSA) framework [47].

Four academic databases—ScienceDirect, Scopus, SCIELO and Google Scholar—were used to identify relevant publications that applied the concept of ES in kelp forests of *Lessonia berteriana* (formerly known as *L. nigrescens* in Peru and north Chile), *L. spicata* (formerly known as *L. nigrescens* in central and south Chile), *L. trabeculata* and *M. pyrifera* along the HCS. The following search string was used to find the relevant literature: “Ecosystem service*” AND (Kelp* OR Laminariales OR *Lessonia* OR *Macrocystis*) AND (Peru OR Chile OR “Humboldt Current” OR “Southeastern Pacific”). All the resulting publications from ScienceDirect ($n = 284$); Scopus ($n = 6$); SCIELO ($n = 1$) and Google Scholar ($n = 186$), were taken to the appraisal stage. In order to identify the most relevant articles, the term “ecosystem service*” was replaced in the search engines with the terms “environmental services”, “provisioning services”, “regulating services”, “cultural services”, “supporting services”, and complemented with additional search words “ecology”, “biodiversity”, “economics” and “subsistence resources”. The new search sourced 1528 additional publications from Science Direct and 8942 from Google Scholar. Some articles appeared in more than one academic search engine and were not counted twice. Overall, 109 papers were sourced from the four databases.

To determine their suitability for inclusion in the review, the abstracts of all papers were analyzed according to the criteria described in Table 1.

Table 1. Inclusion criteria for papers used in the present review, based on their abstracts (appraisal step).

Criteria	Explanation
Ecosystem Service (ES) concept	The paper applies the ES concept in a meaningful way, or the main findings are related to, at least, one of the ES.
Type of article	The paper is an academic peer-reviewed research article.
Species	The content is discussed in relation to <i>Lessonia</i> spp. or <i>Macrocystis pyrifera</i> .
Locality	The content is discussed in relation to the Humboldt Current System (HCS).

After the appraisal step, a total of 86 publications from 1979 to 2022 were deemed suitable for this literature review and considered as the source for the meta-synthesis (Table S1). These were fully read and analyzed with the purpose of identifying the main analytical focus and themes related to kelp forests ES along the HCS. Publication-related metrics were determined as suggested by Donthu et al. (2021) [48]. The papers were categorized and quantified according to ES types, i.e., supporting, regulating, provisioning and cultural [1]. Supporting services are those that make up the basic ecological processes surrounding the ecosystem, which makes way for other ES [49]. The service or capacity to provide suitable living conditions for great diversity is an essential feature of the kelp forests and has been classified as a regulating service or an intermediate service as a product of supporting services [50,51]. Furthermore, regulating services also refer to those that influence climatic conditions, water quality and flood control [52]. Provisioning services are the goods that can be extracted and consumed from ecosystems and are often valued in markets [53]. Cultural services include the environmental basis for esthetic, spiritual and recreational experiences, cultural heritage, sense of place and ways of life [54].

The thematic analysis was conducted in accordance with Mengist et al. (2020) [47], providing an overview of the evidence, knowledge gaps and implications for the topic based on the previously described criteria. Furthermore, we quantified the taxa reported per kelp species for each country according to our final database.

3. Results and Discussion

3.1. The Forest-Forming Species of the Humboldt Current System

In the HCS, kelps commonly occur in subtidal rocky reefs except in the most sheltered or turbid locations, and from the lower shores to depths near 30 m [55–57]. However, kelp forests composed of *Lessonia* and *Macrocystis* have been found in deeper waters (>30 m) [58]. It has been observed that *M. pyrifera* usually forms an upper canopy, while *L. trabeculata*, a lower one [45], playing different roles as habitat-structuring species when occurring in the same forest. The distribution patterns of the four kelp species addressed in this review are shown in Figure 1.

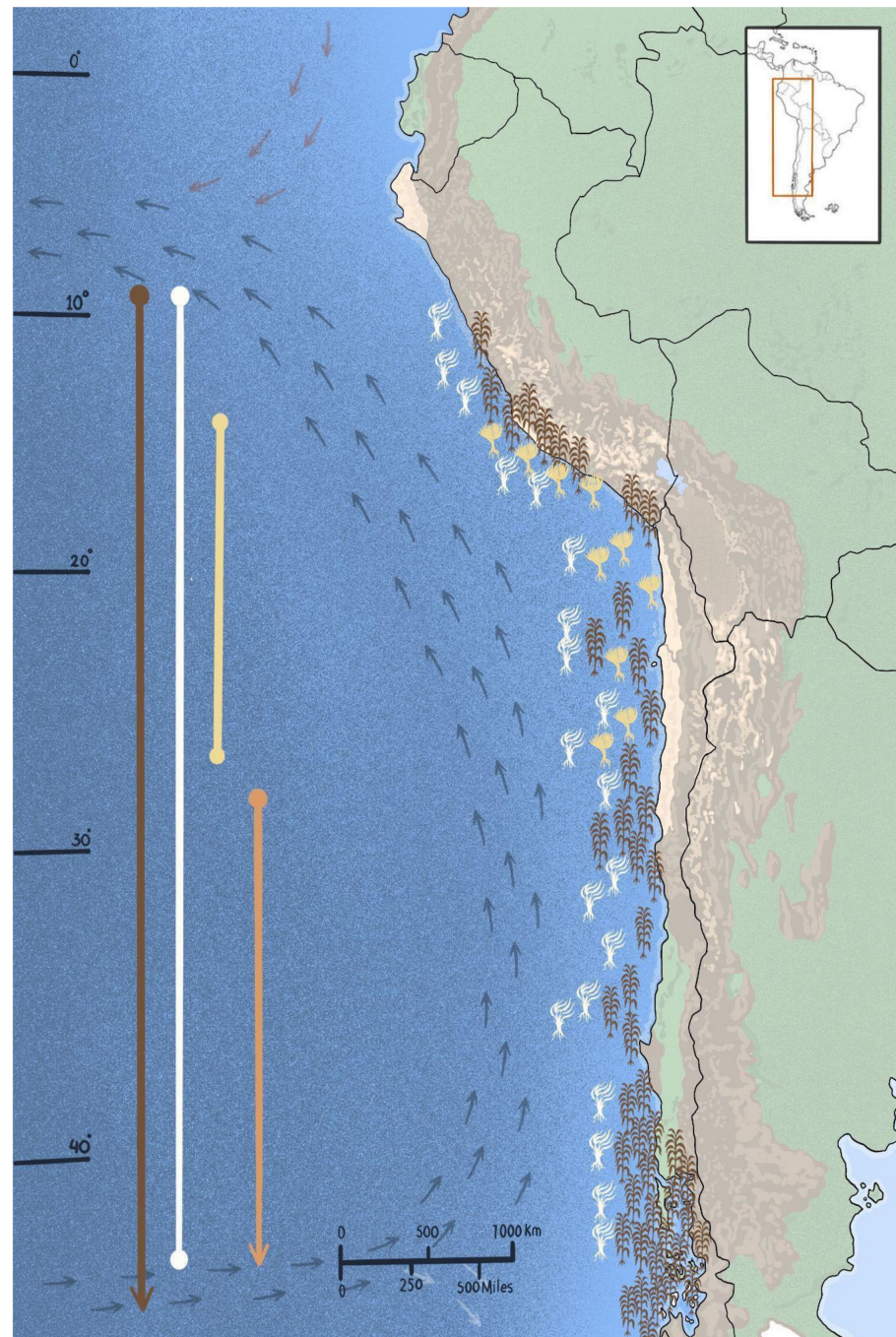


Figure 1. Distribution patterns of kelp species forming marine forests in the Humboldt Current System: *Macrocystis pyrifera* (brown), *Lessonia trabeculata* (white), *L. berteroaana* (yellow), and *L. spicata* (orange).

The kelp forest metacommunities are exposed to different regimes, such as permanent (Peru) or seasonal (Chile) upwelling patterns. The forests located at the northern extreme of the HCS are directly influenced by events associated with the El Niño Southern Oscillation (ENSO), such as the “El Niño Costero” event, which changes the biogeochemical properties of the northern HCS that reduces the availability of nitrates on the upper layer of coastal waters [59] and increases the temperature. On the other hand, cold and eutrophic sub-Antarctic waters predominantly influence the forests in the southern extreme. Although species distribution patterns have been studied for decades, it is still a challenge to monitor the associated assemblages or the ecosystem dynamic at a wide scale in the HCS [60–62].

The assessment of the genetic structure of the giant kelp *Macrocystis* spp. across a broad latitudinal range in the HCS [55], reported low levels of genetic diversity in *M. pyrifera* populations and indicated the presence of a single species for this genus at a regional level. Later, this reduced genetic variation in *M. pyrifera* was reconfirmed from latitudes 12° S to 16° S. However, the presence of unique haplotypes was reported in populations from the San Lorenzo Island (Mpyr8), and from Los Bancos and San Nicolas Bay (Mpyr9) in Peru [61].

Regarding the *Lessonia* genus, the presence of two divergent lineages in central Chile was evidenced. For years, the existence of cryptic species was assumed; however, it was not after a few investigations [62–64], that the scientific name of *L. berteriana* started to be recognized for the northern populations, while *L. spicata* was kept mainly for southern ones. A recent molecular study showed that *L. berteriana* is distributed from at least 15°26' S in Peru to 30° S in Chile [62].

3.2. Overall Search

The SALSA framework provided a large number of articles during the early stages of research. However, this was mainly completed according to the researchers' lecture criteria when conducting the thematic analysis. Based on this, other methods, such as word-mining programs, are worth noting for future reviews.

Research on supporting services was the most prevalent ($n = 59$) and mostly related to ecological studies. This was followed by provisioning services ($n = 19$), most of them focused on fishery studies. Less attention was given to regulating ($n = 3$) and cultural services ($n = 1$). Only three papers discussed general topics related to all types of ES.

Publications predominantly addressed Chilean kelp forests ($n = 77$), with four publications explicitly mentioning ES in Chile [21,22,33,65]. Research on kelp forests in Peru ($n = 5$), or in Chile and Peru at the same time ($n = 4$), were extremely low. The number of publications showed a sustained increase during the last four decades, with more than half of the studies occurring in the last decade (2011–2022) (Figure 2).

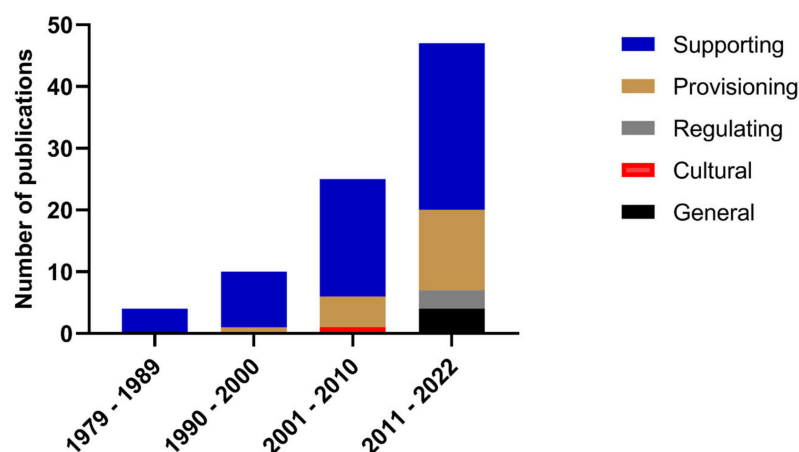


Figure 2. Number of publications per decade.

3.3. General Ecosystem Services of Humboldtian Kelp Forests

In Central Chile, the study of ES using biomass, species richness and personal interviews [65,66] resulted in the identification of provisioning services (e.g., food), regulating services (e.g., biological production), supporting services (e.g., habitat or biodiversity) and cultural services. In northern Chile, an economic valuation of the ES provided by wild kelp populations of *Lessonia* spp. and *M. pyrifera* [22] indicated that kelp beds in this locality would have a value of USD 540 million per year over the next ten years with a constant annual increase. Of the total worth, 9% represented the service of the forests as an environmental buffer for CO₂ capture or O₂ production, 75% is provided by kelp fisheries and 15% by associated-species fisheries. The value of the total ES provided by the coastal benthic ecosystems of three bays (Mejillones, Antofagasta and Tongoy Bays) in northern Chile, including brown algae fisheries [21], was estimated to be about 8% of the total support value that ES provides to the regional economy. This shows the importance and role kelp forests have when providing numerous jobs, a source of income and food to coastal populations.

Kelp forests around the world support economic inputs, i.e., the value of kelp in South Africa is estimated at USD 434 million per year [67], and in the Falkland Islands at USD 342 billion per year [29]. The southeastern Pacific region's kelp forests are dominated by *M. pyrifera* and their value in terms of ES has been evaluated at USD 811,000 per kilometer per year [22]. However, further research regarding the real extent of the species or assemblages are needed to generate accurate estimates in the HCS.

3.4. Supporting and Regulating Services

Kelp primary production enters the carbon cycle as wet biomass, detritus or dissolved organic matter, forming a food source for a wide range of organisms [17,68,69]. In general, ecosystems with a high net primary production generate more food, timber or fiber than less productive ecosystems [54,70]. As habitat formers, a single kelp sporophyte directly provides three distinct primary spaces: the holdfast, the stipe and the lamina. The morphological differences between *Macrocystis pyrifera* and *Lessonia* spp. kelp beds (i.e., stipe number, plant length, dichotomies per stipe and wet mass) influence the composition of the associated characteristic fauna and its functional relationships [69,71] (Figure 3). The kelp holdfast consists of a network of root-like ramifications, which provide galleries and crevices with a high structural complexity, allowing microenvironments to emerge as habitats for macroinvertebrate species such as echinoderms [45,72,73], crustaceans [74–77], polychaetes [76,78], bivalves [76], barnacles and limpets [45,79,80]. Fronds (blades and stipites) can form a dense canopy extending from the holdfast to the upper tip of the long stipes [78], representing habitats for various organisms, both epiphytes and associated fauna that seek shelter or food [36,81–83]. In kelp habitats, amphipods provide a link between kelp and higher trophic level species, including fish, which are voracious predators of amphipods [82,84]. Kelp sporophytes themselves are habitats for essential small-sized benthic suspension feeders which contribute to the recycling of nutrients (regulating services) [85]. Recently, a spatial optimization model to maximize the potential provision of ES was evaluated in coastal areas where *Lessonia* spp. was dominant, accounting for the role of dispersal and larval connectivity (regulating services). It was suggested that future modeling methodologies should encompass the diversity of coastal ecosystems and human activities to develop integrative spatial management [33].

A recent study integrating data of the macroinvertebrates associated with different forest forming species of Peru showed that more than 100 species are associated with *M. pyrifera* and *L. trabeculata* in central and southern Peru. Of these, *L. trabeculata* is the species with the highest diversity recorded [86]. Macroinvertebrate abundance, species richness and biomass significantly increased with holdfast size, explaining why *Lessonia* species have the highest associated diversity [45]. In Chile, at least 45 species were associated with *Lessonia* sp. [87,88] and 30 epifaunal invertebrate species inhabited *M. pyrifera* [80]. According to our search, *L. trabeculata* showed the highest number of taxa reported ($n = 213$)

followed closely by *M. pyrifera* ($n = 210$). However, the number of phyla reported was higher in *M. pyrifera* ($n = 17$) than in *Lessonia* species ($n = 7$ – 13) (Figure 4). Overall, there were more reports of kelp-associated species for Chile than for Peru (Figure 5). The complete list of kelp-forest associated taxa reported per kelp species in Chile and Peru is shown in Table S2. The idea that this could be due to the high rates of speciation occurring in larger biogeographical provinces with lower surface temperatures and high endemism should be considered for further research [89,90].

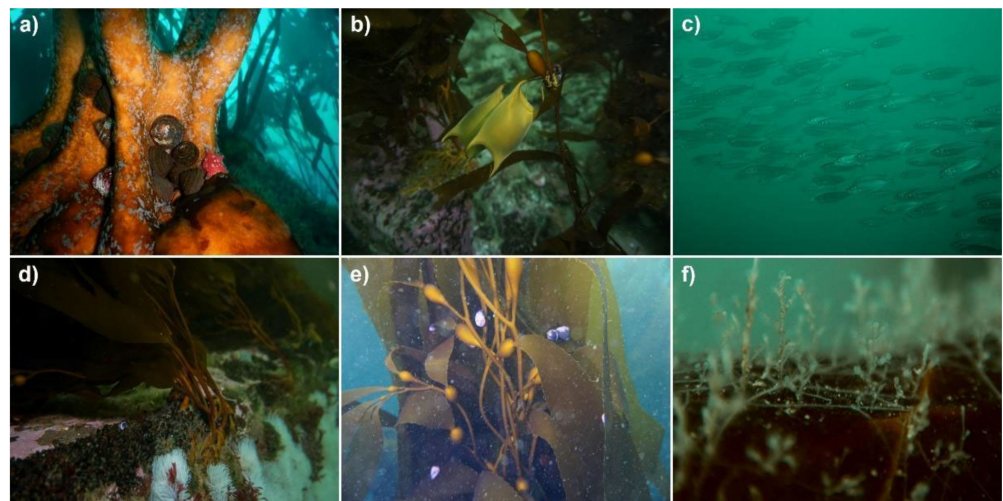


Figure 3. Supporting services of kelp forests along the Humboldt Current System. The genus *Lessonia* usually forms a second canopy (a), while *Macrocyctis pyrifera* forms an upper canopy (e). Kelp forests support habitats for a wide range of fauna, such as motile invertebrates (Pichidanguí, Chile) (a); chondrichthyans that use kelp structures to deposit their capsules (Pucusana, Peru) (b); osteichthyces (*Trachurus murphyi* Nichols 1920; Pucusana, Peru) (c); and sessile organisms (Pucusana, Peru) (d,f).

The reports of fishes associated with kelp forests in southeastern Pacific are mainly from Chile [37,89,91–100] and show that kelp forests provide food and suitable habitats for benthic prey items through the understory community. It was suggested that understory habitats directly affect the diets of the fishes [93]. At least 25 species of reef fishes associated with *Macrocyctis pyrifera* and *Lessonia* spp. were reported from the northern and central rocky coast of Chile, with many of them having socio-economic relevance at a local level [37,93]. Kelp forests provide food for many species. Experimental studies showed that the digestion of *L. trabeculata* is associated with the morphological features and the nutritional and reproductive status of the Zamba marbledfish (*Aplodactylus punctatus*) [99].

Furthermore, kelp forests are strongly associated with food resources for coastal sharks, especially for males [101]. In contrast, pregnant females circle around vertical structures, selecting taller, physically stable and thicker sporophytes to anchor the tendrils of their capsules [39]. The redspotted catshark (*Schroederichthys chilensis*) has been associated with kelp forests dominated by *L. trabeculata* in Chile and Peru [39,101–103]. These consumers concurrently support even higher trophic level organisms, including predators such as seagulls [104], or the endangered sea otter *Londra felina* [92,105]. This is relevant for economies associated with the rich and productive HCS because previous studies have shown that biodiversity, including genetic diversity, is positively associated with the ES provided [106]. It is worth mentioning that our understanding of biodiversity may change over time, as new techniques are developed and integrated into ecological studies.

Regulating services have been mainly represented as the production of larvae that contributes to the regulation and stability of the marine ecosystem [106]. Multiple studies have highlighted the essential role of marine forests in larval dispersion and the colonization of distant habitats [57,73,106–116].

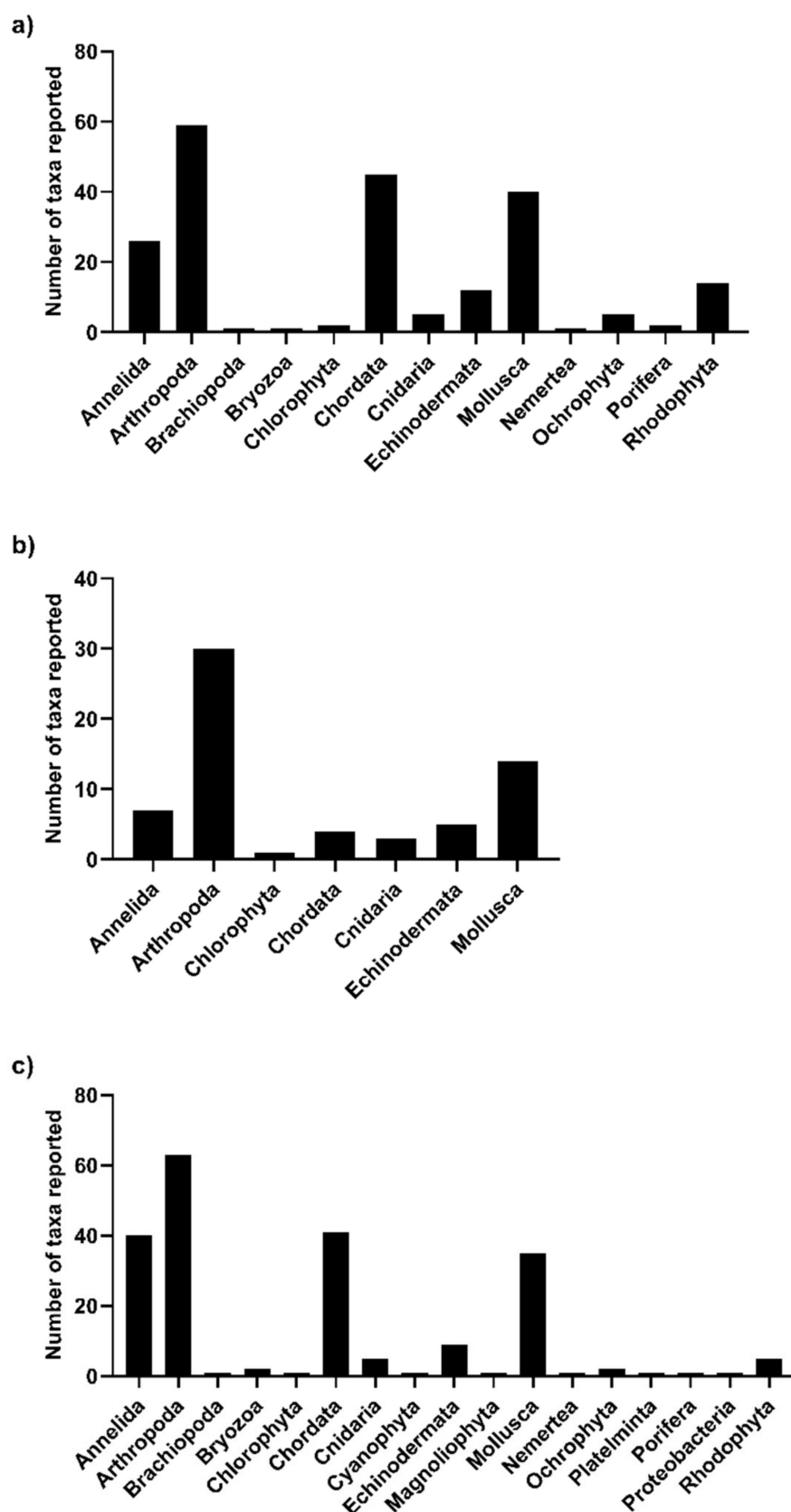


Figure 4. Number of kelp-forest associated taxa reported per Phylum. (a) *L. trabeculata*; (b) *L. berteroa/spicata*; (c) *M. pyrifera*.

It is known that kelp detritus represents a subsidy of energy in low-productive habitats; hence, it is the main source of food for rich and abundant faunal assemblages, increasing the magnitude of carbon flow through consumers [60,75,106–117]. The latter coincides with experiments showing that trophic association with seaweeds is particularly important for epiphytic bryozoans under conditions of reduced particulate-food concentration [118]. Regarding kelp blue carbon studies, only one paper has been identified addressing the capacity of carbon storage by *L. trabeculata* in southern Peru [117]. Additionally, only one study addressed the economic value of the carbon that kelp assemblies capture in northern Chile [22].

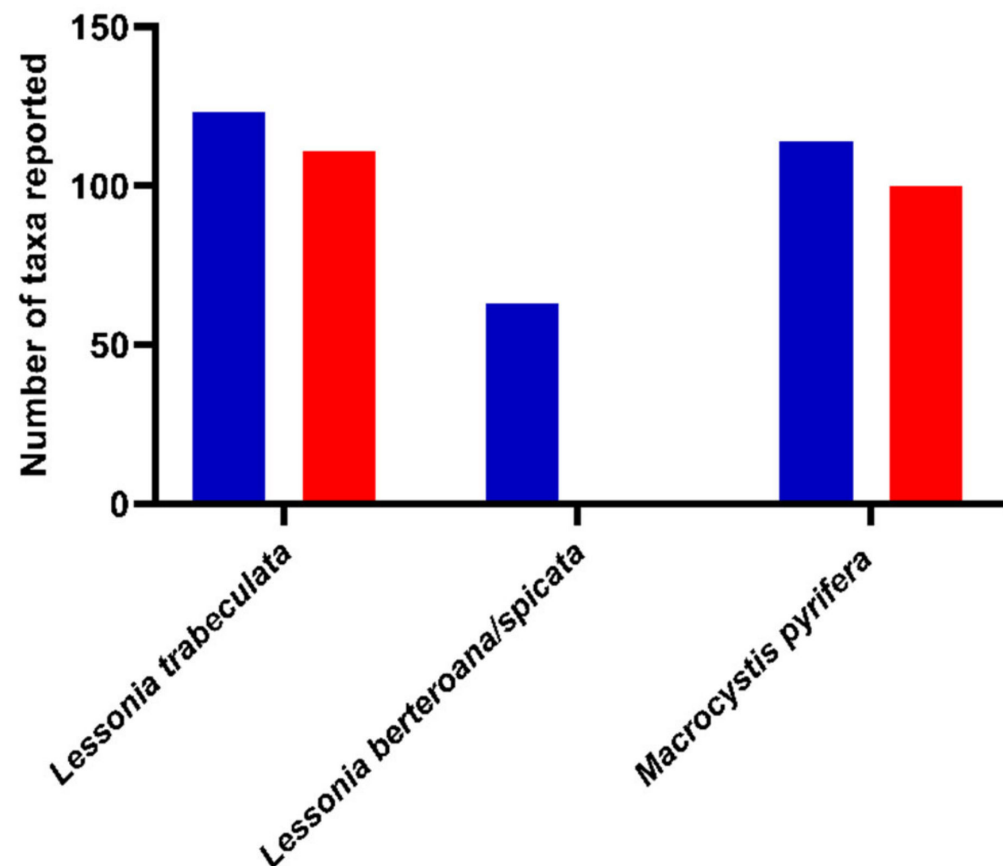


Figure 5. Number of kelp-forest associated taxa reported per kelp species in Chile (blue) and Peru (red).

3.5. Provisioning Services and Economical Benefits

In Chile and Peru, kelp species alone are a valuable bioresource used as raw material for alginate extraction [119]; feed for aquaculture species [120,121], and even stool pigeons [57]; organic fertilizer; biofuels; and human food [57,121–123]. The use of kelp resources along the HCS is based on the harvest and collection of biomass, making Chile the leading producer country of raw material [120–129]. Kelp biomass is destined to alginate production, an industry valued at USD 213 million annually worldwide [129]. In northern Chile alone, more than 11,000 people depend directly or indirectly on the collection and harvesting of these resources [130]. For this reason, and to guarantee the sustainable production of kelps, alternative ways to manage and cultivate them are being investigated with the aim of obtaining these algae-associated benefits with lower ecosystem impacts [71,124,131].

Kelp fisheries are not the only kind of fisheries associated with kelp forests. Numerous fish, mollusks, crustaceans and other invertebrate species are associated with marine forests too, both in Chile and Peru [117,120,132]. Bioresources including *Concholepas concholepas* (Chilean abalone), *Fisurella* spp. (keyhole limpets), *Loxechinus albus* (red sea urchin), *Pyura*

chilensis (red sea squirt), *Octopus mimus* (gould octopus) and various rock fishes, such as *Cheilodactylus variegatus* (Peruvian morwong), *Paralabrax humeralis* (Peruvian rock seabass), *Pinguipes chilensis* (Chilean sandperch) and *Anisotremus scapularis* (Peruvian grunt) have been reported in Humboldtian kelp forests. These species are continually captured by artisanal divers due to their socio-economic relevance, especially as food with high nutritional value [94,117,133,134].

3.6. Cultural Services

A collaborative paper between archaeologists and marine ecologists discussed the influence of kelp forests over the human migration from Asia to the Americas near the end of the Pleistocene. The study mentioned that marine forests provided protected nearshore areas for human migration, so it was easier for people to sail to the open sea. Kelp forests also provided food and materials that humans could keep for their sea voyages (e.g., kelp holdfasts were used for building boats) [135].

According to archaeological records, partially eaten and cooked seaweeds have been found at a 14,000-year-old site in Chile, suggesting that seaweed and associated fauna have been part of the human diet in the Western Hemisphere since ancient times [134–137]. In addition, remnants of algae, presumably *Macrocystis* were found in tombs of the Nazca (10 BC–700 AD) and Paracas (700 BC–200 AD) cultures, revealing the preference for seaweeds in the diet and practices ancient coastal societies of Peru [58,138,139].

3.7. Threats and Gaps

As a result of our research, we have been able to identify a lack of peer reviewed studies related to regulating and cultural services. The perspective of society about the cultural services of kelp forests and the existential values of kelp communities is unknown, suggesting a deficit of public interest towards this topic in Chile and Peru. Kelp forests could be seen as an opportunity to promote ecotourism activities such as natural history education, flora and faunal watching and recreational diving [22]. More research addressing these activities is required, especially in Peru where the small number of peer-reviewed articles evidences a large information gap related to kelp ES. In Chile, the value of kelp forests for tourism, fisheries, education and scientific research is gaining recognition over time; however, few studies have addressed the quantification of their economic value.

Research on climate change-related scenarios is critical for understanding how kelp forests and their ES will be affected. It is known that increasing mean temperatures threatens *Lessonia trabeculata* populations and might have further negative consequences for the continuity of the associated ES [140–142]. Ocean warming or periodic warming events affect the recruiting capacity of *Lessonia* spp. and other kelp species by affecting their early developmental stages and modifying the spatial arrangement of subtidal populations along the HCS [140–143]. Events such as the ENSO lead to massive mortality of kelp species in Peruvian and Chilean coasts [144–149]. Such sharp population declines, or bottlenecks, may translate into losses of genetic variation of marine organisms [145–148].

There is evidence that kelp beds contribute as blue carbon habitats. However, the fraction of carbon fixed by kelps in the HCS, which is effectively removed from the atmosphere over different timescales, is poorly understood. Research to estimate the carbon storage of the Humboldtian kelp species could lead to mitigation or adaptation strategies to confront climate change [117].

Overgrazing by invertebrate herbivores, particularly sea urchins [83,132,150], has been reported to decimate kelp forests and cause phase shifts from structurally and biologically diverse habitats to depauperated “barrens”. Predators such as *Meyenaster gelatinosus*, *Heliaster helianthus*, *Luidia magellanica* and fish naturally control grazer populations, which indirectly benefits the forest’s stability, as well as their services [84,149–151]. Although it is evident that kelp forests are characterized for supporting complex trophic relationships, primary net productivity and secondary productivity need to be explored to a greater

extent. The latter could help to avoid climate or human-induced regime changes, which could be detrimental to the human activities developed within the HCS.

Direct harvesting from natural populations is another threat that kelps face within the HCS because of their value as a raw material for the alginate industry [88,119,123,129]. Increasing demands of *L. trabeculata* for biomedical and pharmaceutical products would require increased harvesting efforts, this could negatively affect the population's sustainability and the associated resources [127]. It has been reported that *L. trabeculata* harvesting reduces the richness of macroinvertebrates with socio-economic value such as *Concholepas concholepas* [88].

Coastal defense represents one of the critical ES that will become more important along many coastlines, as the sea-level rise and magnitude and frequency of storms increase [17]. No research regarding the role of kelp species in the natural protection (first barrel) of the coasts of Peru or Chile was found during our literature review. It is worth highlighting that both countries are located within the Circum-Pacific Seismic Belt, which frequently exhibits seismic activity [152].

The nature of interspecific and regional-scale variability in kelps as habitat formers within Chile and Peru is still poorly understood and remains an important knowledge gap within the field of kelp forest ecology. Moreover, there is a lack of phylogeographic studies in the Southern Hemisphere, particularly in the south-eastern Pacific [153].

Research about teleost fishes directly associated with kelp forests along the Peruvian coast has been limited to one report [117]. In the same way, the impact of kelp forest-associated fisheries on predators such as sharks, birds and marine mammals is not well understood.

Kelp forest insights that are still uncertain would contribute to identifying the sense of place, as well as fostering social cohesion and essentials for human health and well-being linked to those ecosystems. It is crucial to carry out more monetary and non-monetary studies related to cultural services such as contingent valuation, choice experiments, participatory mapping and social media-based services as examples [154].

4. Conclusions

Baseline information and detailed ecological studies remain to be completed or updated on kelp forest ES along the HCS (Peruvian and Chilean coasts). From a total of 88 articles, only 3 directly discussed kelp ES in Chile. Studies on supporting services were the most prevalent followed by provisioning, regulating and, lastly, cultural services. Studies focusing on kelp forests ES in Peru were scarce, while Chile showed a greater effort. At the moment, no articles are available regarding the valuation of the ES provided by these marine forests in Peru. Figure 6 summarizes the ES provided by kelp forests along the HCS.

Over the last few years, it has been possible to properly identify kelp species for both countries due to the use of molecular tools in ecological studies. However, the geographical distribution of these species must be further addressed. Integrating phylogenetics with habitat mapping in different kelp forests along the HCS could support a more realistic valuation and quantification of the services provided by these ecosystems.

Regarding threats, we identified the ENSO as a major factor contributing to the variation of the health and genetic diversity in kelp species at the HCS. Climate change studies were mostly related to effects on the recruitment and early stages of development. On the other hand, kelp harvesting as a growing human activity and the fisheries associated with these forests could lead to an ecosystem decline, along with the services it provides, through trophic cascade effects.

Future Directions

Despite the research completed so far, it is important to continue exploring the dynamics of kelp forests in Chile and Peru and the ES they provide. The proper identification of kelp species is relevant for both the stock management, monetary valuation and the traceability of the products obtained from them. Future efforts by researchers and policy-

makers to quantify the landings per algal species would allow a better understanding of the productivity of kelp forests at a local and regional level. Furthermore, it is essential to standardize the investigation methodologies so that it is possible to apply them in both countries for proper comparisons.

In addition, it is important to focus future research on less studied ES, such as regulating and cultural services, as well as on the mapping and stock quantification of the forests along the HCS. Particularly, the survey of the ecosystem and associated human activities in a socio-ecological framework, could help stakeholders to better understand how these ecosystems will naturally behave and contribute to the local and regional economy. In a specific matter, future studies must focus on the identification and role of microbial diversity in relation to: (1) new biological compounds; (2) microbial species succession; and (3) degradation of kelp detritus in HCS. Genera such as *Ralstonia*, *Cyanobacterium* and *Granulosicoccus* might be crucial for nutrient cycling and epibiont colonization [155], but also susceptible to climate change, according to studies in other regions [155–157].

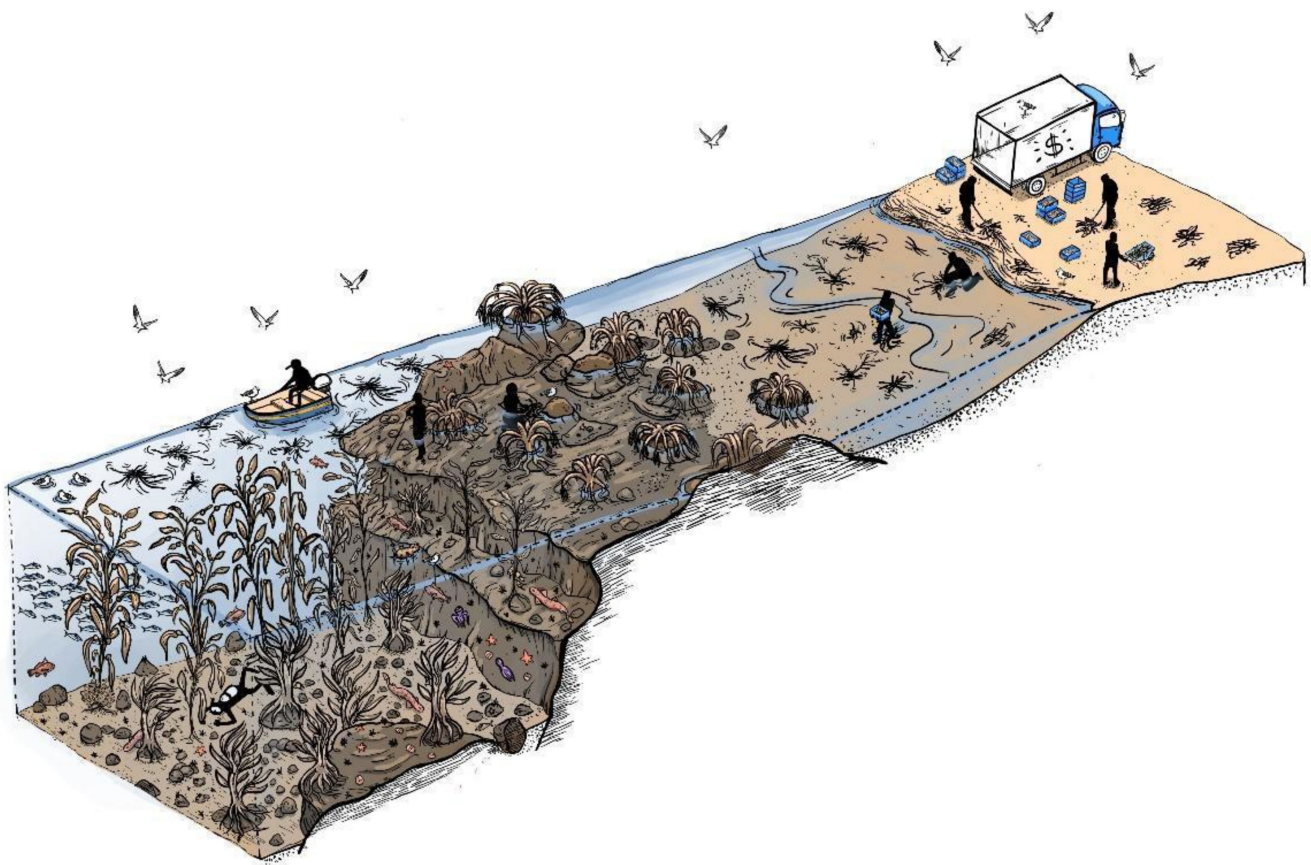


Figure 6. The laminarian assemblages of the HCS are distributed in the intertidal and subtidal areas of rocky shores. They bring coastal protection and structure a habitat for a plethora of threatened and commercial species, allowing them a place to shelter, feed and reproduce, as their fragments help disperse the larvae of organisms associated (Supporting and Regulating Service). The forests have a key role as a blue carbon reservoir and the carbon flux through the sandy beach (Regulating Service). In addition, these coastal hotspots on the coast are key ecosystems for different human activities, mainly fishing directly or recollected (shipped and non-shipped), tourism (diving, recreational fishing, boat sailing), and scientific research (Providing and Cultural services).

Finally, there should be interest in how kelp forests contribute to coastal defense and the physics of the waterflow according to the configuration of the canopy. We stress the need for more studies focusing on the effects of the harvest and collection of kelp, especially due to the importance of kelp-derived detritus as a food resource for plankton and infauna.

Within the context of climate change and global warming, predictive models are a tool that could be applied to identify trends in relation to kelp biomass, associated diversity and distribution. All of this could provide scientific support for better policy making and conservation efforts.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/coasts2040013/s1>, Table S1: List of references selected for the systematic review of Ecosystem Services provided by Kelp Forests of the Humboldt Current System; Table S2: List of kelp-forest associated taxa reported per kelp species in Chile and Peru.

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