

REVIEW

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Seaweed production as a social-ecological system along the southeast Pacific coast

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Abstract

Seaweed production is a globally expanding activity that supports coastal livelihoods, phycocolloid industries, food systems, and emerging blue bioeconomy opportunities. However, its social-ecological implications differ strongly among production models. Chile represents a distinctive case because, unlike aquaculture-dominated systems in Asia, most national production depends on the extraction of wild seaweed populations by artisanal fishers. This narrative review examines Chilean seaweed production along the southeast Pacific coast through the Social-Ecological Systems Framework, integrating peer-reviewed literature, official statistics, technical reports, and institutional information published between 1980 and 2026. We synthesize evidence across four main SES components: Resource System, Resource Units, Governance System, and Actors, and analyze how their interactions shape resilience, vulnerability, and sustainability outcomes. Chile is the main seaweed producer in the Americas and one of the world's leading producers of wild-harvested seaweeds. In 2025, national production reached 426,543 metric tons, with approximately 85% derived from wild populations. Brown seaweeds, particularly species of the *Lessonia nigrescens* complex and *L. trabeculata*, dominate production in northern Chile, whereas red seaweeds, including *Gracilaria chilensis*, *Sarcothalia crispata*, *Sarcopeltis skottsbergii*, and *Chondracanthus chamissoi*, are more relevant in central-southern and southern regions. These spatial patterns reflect biogeographic gradients, environmental heterogeneity, harvesting histories, market demand, and governance arrangements. Chile's governance system combines Territorial Use Rights for Fisheries, Open Access Areas, bans, quotas, management plans, and participatory seaweed roundtables. These instruments can promote stewardship and ecological recovery, but their effectiveness is mediated by enforcement capacity, labour dynamics, market fluctuations, and asymmetries within value chains. Our synthesis shows that Chilean seaweed production is shaped by feedbacks among climate variability, wild population dynamics, international demand, governance responses, and local livelihoods. Dependence on global commodity markets, particularly demand from China, can intensify extraction pressure while concentrating economic benefits among intermediaries, processors, and exporters. At the same time, artisanal fishers and women seaweed workers often bear disproportionate ecological and economic risks. Future sustainability will require strengthening adaptive governance, improving equity across value chains, diversifying production through native species aquaculture and value-added products, and developing integrated long-term monitoring that links ecological indicators, market dynamics, governance performance, and community wellbeing under climate change and uncertainty.

Keywords Seaweed, Social-ecological systems, Governance, Artisanal fisheries, Sustainability, Coastal resources

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Introduction

Seaweed harvesting, primarily for direct consumption, is an activity that has been practiced worldwide by humans since prehistoric times in coastal environments [1–4]. The benefits provided by these ecosystems and their resources have led to coastal areas having the highest human population densities and intricate social and economic systems [5, 6]. Human coastal communities are deeply reliant on the condition and health of these ecosystems and their resources [7, 8] and are significant drivers of change in coastal marine environments [9–11]. The close interdependence between seaweed resources and coastal communities characterizes seaweed production as a social-ecological system (SES) [12–14], in which ecological and social dimensions interact through dynamic feedback relationships and co-adaptive processes [15–17].

Seaweeds are economically and socially significant resources in coastal areas worldwide, playing a crucial role in supporting the livelihoods and food security of local communities [14, 18–20]. These photosynthetic organisms function as ecosystem engineers, providing food and habitat for a wide array of marine species [21, 22] and shaping the structure and dynamics of coastal marine ecosystems [23–26]. Additionally, seaweeds deliver a wide range of ecosystem services including food provision, habitat creation, climate regulation, and cultural and aesthetic benefits [27–32]. Seaweeds are increasingly positioned as a strategic resource within the emerging blue economy, attracting attention due to their potential contributions to climate mitigation, bioeconomy development, food security, and coastal livelihoods. However, the rapid expansion of seaweed industries has also raised concerns regarding social equity, governance, and benefit distribution [33, 34].

Unlike most major seaweed-producing countries, where aquaculture dominates production [35, 36], Chile represents a globally distinctive case in which seaweed production depends primarily on the harvesting of wild populations by artisanal fishers [37–39]. This characteristic creates a highly dynamic SES shaped by the interaction between environmental variability, territorial governance arrangements, global commodity markets, and local livelihoods [40]. The Chilean seaweed production sector is strongly influenced by climatic disturbances associated with the El Niño-Southern Oscillation (ENSO), fluctuating international demand for phycocolloid raw materials, and co-management systems such as Territorial Use Rights for Fisheries (TURFs) [27, 41, 42]. These interacting drivers generate feedback mechanisms that influence ecological resilience, harvesting pressure, market vulnerability, and social wellbeing.

The aim of this study is to examine seaweed production along the Chilean coast through the lens of

the Social-Ecological Systems Framework proposed by Ostrom (SESF) [43, 44]. Using a narrative review approach, we synthesize ecological, governance, socio-economic, and institutional dimensions of Chilean seaweed production to analyze interactions among resource systems, resource units, actors, governance arrangements, and global market dynamics. We further explore how these dimensions shape the resilience and vulnerability of this extractive coastal system, while identifying key challenges and research gaps for long-term sustainability of seaweed production. Finally, we discuss the distinctiveness of the Chilean seaweed extraction sector in relation to contrasting international models, such as China's aquaculture-dominated system and Norway's concession-based extractive model.

Methods and analytical framework

This study was conducted as a narrative review focused on the social-ecological dimensions of seaweed production in Chile. The review integrated ecological, governance, socio-economic, and institutional literature related to seaweed harvesting, aquaculture, artisanal fisheries, and coastal management through the lens of the SESF.

Literature approach

The literature search was conducted primarily using Web of Science and Google Scholar, covering literature published between 1980 and early 2026, and official statistics available through 2025. Search terms included combinations of “seaweed”, “macroalgae”, “kelp”, “Chile”, “Social-ecological systems”, “governance”, “artisanal fishers”, “TURFs”, “coastal management”, and “seaweed harvesting” in both English and Spanish. Additional information was obtained from governmental and institutional sources, including statistical fisheries yearbooks, technical reports, and official databases from the National Fisheries and Aquaculture Service (SERNAPESCA; www.sernapesca.cl) and the Undersecretariat for Fisheries and Aquaculture (SUBPESCA; www.subpesca.cl). The review included peer-reviewed articles, governmental reports, technical documents, fisheries statistics, and book chapters addressing ecological processes, governance systems, artisanal fisheries, aquaculture, socio-economic dynamics and environmental variability associated with seaweed production in Chile and other relevant international contexts, particularly China and Norway.

Social-ecological system framework

The selected literature was organized and synthesized according to the principal categories of the SESF: Resource System, Resource Units, Governance System, and Actors [43]. However, rather than treating these components as isolated categories, the review emphasizes the

dynamic interactions among them, including feedback mechanisms and outcomes. Many conceptual frameworks have been developed to analyze SES, including the Driver-Pressure-State-Impact-Response framework and the Telecoupling framework, which emphasize different aspects of SES dynamics [17, 45]. Among them, the SESF is one of the most comprehensive and widely applied approaches because it examines social and ecological dimensions with similar analytical depth. Building upon common pool resources theory [46], the SESF explicitly integrates resources, users and governance within a common analytical structure, facilitating the analysis of interactions, feedback mechanisms, and cross-scale processes that influence resource sustainability [43, 47].

The SESF disaggregates ecological and social subsystems into hierarchical levels that facilitate analysis of interactions among ecological resources, governance systems, institutions, and people involved as actors within the system (Fig. 1). Within this framework, the Resource System refers to the biophysical or ecological environment that provides the goods and services used by the Actors [43, 47]. The Resource Unit is the extracted

component of the Resource System; Resource Units represent the tangible goods that Actors harvest, exchange, or transform [43, 47]. The Governance System encompasses the norms, rules and institutions, both governmental and non-governmental, that regulate access, use, and management of Resource Units, along with monitoring and sanctions. Governance Systems operate through both formal institutions, such as laws and treaties, and informal arrangements, including local community norms. Governance Systems play a crucial role in monitoring and resolving conflicts affecting SES sustainability [40, 43, 48]. Finally, Actors are individuals or groups who interact with the Resource Systems and Resource Units. Actors possess key characteristics, such as local knowledge, cultural values and socio-economic conditions, while differences in power, access, and decision-making capacity can strongly influence resource use and management [40, 43, 49].

The framework also defines Focal Action Situations within the SES, where Actors interact and make decisions regarding resource management and among themselves. The outcomes of these interactions can differ depending

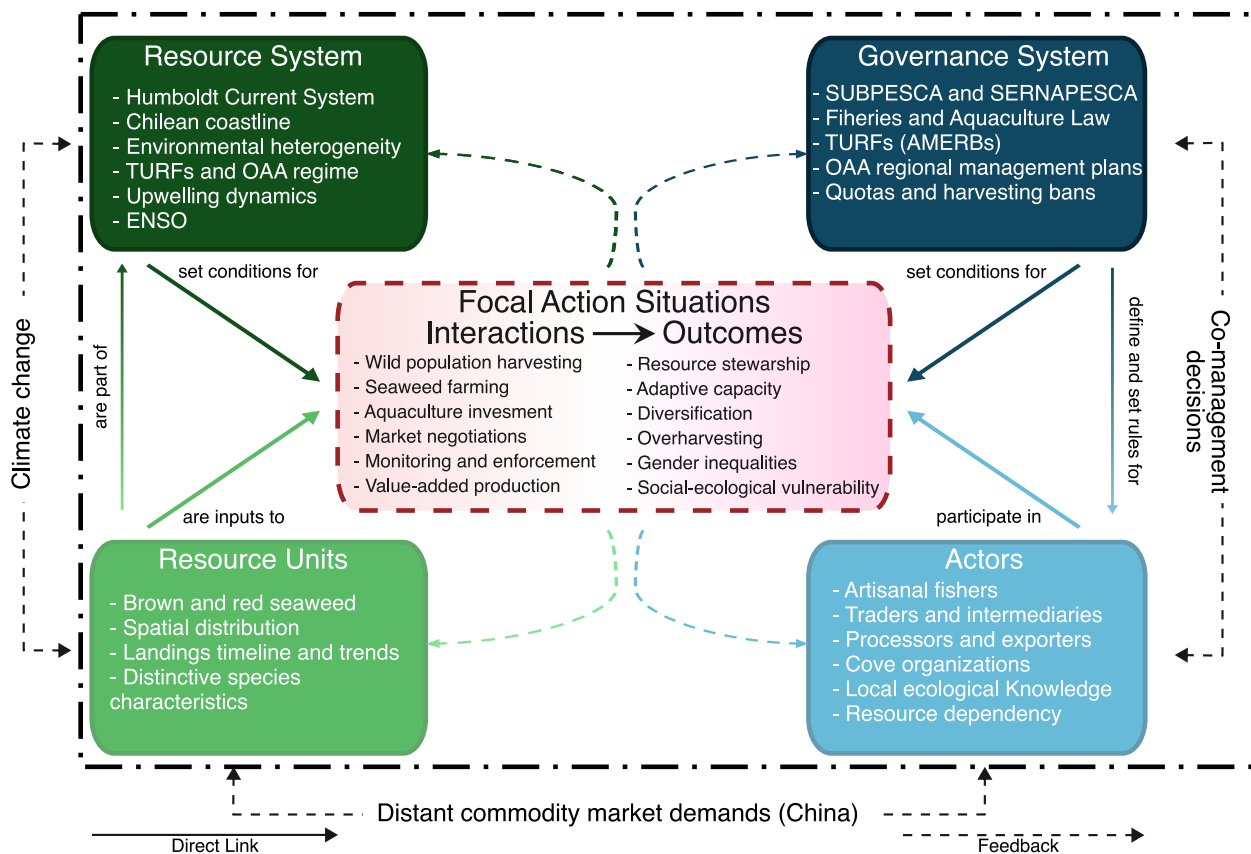


Fig. 1 Conceptual synthesis of the Chilean seaweed production social-ecological system based on Ostrom's SES framework [43, 44]. Solid boxes contain the highest-tier variables and the second-tier variables selected as relevant for Chile. The dashed-line box represents the focal action situation, where relevant interactions and outcomes emerge from the use and management of seaweeds. The dotted-and-dashed line encompasses the entire focal system, separating external and internal drivers that may influence some components in the system. Arrows represent the principal relationships and feedbacks that link different elements of the system

on the effectiveness of the rules, the level of cooperation between Actors, and the biophysical conditions of the resource. At this level, key aspects of the SES, such as sustainability, potential overexploitation and resource collapse, equity in resource use, conflicts between actors, resilience of the SES, and erosion of governance, are assessed [43]. These outcomes feed back into higher hierarchical levels of the SES where decisions must be made to improve the sustainability of the system, reflecting the dynamic nature of complex systems.

Global seaweed production

Seaweed production is an increasingly important economic activity at the global level, driven by rapid farming expansion especially in Asian countries including China, Indonesia, South Korea and the Philippines [50]. Seaweed biomass is used for human consumption, phycocolloid production, and as additives or ingredients in medicinal and cosmetic products [37, 51–54], soil fertilization, livestock feed, and energy generation [55–57]. Seaweed derivatives such as carrageenan, agar, and alginates comprise approximately 40% of the global hydrocolloid market in the food sector. Between the 1950s and 2023, reported seaweed production increased 67-fold, from 0.56 to 35.8 million metric tons [36]. This growing demand has driven the expansion of seaweed farming, particularly in Asian countries [58, 59]. However, further expansion of seaweed farming requires robust risk management based on scientific evidence, adequate regulations, and biosecurity measures to minimize ecological impacts, support sustainability, and enhance the economic and social resilience of coastal communities [60, 61].

The ten leading producers of seaweed biomass, considering both farming and harvesting, are China, Indonesia,

South Korea, the Philippines, North Korea, Chile, Japan, Malaysia, Norway, and Tanzania, with eight of these countries located in Asia (Fig. 2). In 2023, China alone accounted for 56.75% of global seaweed production, equivalent to more than 20 million tons, primarily from farming activities [36, 62]. Chile is the leading producer in the Americas, with an output of 426 thousand tons, representing 1.19% of global production, mostly derived from the extraction of wild populations.

Across most countries, including Chile, seaweed harvesting and farming are predominantly carried out by artisanal fishing communities, which play a significant role in global production [12, 63]. However, global seaweed production systems differ substantially in their ecological basis, economic organization, and governance structure. In Asian countries such as China and Indonesia, production is dominated by large-scale aquaculture systems that integrate industrial processing chains and export-oriented markets [35, 58, 64]. In contrast, countries such as Norway rely primarily on concession-based harvesting and emerging cultivation systems supported by strong regulatory frameworks, marine spatial planning, and technological innovation [65–68]. Chile differs from both models because seaweed production relies predominantly on the extraction of wild populations by artisanal fishers operating under territorial co-management arrangements in TURFs and open access areas (OAA).

Unsustainable seaweed exploitation, particularly in kelp forest ecosystems, has caused ecological and societal impacts, including biodiversity loss, habitat degradation, and disrupted ecosystem functions and services [69–74]. Conversely, integrated seaweed farming offers seaweed biomass along with ecological and socioeconomic benefits, including increased biodiversity, enhanced

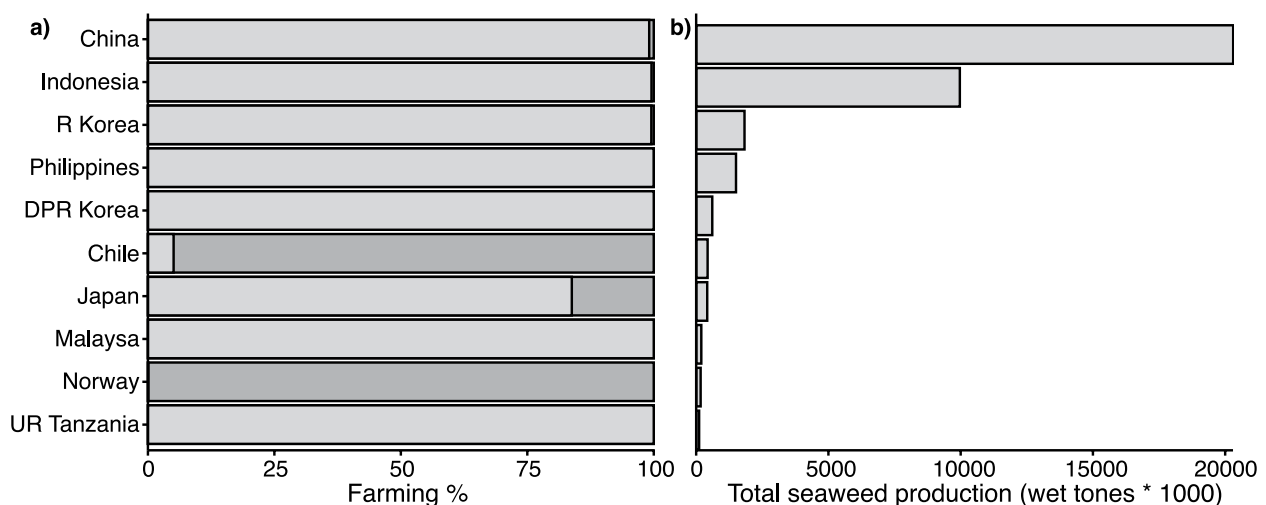


Fig. 2 Summary of seaweed production in the top 10 producing countries worldwide, including: **a**) the percentage of farming (light grey) versus wild population extraction (dark grey), and **b**) total production in tons in 2019 [36]

ecosystem functions and services, improved livelihoods, advances in gender equity, and improved access to education [14, 59, 75, 76]. Therefore, resource management should follow sustainability principles and promote responsible, collaborative practices grounded in a socio-ecological approach [77–80].

The rapid global expansion of seaweed production has also generated important socio-ecological challenges, including market concentration, asymmetric power relationships across value chains, unequal distribution of economic benefits, and increasing dependence on global commodity chains [81, 82]. In many countries, coastal communities remain economically vulnerable because most of the added value of seaweed is captured by industrial processing and export sectors rather than by local harvesters and small producers [35, 83].

The resource system: geographical context of coastal Chile

Chile's continental coastal territory, the Resource System, stretches along the southeast Pacific from 18° to 56°S, encompassing more than 4,200 km of north–south oriented linear coastline and over 88,000 km of shoreline [84]. The Chilean coast is influenced by two major marine currents that originate as the Antarctic Circumpolar Current interacts with the continent between 40° and 45°S, giving rise to the Humboldt Current system to the north and the Cape Horn Current to the south [85, 86]. The Humboldt Current system fosters environmental dynamics that drive the upwelling of cold, nutrient-rich waters, positioning Chile's coastal system among the most productive globally [87].

Chile's continental coastline is situated within two distinct biogeographical provinces: the Peruvian (18 to 30°S) and the Magellan (42 to 56°S) provinces [85, 86]. Between these provinces lies the Intermediate Area (30 to 42°S), characterized by mixed environmental conditions [86, 88–91], that delineates two biogeographic breaks, to the north at 30–33°S and to the south at 41°–42°S, consistent with the distribution and composition of seaweed species along the coastline (Fig. 3).

The distribution of economically significant seaweed species, or Resource Units, exhibits a peak in species richness in central Chile, between 39° and 40°S, where 14 species are recorded (Table 1). However, this region also shows the lowest recorded seaweed landings (Fig. 3). In contrast, northern Chile, between 19° and 32°S, leads in seaweed production biomass, with kelps being the predominant group harvested from wild populations. Meanwhile, southern Chile (between 36° and 56°) primarily harvests and cultivates red seaweeds, particularly *Gracilaria chilensis* (Fig. 3).

The governance system: national and local context

The Governance System that oversees seaweed production in Chile operates at both formal and informal levels, interconnected through key Actors. The structure allows for the creation of rules and norms and grants a degree of autonomy to fishers in resource management while ensuring accountability to state agencies responsible for monitoring and enforcement. The SUBPESCA regulates aquatic production activities in Chile under the General Fisheries and Aquaculture Law (FAL No. 18,892), which defines access, extraction rules, and management strategies such as bans and quotas, while the SERNAPESCA is tasked with enforcement of regulations.

TURFs are one of the most innovative management tools in this Governance System framework, which grant exclusive harvesting rights to registered fishers' associations over specific seabed areas [41, 42, 109]. Based on common-pool resource theory [46], TURFs foster sustainable practices by allowing fishers to exclude non-members and manage resources collectively. In contrast, areas not assigned as TURFs are OAAs, where resources are vulnerable to the "tragedy of the commons" [110]. Despite this, strategies have been applied in these areas, including regional quotas, bans, and access restrictions.

To support sustainability, "seaweed roundtables" have been established, where stakeholders, including fishers, traders, authorities, and scientists, collaboratively define extraction limits based on available biomass. This participatory model has led to sectoral quotas, seasonal bans, and improved traceability from harvest to export. An example is the determination of the annual quotas for kelp species such as *Lessonia berteroana* and *Lessonia trabeculata* in northern Chile (18° to 33°S).

Chile implements a range of policy instruments including Marine Protected Areas (MPAs), TURFs, and OAAs. These measures have proven successful for some seaweed species, often linked to effective enforcement. For example, species of the genus *Lessonia* have higher biomass inside TURFs compared to OAAs, while OAAs that have implemented management plans, regulated since 2017, perform similarly to TURFs [111], and kelp recruits and juveniles are more abundant where exploitation is permitted, while adult kelps are more abundant in MPAs [112]. TURFs and MPAs thus play a key role in conserving wild seaweed populations [111, 113] as fishers report higher levels of compliance, success, and satisfaction compared to those in regional OAA plans. Understanding the dynamics among these governance models is vital for improving management and fostering synergies between approaches [114, 115].

Despite the presence of management efforts, kelp sustainability in northern Chile faces several challenges. These include difficulties in accessing harvesting sites, the extensive coastline combined with limited enforcement

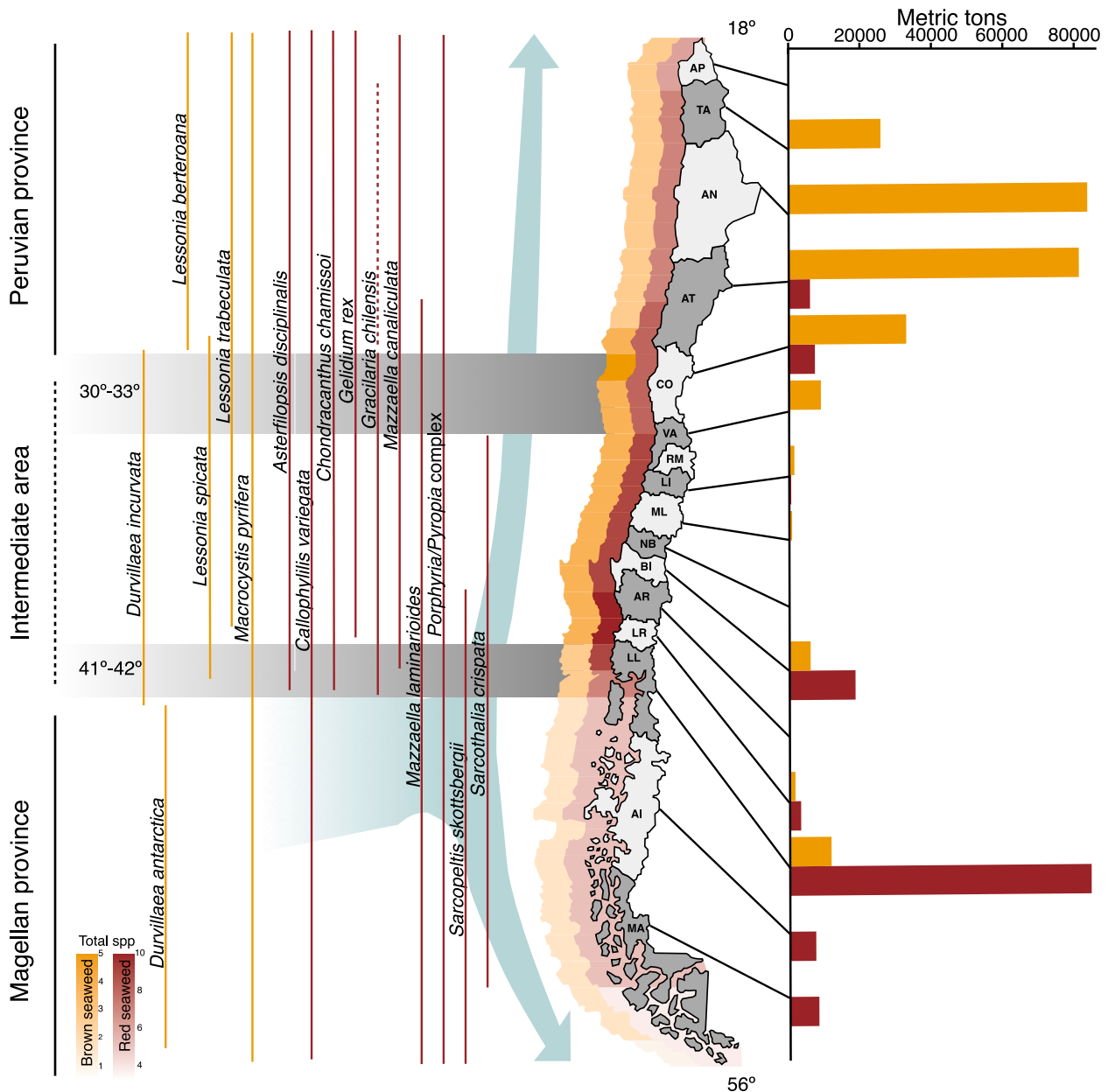


Fig. 3 Biogeography of algae production in Chile. The two biogeography provinces, the Peruvian and Magellan provinces, as well as the Intermediate Area, are shown on the left, followed by the geographic range of distribution of brown and red seaweeds of economic importance in Chile. Heat maps along the coast of Chile display the latitudinal gradient in species richness of brown (in orange) and red seaweed (in red). To the right of the map, the plot shows the total landings in metric tons of brown and red seaweeds by region in 2025. The names of the Chilean administrative regions according to the acronyms in the map are: Arica y Parinacota (AP), Tarapacá (TA), Antofagasta (AN), Atacama (AT), Coquimbo (CO), Valparaíso (VA), Región Metropolitana (RM), Libertador General Bernardo O'Higgins (LI), Maule (ML), Ñuble (NB), Biobío (BI), Araucanía (AR), Los Ríos (LR), Los Lagos (LL), Aysén del General Carlos Ibáñez del Campo (AI), and Magallanes y de la Antártica Chilena (MA)

capacity, the reliance of migrant workers on seaweed harvesting as a livelihood, and socio-economic shifts linked to fluctuations in copper prices [116, 117]. Fluctuations in employment opportunities associated with the mining sector can alter the number of people entering seaweed harvesting activities, thereby modifying harvesting pressure independently of ecological conditions [117]. All these conditions illustrate the influence of cross-scale

interactions on seaweed governance, where resource sustainability depends not only on biological productivity and governance effectiveness but also on broader economic processes operating at regional and global scales.

Alternative governance approaches can be observed in other seaweed-producing countries. In Norway, harvesting rights are commonly granted through concessions to private companies, and management relies heavily on

Table 1 Seaweed species of economic importance, local common name, and their geographic distribution along the Chilean coast

	Species	Local common name	Distribution	Reference
Phaeophyceae	<i>Durvillaea incurvata</i>	Cochayuyo	30–43°S	[92]
	<i>Durvillaea antarctica</i>	Cochayuyo	44–45°S	[93, 94]
	<i>Lessonia berteroaana</i>	Huiro negro or Chascón	18–30°S	[95, 96]
	<i>Lessonia spicata</i>	Huiro negro or Chascón	29–49°S	[95–97]
	<i>Lessonia trabeculata</i>	Huiro palo	18–40°S	[93, 98]
	<i>Macrocystis pyrifera</i>	Huiro, Huiro flotador or Canutillo	18–56°S	[93, 99]
Rhodophyta	<i>Callophyllis variegata</i>	Carola	18–56°S	[93, 99]
	<i>Chondracanthus chamissoi</i>	Chicorea de mar	18–42°S	[93, 99, 100]
	<i>Gelidium rex</i>	Chasca	18–40°S	[101]
	<i>Sarcopeltis skottsbergii</i>	Luga roja	39–56°S	[100, 102]
	<i>Gracilaria chilensis</i>	Pelillo	30–42°S; aquaculture up to 20°S	[103, 104]
	<i>Mazzaella canaliculata</i>	Liquen gomoso	18–41°S	[105, 106]
	<i>Asterflopsis disciplinalis</i>	Liquen gomoso	18–41°S	[105, 106]
	<i>Mazzaella laminarioides</i>	Luga cuchara	28–56°S	[93, 107]
	<i>Porphyra/Pyropia complex</i>	Luche	18–56°S	[108]
	<i>Sarcothalia crispata</i>	Luga negra	33–53°S	[100]

spatial rotation schemes that allow kelp beds to recover between harvesting cycles [65, 118]. Although Norway is frequently presented as a model for the development of sustainable seaweed industries, studies have highlighted persistent mismatches between national blue bioeconomy strategies and local implementation processes, particularly regarding market development, governance arrangements, and the challenges faced by small-scale producers [119]. Particularly for kelp-dominated harvest regions, spatial rotation of harvesting areas, like strategies implemented in Norway, could complement existing management measures in Chilean OAA. Such approaches may strengthen ecological recovery processes while maintaining the central role of artisanal fishers in resource stewardship, monitoring, and harvesting activities.

The SUBPESCA has promoted seaweed farming, almost exclusively for *G. chilensis*, through financial incentives such as the 2018 Seaweed Restocking and Cultivation Bonus (Law No. 20,925), which covers up to 70% of the project costs for small-scale producers. Similar strategies are found in countries such as China, where farming dominates seaweed biomass production (Fig. 2). The Chinese government has supported this sector through diverse policies aimed at sustainable economic development and climate change mitigation [64, 120, 121]. Expanding governmental support for the aquaculture of additional native seaweed species in Chile could diversify production, reduce dependence on wild-harvested resources, and stimulate domestic markets for human consumption and added-value products. Such diversification may also increase the resilience of the Chilean seaweed sector by creating alternative income sources, reducing dependence on export-oriented commodity chains, and allowing coastal communities to

retain a greater share of the economic value generated by seaweed production [122, 123].

Resource units: seaweed production in Chile

In 2025, Chile’s total seaweed production reached 426,543 metric tons, with an average of 443,705 metric tons per year over the last five years (Fig. 4), according to the statistical fisheries yearbooks of SERNAPESCA (www.sernapesca.cl). Official seaweed landing records show a fluctuating but generally increasing trend, with the highest recorded value in 2013, when landings surpassed 500,000 metric tons (Fig. 4). Species from the *Lessonia nigrescens* complex, including *L. berteroaana* and *L. spicata*, dominate in biomass, contributing 290,548 metric tons in 2025 (68.1% of the total), while the subtidal *Lessonia trabeculata* accounted for 13%. The red seaweed *G. chilensis* contributed 11% of total biomass. This is the only species with established commercial farming in Chile, in contrast to global trends where multiple species are cultivated. While some species, such as *Durvillaea incurvata/antarctica*, *Porphyra* spp., and *Pyropia* spp., were originally harvested for human consumption, most currently exploited species are processed for phycocolloids such as agar, carrageenan, and alginates [37, 124].

Approximately 85% of seaweed production originates from wild populations, ranking Chile as the leading global producer of seaweed harvested from wild sources (Fig. 2). In response to increasing global demand and associated ecological concerns, significant scientific and technological efforts have been made in the last two decades to promote more sustainable practices [39]. Growing concerns regarding the sustainability of wild populations, their ecological roles, and the need to ensure a consistent supply of high-quality biomass have underscored the importance of transitioning from extraction-based

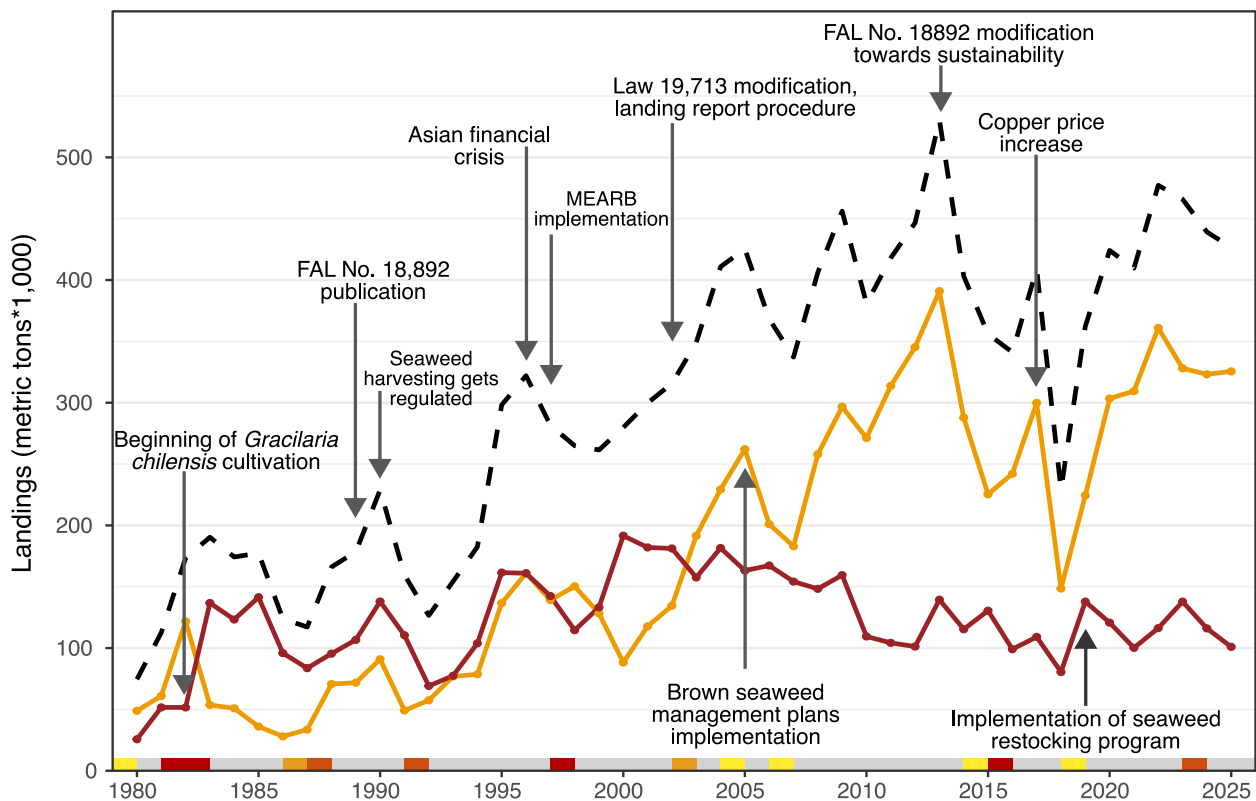


Fig. 4 Annual metric tons of total seaweed landings (black dashed line) in Chile, with brown and red seaweeds represented by orange and red lines, respectively. Significant national and international milestones that may have influenced the landings are indicated with arrows. Above the X axis, the color bars represent the occurrence and intensity of the ENSO phenomenon, including neutral periods (grey), weak ENSO (yellow) to severe ENSO events (red) (SERNAPESCA 2025; Golden Gate Weather Services)

to farming-based approaches. Although this transition has become a key research focus, its full implementation remains a long-term challenge [38, 125–127].

Kelps represent a large portion of Chile's seaweed industry and are primarily harvested from wild populations along the country's extensive coastline. Management measures vary among species and region according to local ecological and socio-economic conditions. Due to their high commercial value and sustained harvesting pressure, kelp species have been subjected to increasingly strict management regulations since 2004. In central-northern Chile, between 26° and 32°S, management plans in OAAs include periodic bans and annual catch quotas. In contrast, the extreme northern regions, between 18° and 26°S, regulations apply an annual extraction ban, while allowing the collection of stranded seaweed and harvest from wild populations within TURFs. The main harvesting areas are located between 18°S and 32°S, where proximity to the Atacama Desert reduces processing costs, particularly drying and grinding kelp for alginate production [116]. Due to the low production costs and minimal processing, most of this biomass is exported as a commodity with limited added value [39, 116].

Annual variation in seaweed landings is driven by multiple environmental and socio-economic factors (Fig. 4). One key driver is the El Niño-Southern Oscillation (ENSO), which strongly affects coastal ecosystems by increasing sea-surface temperatures, causing kelp mortality, and generating large amounts of detached biomass that wash ashore and can temporarily increase landings [116]. However, years following intense ENSO events are often marked by sharp declines in landings, associated with population reductions and overexploitation [128, 129] (Fig. 4). A historical example is the 1982–83 ENSO event, which caused such extensive kelp mortality that, two decades later, *L. berteroa* had recolonized only 50 km of the 600 km of affected coastline [130]. Kelp harvesting intensity in northern Chile is also shaped by the mining sector, one of the main contributors to Chile's gross domestic product. Socio-economically, declines in copper prices can increase unemployment, making kelp harvesting a temporary livelihood strategy, including through illegal extraction. When copper prices rebound, harvesting pressure may decrease, allowing kelp populations to recover [27, 117]. This dynamic may help explain the decline in brown seaweed landings in northern Chile in 2018, a year of rising copper prices, a pattern not

mirrored by red seaweeds (Fig. 4). Ecologically, mining industry waste has been associated with reduced connectivity in *L. nigrescens* complex [131], while heavy metals from mining activities can affect abundance, morphology and early development [132]. These impacts could reduce or delay kelp recovery after disturbance.

Seaweed harvesting is further modulated by shifts in the availability or demand for other marine resources, such as benthic invertebrates [116]. When populations of these resources decline, or when market demand drops, fishing effort is often redirected toward seaweed harvesting [133]. In such cases, extraction may involve illegal activities carried out by unregistered fishers, outside designated areas, or outside authorized harvest seasons [117, 134].

We summarize below the main extraction trends for economically important seaweed species in Chile. The intertidal *Lessonia nigrescens* complex, currently the most exploited group, and the subtidal *L. trabeculata* have been intensively harvested since the early 2000s. Historically, extraction was based on naturally detached biomass, an activity traditionally carried out by women [135, 136]. Since then, the relative importance of gathering stranded biomass versus harvesting attached individuals from wild populations has varied among fisher associations. Some fishers prefer to collect “*what the wave leaves behind*”, rather than harvesting established wild populations within TURFs or OAAs. Landings of the *L. nigrescens* complex peaked in 2013 at 313,341 metric tons, declined to 67,241 metric tons in 2018, and have subsequently fluctuated around an average of 220,000 metric tons. In contrast, *L. trabeculata* landings, although lower in magnitude, increased steadily from 18,107 metric tons in 2000 to 53,887 in 2025.

Landings of the kelp *Macrocystis pyrifera* have increased steadily since 1990, with marked growth after 2007, reaching a maximum of 39,705 metric tons in 2020 before declining to 23,148 in 2025. This initial rise is likely to partly reflect the expansion of abalone aquaculture, which created a demand for *M. pyrifera* as feed [116, 137, 138]. Although this use still consumes about 4,800 metric tons annually, it remains as secondary demand from the phycocolloid industry. In northern Chile, between 18° and 26°S, harvesting of *M. pyrifera* is limited to stranded biomass and regulated through specific management plans. Farther south, between 40° and 56°S, all extraction has been prohibited for 10 years to protect kelp-dominated environments.

The other two relevant kelp species, *Durvillaea incurvata* and *D. antarctica*, are harvested along the central and southern coast, from 29° to 45°S, and are traditionally consumed as food. Although their contribution to total seaweed landings is small, harvested biomass has increased steadily from 17 metric tons in 1980 to 11,852

in 2025. A seasonal ban between 33.9° and 34.6°S prohibits shore harvesting and patch removal between May and November. Experimental farming trials for *Durvillaea* species have been implemented in TURFs to promote diversification in seaweed aquaculture. These species are now used in a broader range of products, including snacks, jams, and cosmetics, increasing their economic value beyond traditional food consumption.

Economically relevant red seaweeds are more diverse than kelps, although their total biomass is smaller (Table 1). Red seaweed production is concentrated in southern coastal areas, between 36° and 56°S (Fig. 3). In 2025, landings were recorded for eight species, with *Gracilaria chilensis*, *Sarcothalia crispata*, *Sarcopeltis skottsbergii*, and *Chondracanthus chamosoi* accounting for the main contributions.

The total landings of *G. chilensis* were 20,275 metric tons in 1980, followed by a steep increase to 112,597 in 1985. Landings then declined and surged again to 120,950 metric tons in 1996, before decreasing during the Asian financial crisis, consistent with reduced global demand for agarophyte species [124]. Landings recovered in the early 2000s but declined again, and since 2011 have fluctuated around a decadal average of 48,828 metric tons. This species has been farmed in small aquaculture areas since 1991, with farming practices strengthening over time while artisanal gathering has continued. Low-cost techniques have increased extracted quantities, including the burial of vegetative fragments in sandy intertidal substrates in southern regions, between 36° and 42°S, and in shallow subtidal habitats in northern regions, between 20° and 32°S. In 2018, the government provided funding to support farming and restocking in TURFs and to promote the sustainable use of *G. chilensis*. Currently, more than 600 farming centers are registered in Chile's National Aquaculture Registry.

Several carrageenophyte species are harvested in southern of Chile (Fig. 3). Landings of *Sarcothalia crispata* reached 20,047 metric tons in 2002 and remain high thereafter, reaching 18,218 in 2025. This species is harvested from 36° to 53°S between January and April and lacks specific management plans. Its perennial attachment disc enables regrowth, allowing repeated extraction across seasons [139]. *Sarcopeltis skottsbergii* averaged 40,000 metric tons between 2005 and 2008 before declining sharply due to overexploitation, reaching a low of 14,616 metric tons. In the last five years, landings have averaged 27,147 metric tons. Despite studies and conservation efforts since 2008, no specific regulations are in place. *Chondracanthus chamosoi* is primarily harvested from wild populations, although aquaculture has also been piloted [140]. These efforts supply raw material to local and international carrageenan producers and food industries, mainly in Japan [141]. Landings began at 6

metric tons in 1981, increasing to 15,169 in 1990, and peaked at 23,778 in 2000. Subsequent overharvesting led to declines and prompted cultivation efforts [142, 143]. Over the past two decades, landings have stabilized at an average of 1,795 metric tons.

Although green seaweeds are not currently recognized as economically important resources, a recent study shows that *Ulva uncialis* has the potential to be a source of nutritional and bioactive compounds for food and biotechnology applications [144]. Consequently, *Ulva* species may represent a promising candidate for resource diversification and the development of value-added products.

In contrast to the Chilean case, seaweed production in China relies on the cultivation of multiple species, including *Saccharina japonica*, *Undaria pinnatifida*, *Porphyra yezoensis*, and *Gracilaria lemaneiformis*, among others, supporting a diversified portfolio of products and markets, particularly in the domestic food sector [145–147]. Although a wide variety of seaweed species are harvested and used in Chile, commercial cultivation remains almost exclusively concentrated on *G. chilensis*. Norway has also increasingly promoted kelp cultivation as part of a broader strategy to diversify its marine production sector [66, 68], whereas Chilean seaweed production continues to depend largely on the extraction of wild kelp populations. This contrast suggests that Chile may be more exposed to fluctuations affecting a limited number of commercially important resources, while diversification through native species cultivation could generate alternative products, market opportunities, and income sources under changing environmental or economic conditions. A major remaining gap is the lack of successful technological developments to support the aquaculture of local kelps and other native seaweeds.

Key actors

The primary Actors of Chile's seaweed production are the artisanal fishers, who are the direct users of the resources by harvesting wild populations, gathering cast ashore seaweed, and farming seaweeds. Fishers are responsible for managing and caring for these resources, and to operate legally, each must have a fishing license and declare the species they intend to harvest and trade. Approximately 84,000 people are engaged in seaweed-related activities and are listed in the Chilean artisanal fishing registry, which includes gatherers (*algueros* and *algueras*) and divers, although not all divers are involved in seaweed extraction (data from SERNAPESCA).

Although artisanal fishers are the primary users of seaweed resources and play a central role in stewardship and harvesting activities, in Chile and elsewhere they do not necessarily capture the largest share of the economic benefits generated throughout the production chain

[134, 148–151]. International demand, particularly from China, strongly influences harvesting intensity, prices, and market opportunities, creating feedbacks between distant markets and local resource use [64, 147, 152]. This scenario affects fishers, who bear much of the ecological and economic risk associated with environmental variability, resource depletion, and market fluctuations, while a substantial proportion of the value generated from seaweed production is captured by intermediaries, processing industries, and export companies that transform raw biomass into higher-value products. These asymmetries can increase the vulnerability of seaweed-dependent coastal communities and illustrate broader blue justice challenges, particularly the unequal distribution of benefits, risks, and decision-making power within marine resource value chains [83, 134, 153].

While both genders participate in seaweed production, women represent only 29% of gatherers over the last five years (Fig. 5a), and the magnitude of the gender gap varies across different regions (Fig. 5b). However, irrespective of the specific region, the same trend is observed at the national level (Fig. 5b) (SERNAPESCA) [39]. While men usually dominate offshore roles, such as fishing from boats, women primarily work onshore, gathering seaweed, assisting in processing tasks, and innovating by adding value through new products. This division has historically led to exclusion of women from public initiatives and funding opportunities. Although steps are being taken to formally recognize women's contributions, disparities persist due to gender-blind policies and lack of targeted resources. Despite international commitments to gender equity, Chile has yet to implement them effectively, owing to a longstanding gap between policy design and realities faced by fishers [135]. Nonetheless, since the 2000s, women's participation has increased significantly [149, 154]. More women now engage in harvesting and hold leadership positions in fishing organizations. Around 1,190 women currently serve as presidents, secretaries, or treasurers, gaining greater influence on decision-making [82, 149]. Women contribute significantly to harvesting, processing, commercialization, innovation, and value-added activities, yet many of these contributions remain insufficiently recognized in fisheries policies and management programs [155, 156]. This underrepresentation may limit the incorporation of diverse knowledge systems, local experience, and social perspectives into governance processes, reducing the capacity of coastal communities to adapt to environmental, economic, and social change [135, 157]. If these disparities persist, opportunities to enhance both social equity and the long-term resilience of seaweed-producing communities may be constrained, despite recent advances in women's participation and leadership within artisanal fisheries. In general, a significant proportion of fishers do

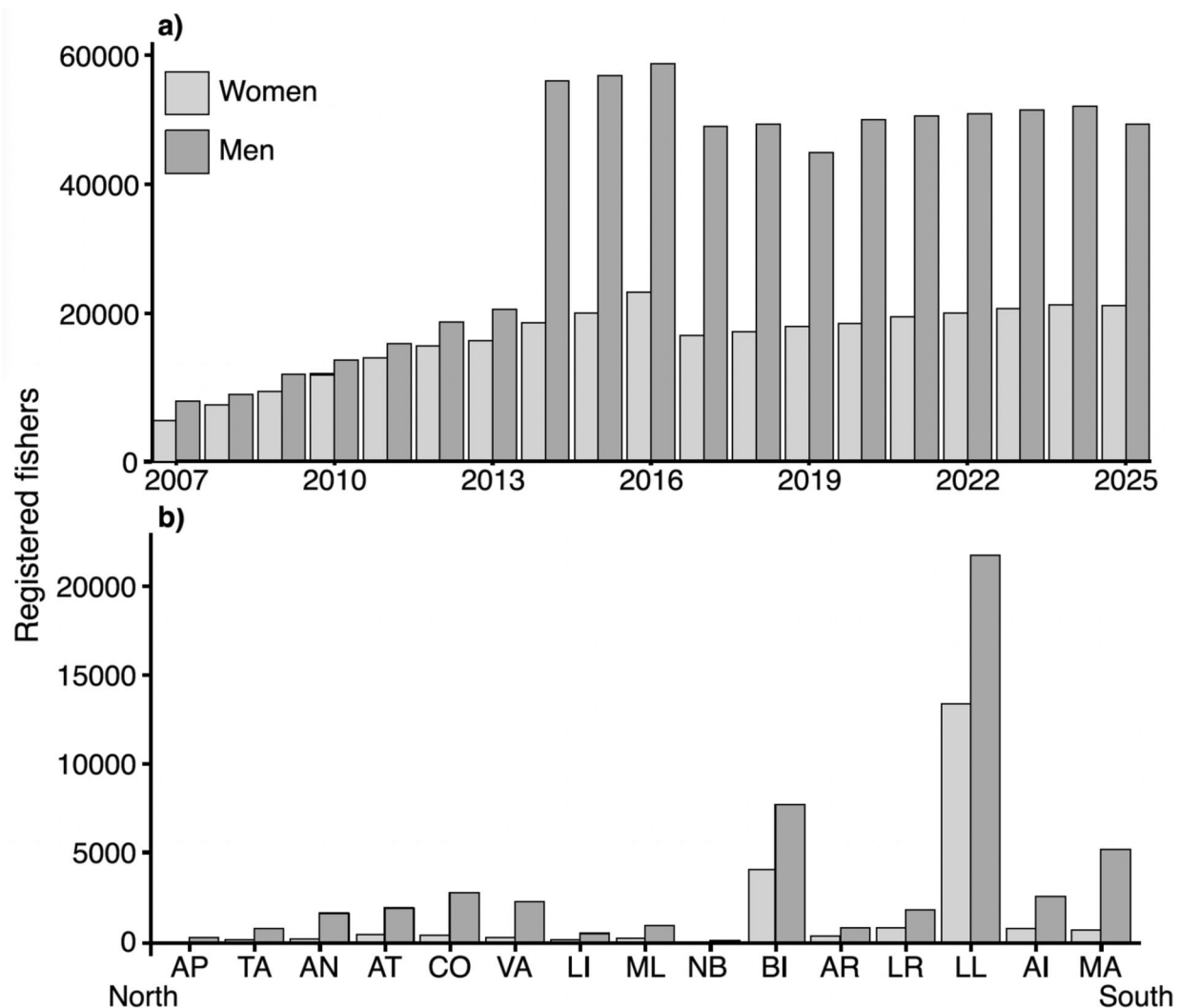


Fig. 5 Gender distribution of fishers registered in the national artisanal fishery registry of Chile as seaweed shore gatherers, across years (**a**) and by region of Chile (**b**) in 2025. Acronyms are as in Fig. 3

not have access to higher education, which can hinder their capacity to obtain information about sustainable practices and market opportunities [158]. For instance, Vásquez et al., [27] found that 5% of fishers from the kelp seaweed sector in northern Chile are illiterate, and more than 62% have not completed elementary education. However, artisanal fishers often have extensive traditional ecological knowledge, passed down through generations, which is valuable for assessing resource health and can complement scientific knowledge to improve management strategies [159–161]. These trends are not unique to Chile. In many countries, seaweed activities provide complementary income, improving livelihood and expanding access to education, especially for younger generations [14]. As educational access improves, youth may either seek alternative careers or return to fisheries with better skills and understanding of sustainable practices and markets [117].

Fishers are generally organized in fishing coves, with or without associated TURFs. Over 90% of fishing coves in Chile are characterized by underdevelopment, as evidenced by both qualitative and quantitative factors at the regional level, with advancing organizational capacity for development and support of productive projects [162]. Most fishing coves are situated on public or concessioned land; a minority are on private land, risking eviction due to legal challenges. In 2017, Chile enacted Law No. 21,027 officially recognizing fishing coves as a productive and socio-economic unit. This led to the Artisanal Fishing Cove Management Program, which supports infrastructure upgrades and coastal safety improvements. In 2020, the “Closer Cove” pilot program was launched to foster digital literacy and leadership, which was formalized for nationwide implementation in 2024.

Seaweed production and transformation involve a wide network of actors beyond fishers, including transporters,

processors, and exporters. Globally, seaweed harvesting and farming support millions of people in coastal areas [35] with benefits such as poverty reduction, improved access to education and healthcare, and increased agency for women [12, 20]. However, seaweed prices are volatile, driven primarily by global demand for phycocolloid raw material. When demand spikes, harvesting intensifies, sometimes leading to illegal extraction and market saturation, and often followed by sharp declines in prices [163]. Only a fraction of seaweed is processed and sold locally immediately after harvesting. Most of its value is added through transformation processes such as dehydration, agar or carrageenan extraction, or incorporation into biostimulants, either for export or downstream industrial use. Global price fluctuations in the phycocolloid market generate instability for local fisheries. China, a dominant player in the seaweed trade, significantly influences global prices for dried seaweed and derivatives [164].

In Chile, more than 200 small-scale traders were registered for seaweed drying in 2023, alongside four agar-processing plants, one for alginate derivatives, and six for carrageenan production (SERNAPESCA). Most processing facilities are in northern Chile between 19° and 32°S, where kelp landings are highest, and climate offers ideal conditions for sun-drying seaweed. Processing plants vary in scale and technological sophistication depending on their target market, ranging from food and industrial applications to phycocolloid extraction. A growing number of people and businesses are adding value by transforming seaweed into food products, agricultural or cosmetic products, often for niche or local markets. For example, *Durvillaea incurvata* is marketed as snacks, vegan sausages, or marine salt. These innovations mirror similar developments in African fishing communities such as Zanzibar and Mozambique [165].

In southern coastal areas with higher humidity, red seaweeds are sold fresh for phycocolloid extraction, while dried in central and northern coastal areas. The first transaction often takes place between local harvesters and brokers, who purchase fresh or partially dried biomass. These intermediaries often occupy dominant positions over gatherers and artisanal fishermen, reinforcing hierarchical trade relationships that legitimize resource exploitation and perpetuate economic disparity [134]. In Chile, most dried or semi-processed seaweed is exported by companies that capture the highest profit margins.

Chilean seaweed fisheries are integrated into a global producer-driven supply chain [134]. Most exports go to China, followed by the Philippines and Indonesia, primarily for phycocolloid production. Europe is the second-largest market by volume and the top market by value. Yet, stringent regulations on dried seaweed for

human consumption hinder local producers' access, constraining their capacity to move up the value chain.

Integration and perspectives

Seaweed production in Chile represents a complex social-ecological system (SES) in which ecological resources, governance structures, resource users, and both internal and external drivers interact across multiple spatial and temporal scales. The sustainability of the seaweed production SES depends not only on the condition of seaweed populations but also on the capacity of institutions and coastal communities to respond to environmental and socioeconomic change [40, 43, 49]. Chile's strong dependence on wild seaweed harvesting supports the livelihoods of thousands of artisanal fishers and generates significant export revenues, yet it also increases exposure to ecological disturbances and fluctuations in global markets. Consequently, management measures designed to conserve resources, such as quotas, bans, and access restrictions, often involve trade-offs between short-term economic opportunities and long-term ecological sustainability. Despite these challenges, the resilience of the Chilean seaweed production SES is strengthened by strong local ecological knowledge, the participation of artisanal fishers in co-management processes, and institutional innovations such as TURFs, which promote stewardship and collective action [166–168].

International markets generate one of the most important feedback mechanisms within the Chilean seaweed SES. Demand from major importing countries, particularly China, influences prices and harvesting behavior, often increasing extraction pressure on wild populations [82, 151]. When harvesting intensity exceeds the recovery capacity of natural populations, biomass declines and resource availability decreases, which may subsequently trigger management responses such as quotas, harvesting bans, or access restrictions. These interactions illustrate how distant economic drivers can shape local ecological conditions, governance decisions, and coastal livelihoods. The structure of the value chain further reinforces these dynamics, as intermediaries, processors, and exporters frequently determine which resources are purchased and at what price, concentrating decision-making power outside fishing communities [151, 169]. Consequently, fluctuations in international demand for marine products can alter harvesting patterns and increase the vulnerability of coastal communities that depend on seaweed harvesting as a livelihood. Strengthening domestic markets, promoting local consumption, and increasing processing value-added in Chile could help redistribute economic benefits more equitably while reducing dependence on volatile international commodity markets [155].

Climate variability and long-term climate change also generate important feedback within the Chilean seaweed

production SES. ENSO events, marine heatwaves, and changes in upwelling dynamics can reduce the abundance and productivity of seaweed populations, particularly of kelps, leading to lower harvests and reduced income for artisanal fishers [128, 170–172]. In a system that relies heavily on wild populations, ecological disturbances can propagate through the social dimension, affecting livelihoods, harvesting decisions, and community wellbeing. A standing challenge is to increase adaptive capacity, an essential feature under future climate scenarios. Collaborative efforts among fishers, scientists, government agencies, and private stakeholders can facilitate adaptive management and strengthen the resilience of both ecological and social components of the system [65, 68, 173]. This adaptive process is often characterized by interactive learning and the gradual adjustment of institutions to local social-ecological conditions [174].

The growing interest in seaweed-based blue bioeconomy initiatives, including blue carbon, biomaterials, and novel food products, creates opportunities for diversification [175, 176]. Diversification through small-scale and integrated multitrophic aquaculture may reduce dependence on wild harvesting, alleviate pressure on natural populations, and provide alternative income sources for coastal communities [177–179]. However, the expansion of seaweed aquaculture will require sustained public and private investment, supportive regulatory frameworks, and governance systems capable of balancing technological innovation, ecosystem conservation, social equity, and climate resilience [180–182]. In this regard, adaptive governance, polycentric institutions, and just-transition principles may provide important pathways towards a more resilient and regenerative seaweed sector [183]. The resilience of the Chilean seaweed production SES is also shaped by social inequalities that influence access to resources, markets, and decision-making processes. Actors often occupy unequal positions within seaweed value chains, limiting their capacity to capture economic benefits and respond to environmental or market disturbances [155]. These patterns are consistent with broader blue justice concerns identified in small-scale fisheries worldwide, where unequal access to resources, decision-making processes, and economic benefits contributes to persistent social vulnerabilities, specially where extractivist governance models prioritize economic growth and commodity production over subsistence needs and local wellbeing [184, 185]. These vulnerabilities are not experienced uniformly. Women play essential roles in harvesting, processing, commercialization, administration, and value addition, yet they frequently face barriers to accessing funding opportunities, technical training, leadership positions, and formal recognition of their contributions. Evidence from seaweed-producing regions worldwide suggests that climate-related stressors can amplify these

pre-existing inequalities and potentially reduce the adaptive capacity of vulnerable groups while increasing their exposure to livelihood risks [186]. At the same time, women often contribute substantially to innovation, livelihood diversification, and community organization, making them important actors in strengthening social resilience and facilitating adaptation to environmental change [186]. Addressing social asymmetries may therefore be as important as ecological management interventions for enhancing long-term sustainability. More broadly, recognizing seaweeds not only as commercial commodities but also as components of cultural identity, social relations, and ecological relationships may support more inclusive and equitable governance pathways [187].

Despite the considerable amount of information available on Chilean seaweed production, important knowledge gaps remain across several components of the SESF. In governance and actor systems, further understanding is required on how power asymmetries among fishers, intermediaries, exporters, and regulatory institutions influence the design, implementation, and adaptation of management arrangements, as well as how gender-related barriers affect participation in governance, leadership opportunities, and the equitable distribution of benefits. Within the resource system and resource units, the potential role of underutilized native species, such as *Ulva* spp., remains poorly understood despite their potential contribution to diversification through new culture systems, value-added products, and alternative markets. A cross-cutting gap is the lack of integrated, long-term, and spatially explicit information linking seaweed biomass, recruitment, and recovery dynamics with landings, prices, governance arrangements, and indicators of community wellbeing. This limits the capacity to distinguish ecological decline from market- or labour-driven changes in landings, and to evaluate whether current management instruments reduce vulnerability under interacting climate and market shocks. Furthermore, a key gap concerns how social-ecological vulnerability differs between TURFs and OAAs under climatic and economic disturbances, and how these differences shape resilience outcomes for both coastal communities and seaweed resources. Collectively, these gaps limit our understanding of the feedbacks and interactions that determine the long-term sustainability of the Chilean seaweed SES. Accordingly, future research should prioritize the effects of climate change, marine heatwaves, and increasing environmental variability on the livelihoods, adaptive capacity, and wellbeing of artisanal fishing communities that depend on wild seaweed resources. Further research is also needed to evaluate the potential of diversification strategies, including the cultivation of additional native seaweed species and integrated aquaculture systems, to reduce social-ecological vulnerability

without reproducing existing asymmetries in benefit capture. Finally, a better understanding of how governance arrangements, value-chain structures, gender relations, and other social inequalities influence the distribution of benefits and risks would contribute to the development of more equitable and sustainable seaweed production systems.

Conclusions

Through the lens of the SESF, this review shows that the sustainability of Chilean seaweed production depends on the interactions among ecological processes, governance institutions, artisanal fishers, and global markets. Rather than being determined by any single component, system outcomes emerge from the dynamic relationships and feedbacks among these elements. The main findings of this review are:

- Chile's dependence on wild kelp populations creates a distinctive social-ecological configuration that differs fundamentally from aquaculture-dominated production systems.
- TURFs have become one of the most distinctive features of the Chilean governance system, contributing to stewardship, resource conservation, and fisher participation, while important management challenges persist in OAAs.
- International market demand strongly influences harvesting intensity, prices, and management decisions, connecting distant markets with local ecological conditions and coastal livelihoods.
- The seaweed value chain is characterized by an unequal distribution of benefits, whereby fishers often capture a relatively small proportion of the final product value despite being the actors most directly dependent on the resource.
- Climate variability and long-term climate change represent major sources of ecological and socioeconomic vulnerability.
- Power asymmetries, gender equity, and fair distribution of benefits remain important challenges for the long-term sustainability of Chilean seaweed production.

The findings of this review highlight the need to strengthen adaptive governance, promote diversification through aquaculture and value-added products, improve equity across the seaweed value chain, and increase the capacity of coastal communities to respond to environmental and market-driven change. Future research should prioritize evaluating the effects of climate change on seaweed-dependent SES, assessing the long-term performance of governance arrangements, and addressing persistent knowledge gaps related to gender equity,

value-chain dynamics and blue justice in the Chilean seaweed production SES. Advancing these areas will be critical for enhancing the resilience of both coastal communities and seaweed populations in an increasingly uncertain future. The key challenge lies in strengthening the interaction between resources, ecosystems, governance structures, and the actors involved to help secure a future of seaweed production characterized by resilience and shared prosperity.

Abbreviations

ENSO	El Niño-Southern Oscillation
MPA	Marine Protected Areas
SERNAPESCA	National Fisheries and Aquaculture Service
SES	Social-ecological System
SESF	Social-ecological System Framework
SUBPESCA	Undersecretariat for Fisheries and Aquaculture
TURF	Territorial Use Rights for Fisheries
OAA	Open Access Areas

Acknowledgements

We thank Universidad Católica del Norte, Instituto Milenio SECOS (ICN2019_15), FONDECYT Regular grant 1231579, and FONDECYT Postdoctoral grant 3240664 for funding support.

Authors' contributions

P.A.H. and N.L.P. conceptualized and planned the manuscript. N.L.P. analyzed data and developed figures; wrote the first draft of the review. P.A.H., N.L.P., F.T. and J.A.V. edited the manuscript.

Funding

This work was supported by the Chilean National Research and Development Agency (ANID) with the regular grant 1231579, postdoctoral grant 3240664 and Instituto Milenio en Socio-Ecología Costera (SECOS) grant ICN2019_15.

Data availability

Data of seaweed landings and ENSO intensities used are publicly available at sernapesca.cl and Golden Gate Weather Services available at <https://ggweather.com/enso/oni.htm>.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 6 January 2026 / Accepted: 10 June 2026

Published online: 25 June 2026

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