Research Article

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Analysis of Peruvian seaweed exports during the period 1995–2020 using trade data

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Abstract: Peru is the second largest seaweed producer in the Americas. Nevertheless, the actual extent and trends of exports of various seaweeds are not known. This study is the first to summarize and analyze the official seaweed export statistics for Peru, which cover 1995–2020. Total exports showed a considerable increase from 2008, reaching their highest historical volume in 2019 (33,948 metric tons dry weight plus 3 metric tons of fresh/frozen weight). China dominated the market by importing 90% of the total Peruvian production of seaweeds. A low percentage of the exports (3%) corresponded to red seaweeds (mainly *Chondracanthus chamissoi* for industrial use). Export volumes of *C. chamissoi* have been decreasing since 2015, however prices have continued to increase. Brown seaweeds accounted for 97% of the exports. These were dominated by *Lessonia berteroana* until 2007 and then by *Macrocystis pyrifera*. The latter showed the highest overall growth rate (47%). Wet biomass estimations showed a gap between the data reflecting what is officially harvested versus what is actually exported. This “unreported biomass” might reflect the government’s lack of control of seaweed harvesting. Finally, the COVID-19 pandemic showed a negative impact on exports with *M. pyrifera* being the most affected species.

Keywords: growth rate; instability; prices; seaweed exports.

1 Introduction

Seaweeds are a group of marine photosynthetic organisms that come in various morphologies, from simple filamentous or sheet-like thalli to complex ones resembling plants, and in different colors, i.e., brown, red, and green (FAO 2018). They are widely used as food (Mouritsen et al. 2018), medicine (Dharmananda 2002; Leandro et al. 2019), and as a raw material for the hydrocolloid industry due to the presence of carrageenans and agars (in red seaweeds), and alginates (in brown seaweeds), which are derived from their cell walls (Bixler and Porse 2011). Total global seaweed production reached 35.8 million tons in 2018, with 97% coming from seaweed farms (Cai et al. 2021). The global seaweed industry is estimated to be worth more than USD 6 billion per annum. China and Chile are the leading producer countries for cultivated and wild harvested species (FAO 2018).

Peru is amongst the top seven producing countries for global capture fisheries, just behind China and Indonesia (FAO 2020). While Peruvian fisheries have attracted a lot of attention due to their productivity (Bakun and Weeks 2008), the seaweed production of the country has received much less focus. Seaweeds have been consumed in Peru since ancient times (Patterson and Moseley 1968). An example of this is the traditional Peruvian ceviche, which contains fresh *Chondracanthus chamissoi* (C.Agardh) Kützing, a red alga commonly known as “yuyo”. However, apart from *C. chamissoi*, and other red seaweeds like *Pyropia/Porphyra*, few species are used as human food in Peru (Acleto 1998). In fact, only 1.4% of seaweed landings are destined for wholesale markets (PRODUCE 2021a).

In contrast, several brown and red species are exported as raw materials to produce a diverse range of polysaccharides (Acleto 1998; Noriega 2011). For instance, cold-water seaweeds for carrageenan extraction are largely harvested in Peru and Chile. The demand for raw materials is expected to increase as the seaweed hydrocolloid industry continues to grow (Porse and Rudolph 2017). Nevertheless, the country’s annual statistical reports for fisheries and aquaculture do not provide information regarding seaweed exports (PRODUCE 2021a). Thus, the volumes and the trends for different species, are not known.

The seaweed resources in Peru face a constant threat from overexploitation, as all the biomass used for local consumption and export comes from natural beds. Species

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such as *Lessonia berteroana* Montagne, *L. trabeculata* Villouta and Santelices, and *Macrocystis pyrifera* (Linnaeus) C. Agardh used in the alginate industry, constitute a vital ecosystem (kelp forest) in central and southern Peru (Carbajal et al. 2022; Carbajal and Gamarra 2018). Despite some efforts by the Peruvian government to regulate the harvesting of these species (IMARPE 2014), their populations are still threatened by illegal harvesting and inefficient regulations (La República 2018; Noriega 2011; Pérez-Araneda et al. 2020). To avoid the collapse of the resource, such as the well-known 1971–1972 crash of Peruvian anchovy due to overfishing (Pauly et al. 2002), it is important to understand the developmental trends and status of Peruvian seaweed exports. This would allow a better characterization of overexploited species and an estimation of the actual biomass harvested, which might exceed what is officially reported.

This study summarizes and provides an analysis of official Peruvian seaweed export statistics from 1995 to 2020. We provide a detailed analysis of the main species compositions, export volumes, Free On Board (FOB) values, prices, destination countries, and a number of companies involved. We then conducted deeper analyses to understand the historical and current status of Peruvian seaweed exports and developmental trends. Based on the primary data analyses, this study can better inform the development of future conservation strategies and make Peruvian statistical data more accessible to the world.

2 Materials and methods

2.1 Data collection

Time series export data (1995–2020) were collected from the National Superintendency of Customs and Tax Administration (SUNAT, from its acronym in Spanish; http://www.aduanet.gob.pe/cl-ad-itestdesp/FrmConsultaSumin.jsp?tcon=B). Data were obtained based on the tariff headings 12.12.20.00.00 (fresh, refrigerated, frozen or dried, and powdered seaweed), 12.12.21.00.00 (seaweeds for human consumption), and 12.12.29.00.00 (others).

Species identification was performed according to the information provided by the export companies, additional descriptions from the single custom declarations (DUA, for its acronym in Spanish), and each species' FOB values from a single exporter. Exports of the red seaweed *Chondracanthus chamissoi* were further classified according to their use: industrial (IN) or human consumption (HC).

Brown seaweed export volumes were expressed as dry weight unless otherwise specified. In the case of red seaweeds, the reported values were a combination of salt-dried, frozen, and discolored biomass.

2.2 Data analyses

The data collected were analyzed using compound growth rates (CGRs) and Coppock's instability index (CII). CGR has been used in export analyses to examine the tendency of variables to increase, decrease or remain stagnant over a period. Instability refers to a deviation from the "trend". Instability analysis was studied using CII, which has been applied in various assessments of fisheries (Fauzi and Anna 2012).

According to Kalidas et al. (2020), CGR can be expressed as:

$$\mathrm{Ln}\,(Y) = \mathrm{Ln}\,(b_0) + b_1 t$$

where t is the time variable, Y is the variable for which growth is calculated and b_1 is the regression coefficient of t on Y.

The above expression can be multiplied by 100 to give the CGR of Y as a percentage. The mathematical form of the log-linear function is as follows:

$$\mathrm{CGR}\,(\%) = \left(\mathrm{Antilog}\, b_1 - 1\right) \times 100$$

According to Radhakrishnan et al. (2016), CII can be calculated as follows:

$$\mathrm{CII}\,(\%) = \mathrm{Antilog}\left(\sqrt{\mathrm{VLog}} - 1\right) \times 100$$

where VLog is the logarithmic variation of the series.

The overall CGR and CII with, or without, COVID-19 pandemic data (2020), were calculated for seaweed exports. When divided by species, the whole period of study was also separated into five periods of five years each. One more period was included using COVID-19 pandemic data (2020) for CGR and CII calculations.

3 Results

3.1 Overall seaweed exports

Over the last 25 years, Peruvian seaweed exports were dominated by the relatively small number of five species. Red seaweeds [i.e., *Chondracanthus chamissoi* and *Gracilariopsis lemaneiformis* (Bory de Saint-Vincent) E.Y.Dawson, Acleto *et* Foldvik] accounted for 3.0% of the total seaweed exports (Figure 1), ranging from around 100 to 1084 metric tons (MT) year^{-1}. Brown seaweed exports (i.e., *Lessonia berteroana*, *L. trabeculata*, and *Macrocystis pyrifera*) started in 1996 and accounted for more than 95% of the total seaweed exports during the study period (Figure 1). From 1996 to 2007, exports did not exceed 10,000 MT year^{-1}; however, from 2008 to 2019, this value increased to over 20,000 MT year^{-1}, except for 2009 when national seaweed regulation began. This increasing trend was more evident after 2010. This was after Peru – China Free Trade Agreement (FTA) entered into effect (Figure 2; Supplementary Table S1). The overall CGR and CII until 2019 was higher for brown

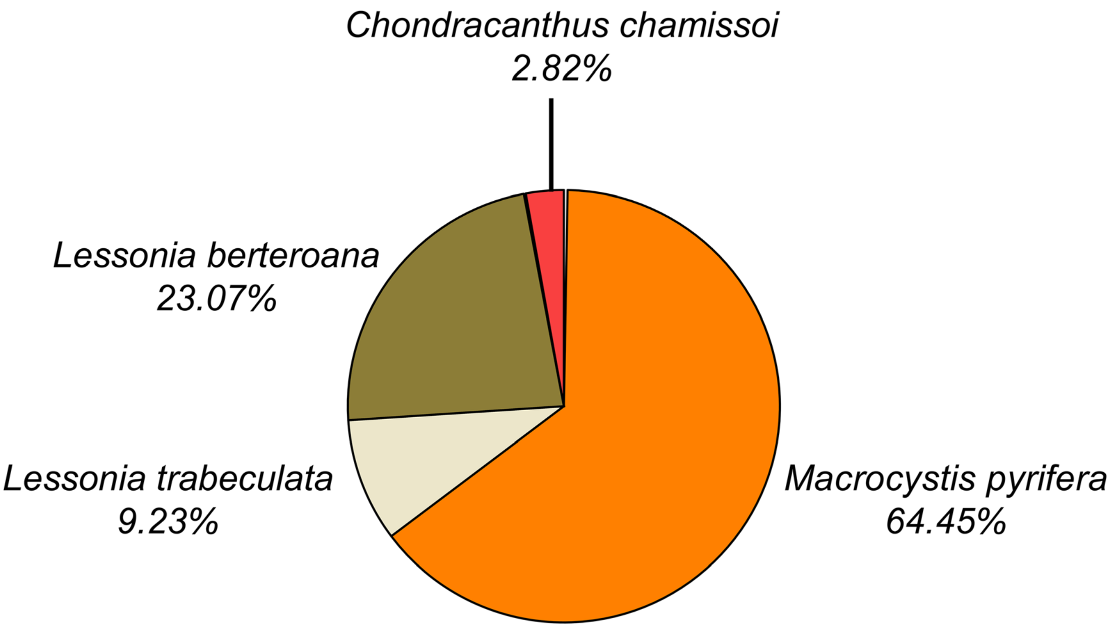

Figure 1: Species composition of Peruvian seaweed exports from 1995 to 2020 (total biomass = 360,211.9 metric tons). *Gracilariopsis lemaneiformis* and seaweeds classed as "others" are not shown as they accounted for only 0.15% and 0.28% of the total seaweed exports, respectively.

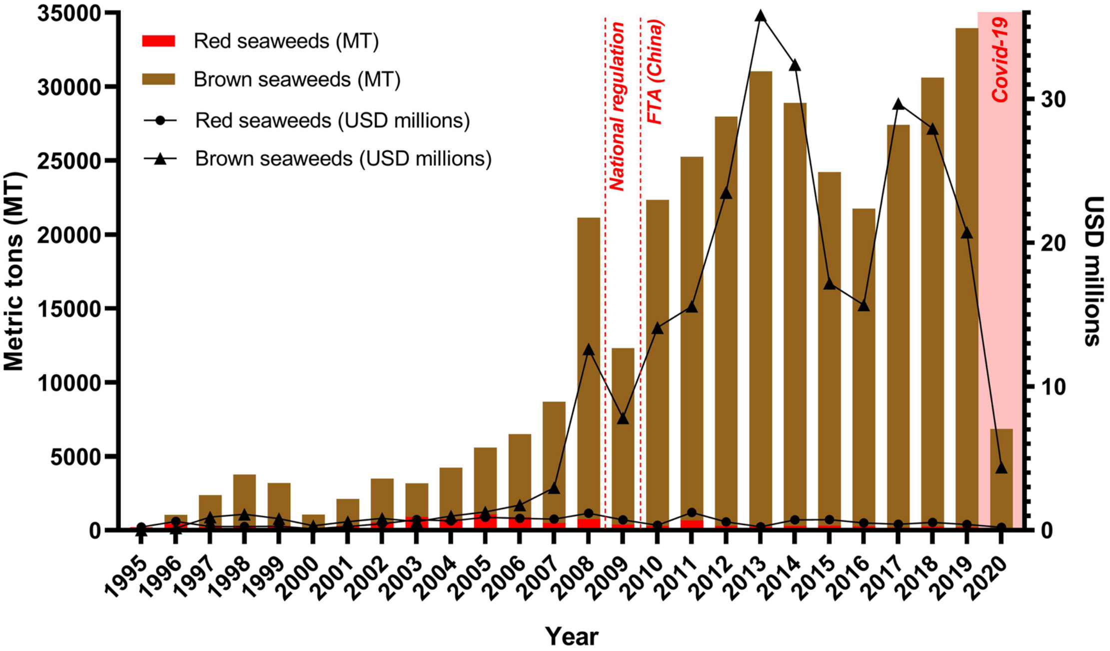

Figure 2: The annual Peruvian seaweed exports in metric tons (MT) and their corresponding Free on Board (FOB) values (USD millions) from 1995 to 2020. Seaweeds classed as "others" are not shown as they accounted, on average, for 0.01% of the annual seaweed exports. Major events affecting seaweed exports are also depicted. FTA, Free Trade Agreement.

(i.e., CGR = 17.87%, CII = 35.14%) than for red seaweeds (i.e., CGR = –0.87%, CII = 18.10%).

In terms of economic revenue, FOB values for red seaweed exports ranged from USD 0.21–1.24 million year^{-1}. A remarkable increase was observed from 2000 to 2003, followed by high fluctuations until 2014. From 2015 onwards, FOB values have been decreasing. On the other hand, FOB values for brown seaweed exports ranged from USD

0.15–35.83 million year^{-1}. These values showed a sharp increase from 2009 to 2013, followed by a marked decline during 2015–2016 and a temporary recovery during 2017. FOB values have been declining since then (Figure 2; Supplementary Table S2). The overall CGR and CII until 2019 were higher in brown (i.e., CGR = 25.46%, CII = 56.80%) than in red seaweeds (i.e., CGR = 3.11%, CII = 18.27%).

When including data from the COVID period (2020), the growth rates from exports and the FOB values were reduced. This trend was more notable in brown than in red seaweeds. In contrast, CII showed little variation, except for FOB values for brown algal species (Table 1)

The number of export companies increased from three in 1995 to 18 in 2019, with the steepest increase from 2003 to 2006. This number then stabilized at around 14–18 companies until 2019, followed by a decrease during the COVID pandemic (Figure 3). Globe Seaweed International S.A.C., a Chinese-owned company, dominated the market by exporting 43.4% of the total Peruvian seaweed production, mainly *L. berteroana*, *L. trabeculata* and *M. pyrifera*, during 1995–2020. Other important companies were: Almacenajes Arequipa E.I.R.L. (12.5%), Algas Multiexport del Peru S.A.C. (10.1%), Algas Sudamerica S.A.C. (9.9%), Inka Sur Pacifico S.A.C (6.4%) and Algas Arequipa E.I.R.L. (5.5%). The remaining companies exported altogether 12.2% of the total seaweed production (Supplementary Table S3). China was by far the major destination country (Figure 4; Supplementary Table S4).

3.2 Red seaweeds

Chondracanthus chamissoi IN (i.e., *C. chamissoi* for industrial use) exports were predominant throughout the study period, comprising around 60% to almost 100% of total *C. chamissoi* exports. These ranged from 98–1038 MT year^{-1}

Table 1: Compound growth rate (CGR) and Coppock's instability index (CII) of Peruvian red (R) and brown (B) seaweed exports and their free on board (FOB) values.

Period	**Compound growth rates (%)**				**Coppock's instability index (%)**			
	Exports		**FOB values**		**Exports**		**FOB values**	
	R	**B**	**R**	**B**	**R**	**B**	**R**	**B**
1995–2019 (without COVID-19 pandemic)	−0.87	17.87	3.11	25.46	18.10	35.14	18.27	56.80
1995–2020 (with COVID-19 pandemic)	−1.83	15.48	2.02	22.32	18.78	34.24	18.46	54.77

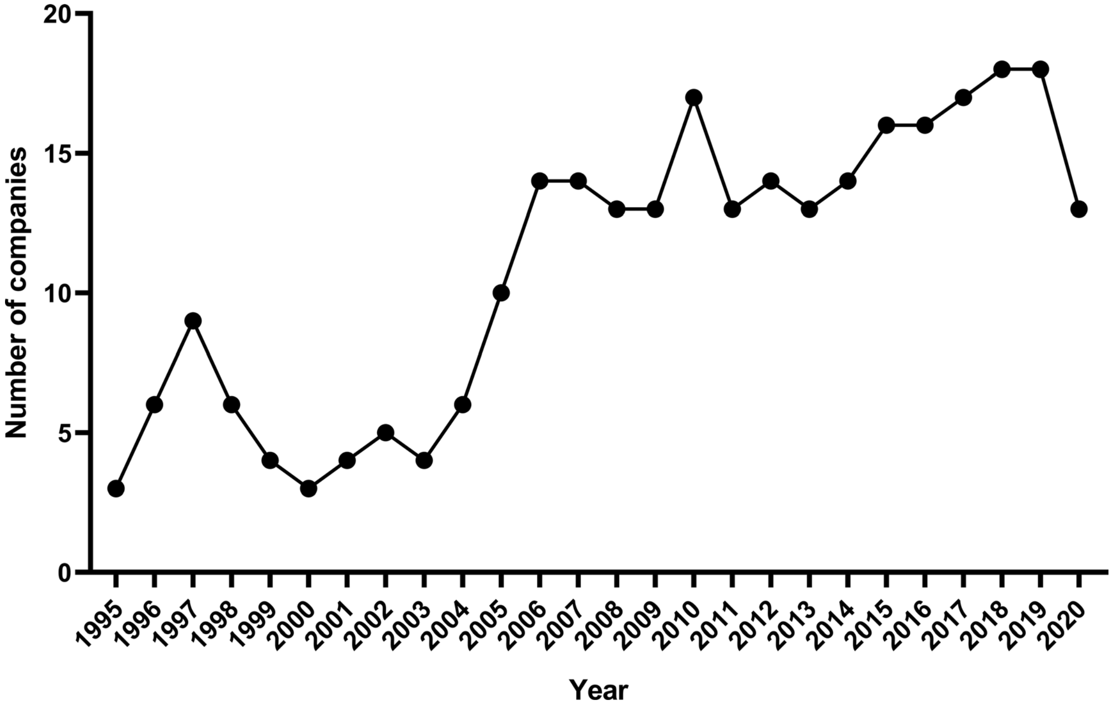

Figure 3: Number of seaweed export companies in Peru from 1995 to 2020.

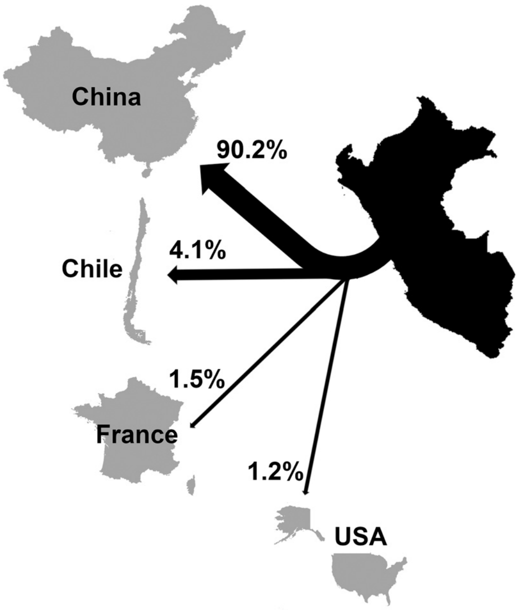

Figure 4: Top country destinations for Peruvian seaweed exports from 1995 to 2020. Twenty other countries accounting together for only 3% of total seaweed exports are not shown.

(Figure 5(a)). Growth rates showed an increasing trend during the first ten years, especially 2000–2004. However, exports started to decline after 2004. *Chondracanthus chamissoi* HC (i.e., *C. chamissoi* for human consumption) exports ranged from 0.11-222 MT year^{-1} without a defined trend (Figure 5(a); Supplementary Table S1), reaching their highest growth during 2005–2009. The highest instabilities were observed in 2000–2004 for both uses (i.e., industrial use and human consumption). The overall CGR and CII were higher for *C. chamissoi* HC than for IN (Tables 2 and 3).

Chondracanthus chamissoi IN and HC prices (FOB) ranged from USD 700–1995 MT^{-1}, and USD 1540–16,425 MT^{-1}, respectively. In the case of IN, positive growth has been observed since 2005, reaching the highest growth rates in 2005–2014. For HC, prices increased from 2010 onwards (Figure 5(a); Supplementary Table S5). The growth rate for prices reached its highest value in 2015–2020 (Table 2). The overall CGR and CII were higher in *C. chamissoi* IN than HC. CII reached their highest points during 2005–2009 (IN) and 2000–2004 (HC) (Tables 2 and 3).

When including data from the COVID period (2020), only the overall CGR for human consumption showed changes, e.g., decreasing by 2.6% for exports and increasing by 1.3% for prices. On the other hand, the CII for both uses showed little variation during the COVID year (Tables 2 and 3).

Gracilariopsis lemaneiformis accounted for a very low proportion of the total seaweeds exported (i.e., 0.15%). Exports were not sustained and mainly occurred from 2001 to 2005, falling to zero in 2009. Volumes were between 12 and 230 MT year^{-1}, with an overall growth rate of 4.3% and a CII of 24.4%. *Gracilariopsis lemaneiformis* prices (FOB) ranged from USD 710–1650 MT^{-1}, with an overall growth rate of –4.4% and a CII of 13.3% (Figure 5(b); Table 2 and 3; Supplementary Tables S1 and S5).

The main destinations for red seaweeds were: USA (*C. chamissoi* IN), China (*C. chamissoi* HC), and Argentina (*G. lemaneiformis*) (Figure 7(a)–(c); Supplementary Table S6)

3.3 Brown seaweeds

Lessonia berteroana was the first species to appear in the brown seaweed export records. Values ranged from 602 to 7020 MT year^{-1}, increasing until 2008, but dropping in 2009 before recovering in 2010. Exports have shown low growth since then. *Lessonia trabeculata* exports started in 1997 and reached their peak in 2010 (8434 MT year^{-1}). Positive growth rates were reported during 1996–1999 and 2005–2009. A decreasing trend has been reported since then. *Macrocystis pyrifera* exports started in 1997 but were not sustained. Export volumes ranged from 16 to 28,864 MT year^{-1}, with an increasing trend from 2003 to 2019 (Figure 6; Table 4; Supplementary Table S1). The highest instabilities were reported during 2000–2004 for *L. berteroana* and 2005–2009 for *L. trabeculata* and *M. pyrifera*. Among the three brown algal species, the overall CGR and CII were notably higher in *M. pyrifera*. This species is currently predominant amongst Peruvian seaweed exports (Tables 4 and 5).

Prices (FOB) for *L. berteroana*, *L. trabeculata*, and *M. pyrifera* were USD 240–1445 MT^{-1}, USD 235–1090 MT^{-1}, and USD 155–1120 MT^{-1}, respectively. In the case of *L. berteroana*, prices showed the highest growth rate from 2005 to 2014 and then started declining. A notable increase in *L. trabeculata* prices was observed from 2007 to 2009, with values staying above USD 800 MT^{-1} in the following years. A similar trend was registered for *M. pyrifera* (Figure 6; Supplementary Table S5). CII reached their highest points during 2005–2009 for all brown seaweed species. The highest overall CGR and CII were observed in *M. pyrifera* (Tables 4 and 5).

When including data from the COVID period (2020), the overall CGR and CII diminished. This reduction was especially remarkable for *M. pyrifera* exports (Tables 4 and 5). The main country destination for brown seaweeds was China (Figure 7(d)–(f); Supplementary Table S6).

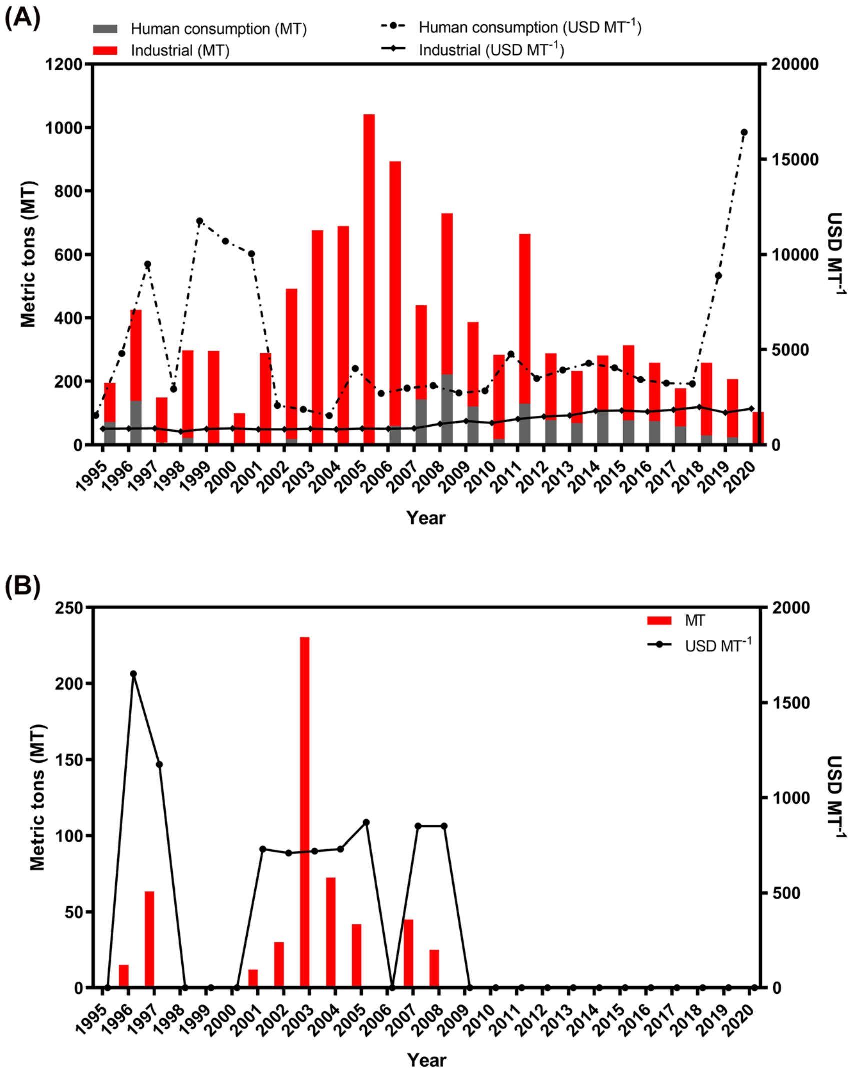

Figure 5: Annual exports of Peruvian red seaweeds in metric tons (MT) and their corresponding average Free-on-Board prices (USD MT^{-1}) from 1995 to 2020.
(A) *Chondracanthus chamissoi*.
(B) *Gracilariopsis lemaneiformis*.

4 Discussion

This work is the first to summarize and analyze the official seaweed export statistics for Peru. Peru is the second largest seaweed producer in the Americas, although all the reported biomass is collected from natural populations (Cai et al. 2021). It is clear from the national statistics that most seaweeds landed are destined for export (PRODUCE 2021a). In this sense, the present study is crucial for understanding the current status of the Peruvian seaweed industry, which in turn can serve for developing conservation strategies and making Peru's statistical data easily accessible.

Seaweed export data prior to 1995 lack information about species composition and include seaweeds as both fresh and dried materials. From 1990 to 1994, exports did not exceed 120 MT year^{-1}, with the USA being the main destination country (Acleto 1998). Exports have shown an increasing trend since 2003, with a sharp increase from 2008 and reached their historically highest volumes in 2019 (i.e., 33,951 MT). However, most of this increase is attributed to brown seaweeds, which accounted for more than 95% of the total Peruvian seaweed exports. This contrasts with the neighboring country Chile, where brown algae constitute 50–60% of the seaweed production and there is a greater variety of economic red seaweeds (10 species) (Buschmann et al. 2001; Camus et al. 2019). It is worth mentioning that some of these species are not present (e.g., *Gigartina skottsbergii* Setchell *et* N.L.Gardner) or have a restricted distribution in Peru (e.g., *Gracilaria chilensis* Bird, McLachlan *et* Oliveira; Arakaki et al. 2015). Brown seaweed exports were almost twice as unstable as red ones, as shown by the CII. This was expected since exports relied primarily on brown algal species, whose volumes and prices are mostly dictated by the Chinese market and its alginate industry, which usually struggles to get enough kelp raw materials (Kang et al. in press; Zhang 2018).

Table 2: Growth rate of Peruvian red seaweed exports and their average prices.

Period	Compound growth rates (%)					
	Exports			Average prices		
	CC^{IND}	CC^{HC}	GL	CC^{IND}	CC^{HC}	GL
1995–1999	18.60	−59.47		−2.39	42.76	
2000–2004	60.99	−31.39		−0.94	−42.68	
2005–2009	−27.56	130.99		10.92	−6.01	
2010–2014	−18.66	34.65		10.56	6.39	
2015–2019	−2.88	−28.14		0.05	16.33	
2015-2020 (including COVID-19 pandemic)	−10.24	−39.26		0.67	32.59	
Overall (without COVID-19 pandemic)	−1.24	10.23	4.28	4.35	−0.46	−4.41
Overall (with COVID-19 pandemic)	−1.17	7.67		4.33	0.83	

CC^{IND}, *Chondracanthus chamissoi* for industrial use; CC^{HC}, *C. chamissoi* for human consumption; GL, *Gracilariopsis lemaneiformis*.

Table 3: Instability of Peruvian red seaweed exports and their average prices.

Period	Coppock's instability index (%)					
	Exports			Average prices		
	CC^{IND}	CC^{HC}	GL	CC^{IND}	CC^{HC}	GL
1995–1999	15.30	55.66		10.94	23.05	
2000–2004	22.52	65.59		10.30	26.17	
2005–2009	18.31	52.15		11.98	11.73	
2010–2014	16.21	21.72		11.76	12.20	
2015–2019	13.08	17.27		10.63	15.41	
2015–2020 (including COVID-19 pandemic)	14.26	27.49		10.59	19.74	
Overall (without COVID-19 pandemic)	18.79	64.57	24.39	14.09	17.83	13.26
Overall (with COVID-19 pandemic)	19.18	63.64		14.21	18.85	

CC^{IND}, *Chondracanthus chamissoi* for industrial use; CC^{HC}, *C. chamissoi* for human consumption; GL, *Gracilariopsis lemaneiformis*.

All brown and most red Peruvian seaweed species were probably exported for phycocolloid extraction. The increasing trend of both exports and the number of export companies follows the continuous growth of the phycocolloid industry worldwide (Porse and Rudolph 2017). China dominated the market by importing 90% of the total seaweeds from Peru, which exceeds that reported for Chilean seaweed exports (FAO 2018). The Chinese seaweed market largely influences the export trends in Peru. For example, since 2005, there has been an increasing demand from China to buy raw materials for their alginate industry (Zhang 2018). Together with the FTA signed in 2009, this demand explains the rise of the export volumes and FOB values of brown algal species during 2005–2019. Other important markets for Peruvian seaweeds were Chile, France, and the USA, which amounted to 6.8% of total sales.

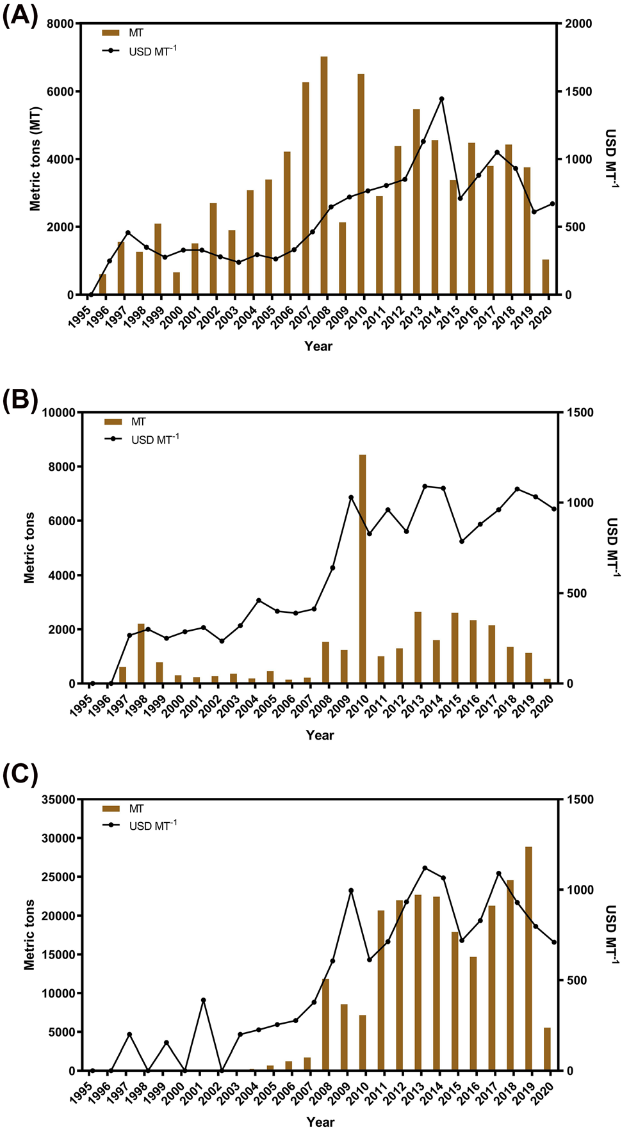

Figure 6: Annual exports of Peruvian brown seaweeds in metric tons (MT) and their corresponding average Free-on-Board prices (USD MT^{-1}) from 1995 to 2020. (A) *Lessonia berteroana*. (B) *L. trabeculata*. (C) *Macrocystis pyrifera*.

Exports of red seaweeds exports were dominated by *Chondracanthus chamissoi* IN. Around 60% of this biomass

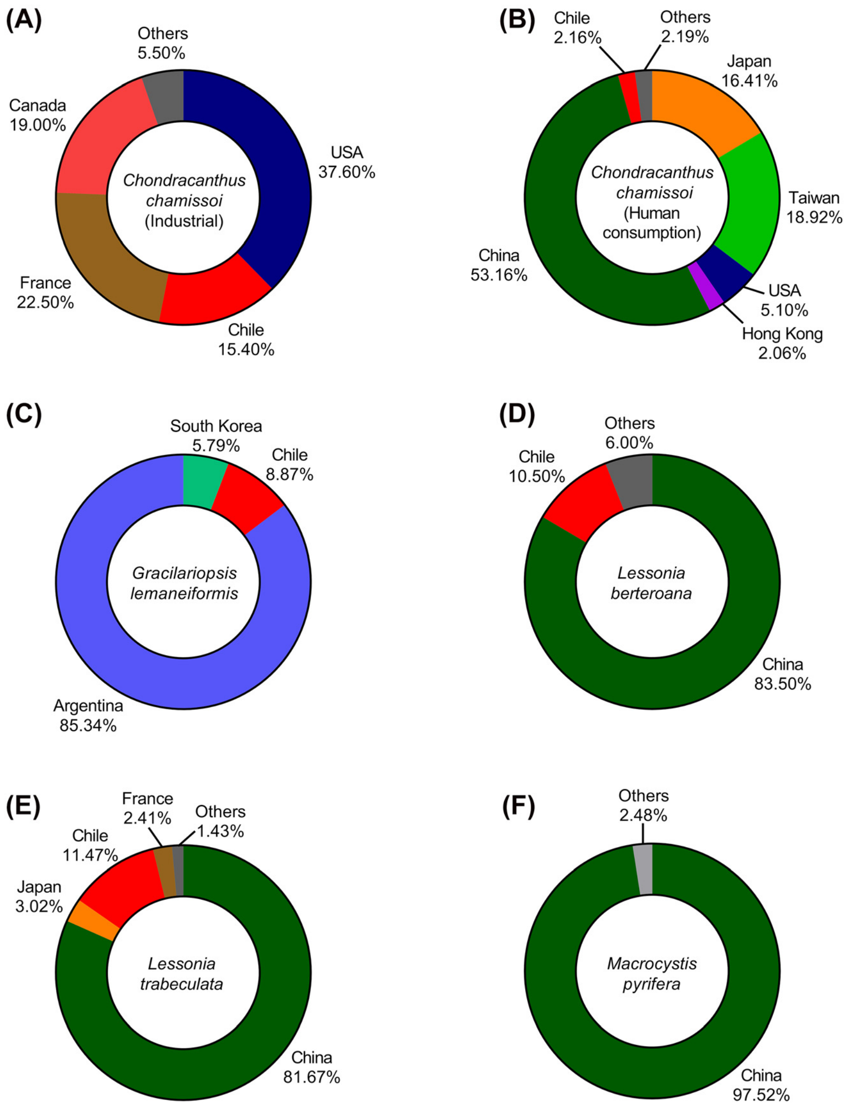

Figure 7: Countries of destination for the export of six species of Peruvian seaweed from 1995 to 2020.

was destined for USA and France, which are key players in the carrageenan industry in their respective regions (Campbell and Hotchkiss 2017). 87% of *C. chamissoi* HC was exported to East Asia (i.e., China, Japan, and Taiwan), where it is traditionally used in soups and salads (Macchiavello et al. 2012). In both cases, exports have declined during the last five years, as shown by the negative growth rate. However, prices followed an opposite trend. This is especially evident for *C. chamissoi* HC, where prices have increased sharply since 2019, reversing the negative trend and low growth experienced from 2000 to 2014. This scenario might be explained by the limited number of existing natural beds, and the short periods allowed for population regeneration between harvest and small-scale harvesting of *C. chamissoi*, which in turn increased its value (Hayashi et al. 2013). Despite the low contribution of *C. chamissoi* HC to seaweed exports, these seem highly unstable, especially in terms of volume, as shown by their CII throughout the studied period. Although the reasons behind this instability are not well-known, they might be related to the high dependence on the Chinese seaweed market and its fluctuations (Kang et al. in press).

Gracilariopsis lemaneiformis was mainly exported to Argentina for a short period. It accounted for only 0.15% of the total seaweed exports. In 1996, *G. lemaneiformis* was cultivated at Cherrepe Bay in northern Peru. Despite the initial success, the El Niño phenomena of 1997–1998 brought an end to this effort (Hayashi et al. 2013). Although there is a current project investigating *G. lemaneiformis* cultivation (PRODUCE 2021b), no further attempts have been reported since then. It is worth mentioning that *Porphyra/Neopyropia*, a well-known group of economic seaweed species, did not appear in the export records. However, we assume that they are classified in the records

Table 4: Growth rate of Peruvian brown seaweed exports and their average prices.

Period	Compound growth rates (%)					
	Exports			Average prices		
	LB	LT*	MP**	LB	LT*	MP**
1996–1999	42.59	13.47	26.77	0.44	−3.17	2.99
2000–2004	39.03	−5.20		−5.22	10.28	
2005–2009	−4.15	55.38	109.17	30.50	26.94	42.13
2010–2014	−0.78	−21.06	26.97	17.49	6.81	16.82
2015–2019	2.02	−19.98	15.85	−2.46	7.77	3.23
2015-2020 (including COVID-19 pandemic)	−16.34	−37.03	−10.03	−4.21	4.76	−0.99
Overall (without COVID-19 pandemic)	6.88	8.77	46.99	6.66	8.02	9.47
Overall (with COVID-19 pandemic)	5.08	5.97	41.38	6.12	7.60	8.64

LB, *Lessonia berteroana*; LT, *L. trabeculata*; MP, *Macrocystis pyrifera*. *Exports started in 1997. **Data from 1997 to 1999 were pooled together with the data from 2000 to 2004 as data points in the first period were scarce (2 data points) for compound growth rate calculation.

Table 5: Instability of Peruvian brown seaweed exports and their average prices.

Period	Coppock's instability index (%)					
	Exports			Average price		
	LB	LT*	MP**	LB	LT*	MP**
1996–1999	17.02	19.83	30.00	13.07	10.97	14.08
2000–2004	18.34	12.91		11.42	12.77	
2005–2009	16.20	28.57	35.09	15.30	15.25	17.72
2010–2014	13.52	23.17	16.55	13.09	11.41	12.97
2015–2019	11.27	14.43	13.03	12.44	11.35	11.72
2015–2020 (including COVID-19 pandemic)	17.39	27.54	18.07	12.36	11.20	11.77
Overall (without COVID-19 pandemic)	19.35	28.88	149.77	17.43	17.66	19.52
Overall (with COVID-19 pandemic)	19.69	29.67	140.64	17.27	17.63	19.26

LB, *Lessonia berteroana*; LT, *L. trabeculata*; MP, *Macrocystis pyrifera*. *Exports started in 1997. *Data from 1997 to 1999 were pooled together with the data from 2000 to 2004 as data points in the first period were scarce (2 data points) for Coppock's instability index.

as "others". It seems that they are mostly destined for wholesale markets in Peru. *Porphyra/Neopyropia* are commonly used in Peruvian cuisine for preparing salads or stews (Acleto 1986; Noriega 2011).

Brown seaweed exports comprised *Lessonia berteroana* (formerly known as *L. nigrescens*), *L. trabeculata*, and *Macrocystis pyrifera*. This last example became the dominant export species in 2008 when its volumes exceeded *L. berteroana*. Among the three, *M. pyrifera* showed by far the highest overall growth rate, representing around 5 to 8 times the rates reported for *L. berteroana* and *L. trabeculata*. The predominance of *M. pyrifera* could be explained by its high abundance in the lower intertidal and up to 5 m depth in some important localities such as Marcona (southern coast of Peru), which might limit the presence of *L. berteroana* in the coastline (Pérez-Araneda et al. 2020). In contrast, brown seaweed production in the neighboring country Chile is dominated by *L. berteroana*/*spicata*, which has an almost continuous distribution along the whole Chilean continental coast (Araya et al. 2018; Vásquez 2016). Also, *M. pyrifera* exports were highly unstable compared to the other two kelp species, especially in terms of volume. This instability might be due to variations in the natural biomass, demand of the Chinese market, price competitiveness, and governmental policies. Environmental conditions can also have a critical impact on exports. For example, the El Niño event of 1997–1998 was a catastrophic occurrence that caused high kelp mortality and produced local extinctions (Fernández et al. 1999; Vásquez et al. 2006). The high drifted biomass resulting from this mortality might have sustained the exports during this period. However, a decrease in brown algal export volumes during 1999–2000, especially of *L. berteroana* and *L. trabeculata*, could be attributable to reduced drifted biomass and the fact that natural beds had not recovered yet (Vásquez et al. 2006).

From December 2008 to June 2009, the Peruvian government banned the harvesting of kelp species to protect their natural populations. This resulted in a reduction of export volumes during 2009. The same year, the National Seaweed Regulation came into effect to establish sustainable use of marine macroalgae, emphasizing brown algal species. However, the increasing export volumes of the last years might indicate that the regulation has failed to some extent. In fact, illegal harvesting of kelp species is still reported (La República 2018; Noriega et al. 2011) and constitutes a severe threat to the ecological goods and services that the kelp forest ecosystem provides (Lotze et al. 2019). Furthermore, the decreasing trend of prices since 2017, especially for *M. pyrifera*, could further increase the extractive pressure as more biomass is needed to maintain the economic returns.

Assuming a 15–20% moisture content for dried brown seaweeds destined for export (Araya et al. 2018; McHugh 1987; PRODUCE 2009), we can estimate that, in 2019, a wet biomass equivalent to 20,684–25,019 tons of *L. berteroana*, 6205–7512 tons of *L. trabeculata*, and 159,082–192,432 tons of *M. pyrifera* were harvested. The sum of these values considerably exceeds the 36,348 tons (wet biomass) of total seaweed landings reported for the same year for Peru in the official records (PRODUCE 2021a). The FAO statistics also reported 2043 tons of *Lessonia* collected in the country during 2019 (Cai et al. 2021). This represents at least 13 times less than the calculated fresh biomass of *Lessonia* in the same year. The gap between what is officially collected or landed and the export volumes might reflect the government's lack of control, especially in remote areas where ports and official control centers are difficult to access. This "unreported biomass" could be even higher as we did not include the losses during the processing for wet biomass calculations.

The outbreak of COVID-19, ongoing at the time of analysis, has already negatively impacted trade among key exporters and importers (FAO 2020), either by transport restrictions and increased transportation costs or the closure of international markets due to sudden and prolonged lockdowns (Mangano et al. 2022). According to our analysis, this impact was most marked in brown seaweed exports, with *M. pyrifera* the most affected species. Despite reducing exports, brown seaweeds experienced positive growth during the studied period, while red ones showed a negative overall growth rate. However, it is difficult to predict whether this negative effect will continue in the following years or not, as COVID-19 has added more uncertainties to the projections for the fisheries and aquaculture sector (FAO 2020), which in turn are occurring in the context of other anthropogenic-driven threats including global climate change (Sarà et al. 2021).

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