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Carbon capture in *Chondracanthus chamissoi* (Gigartinaceae) algal meadows: a case study on the Peruvian coast

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ABSTRACT

Introduction: Algal meadows can significantly contribute to carbon (C) capture; nevertheless, few studies on Peruvian coast reserves are available. Evaluation of these stocks allows proposing better measures for the sustainable use of these habitats and maintaining their ecosystem services.
Objective: To estimate biomass distribution and quantify the C captured as standing stock biomass in natural algal meadows of red algae *Chondracanthus chamissoi* on the Laguna Grande coastal lagoon (Ica-Peru), place of main extraction of these economically important algae.
Methods: To calculate the biomass, the area occupied by each patch of algae in each sampling zone was delimited and transects perpendicular to the coast were used in randomly located plots. In the laboratory, the dry biomass and C content were measured (the latter using an elemental analyzer).
Results: Monthly variation in the distribution and area was identified. September 2021 presented the highest total biomass (50 416.4 kg; 50.4 t) and C captured (13 t C or 47.58 t CO_2) while from February to June no algal biomass was found. Differences were found in the biomass and C capture in the sampling zones, the months of C capture, and the interaction between these two variables. C capture decreases with warm months and more intensive anthropogenic extraction of algae.
Conclusions: This study highlights the interaction between the anthropogenic extraction of *C. chamissoi* and seasonal environmental changes, alongside the net contribution of macroalgal biomass.

Key words: assimilation of carbon; blue carbon; red algae; sustainable extraction.

RESUMEN

Captura de carbono en praderas algales de *Chondracanthus chamissoi* (Gigartinaceae): un estudio de caso en la costa peruana

Introducción: Las praderas algales pueden contribuir significativamente a la captura de carbono (C); sin embargo, hay pocos estudios disponibles sobre reservas costeras peruanas. La evaluación de la biomasa de estas algas permite proponer mejores medidas para el uso sostenible de estos hábitats y el mantenimiento de sus servicios ecosistémicos.
Objetivo: Estimar la distribución de biomasa y cuantificar el C capturado por la biomasa en pie de praderas algales naturales del alga roja *Chondracanthus chamissoi* en la laguna costera Laguna Grande (Ica-Perú), lugar de principal extracción de estas algas de importancia económica.

Métodos: Para calcular la biomasa, se delimitó el área ocupada por cada parche de alga en cada zona de muestreo y se utilizaron transectos perpendiculares a la costa en parcelas ubicadas aleatoriamente. En el laboratorio, se midió la biomasa seca y el contenido de C (este último utilizando un analizador elemental).
Resultados: Se identificó la variación mensual en la distribución y el área. Septiembre de 2021 presentó la mayor biomasa total (50 416.4 kg; 50.4 t) y C capturado (13 t C o 47.58 t CO_2), mientras que de febrero a junio no se encontró biomasa algal. Se encontraron diferencias en la biomasa y la captura de C en las zonas de muestreo, los meses de captura de C y la interacción entre estas dos variables. La captura de C disminuye en los meses cálidos y con la extracción antropogénica más intensiva del alga.
Conclusiones: Este estudio resalta la interacción entre la extracción antropogénica de *C. chamissoi* y los cambios ambientales estacionales, junto con la contribución neta de la biomasa macroalgal.

Palabras clave: asimilación de carbono; carbono azul; algas rojas; extracción sostenible.

INTRODUCTION

The increase of greenhouse effect gases such as CO_2, as a result of human activities represents one of the most critical problems of this century (Dai et al., 2017). The Intergovernmental Panel on Climate Change has proposed nature-based solutions with a critical approach for its mitigation and reduction (Cohen-Shacham et al., 2016). These solutions include care, restoration, and sustainable use of environments that serve as carbon storage and capture (Pendleton et al., 2012). Carbon capture implies the retention of carbon in biomass (inside the body of organisms) through photosynthetic assimilation (Barnes et al., 2021) for a short time as part of an organism cycle (Duarte et al., 2005) as well as the transfer of atmospheric carbon dioxide to other long-lived reserves, such as oceanic, pedological, biotic and geological sediments (Lal, 2008), which can remain for thousands of years (Nellemann et al., 2009; Vierros, 2017). Vegetated marine-coastal ecosystems, including mangroves, kelp beds, seagrasses, and salt marshes, store and sequester large amounts of carbon, called "blue carbon" (Barbier et al., 2011).

Initially, algal meadows were not considered a possible blue carbon contributor (Duarte et al., 2005) due to their limited long-term potential for carbon sequestering (Smale et al., 2018). However, recent studies have demonstrated that thanks to the source-sink mechanism (transport of a large amount of algae biomass from euphotic coastal waters to the seabed), macroalgae can contribute significantly to the vertical flux of organic carbon and its sequestration in ocean sediment (Hidayah et al., 2019; Oreska et al., 2018). Occasional deposits of *Macrocystis* sp. and *Sargassum* sp. on the seabed off the East and West coasts of the United States and in the Caribbean have been described (Harrold et al., 1998; Kokubu et al. 2019).

Currently, it has been proposed to consider all pathways of the carbon cycle as blue carbon, based on the "Odum outwelling" hypothesis, which suggests that lateral flows or horizontal exports of carbon sustain a large part of biological productivity (Odum, 1968). Algae meadows can also be considered blue carbon contributors by having exceptionally high rates of primary production per unit area and transporting dissolved and particulate organic carbon (Santos et al., 2021).

Algal habitats are the most extensive and productive coastal habitats in the ocean, covering about 6.06-7.22 million km^2, and support a primary global net production of around 1.32 Pg C yr^{-1} (Duarte et al., 2022). Carbon capture studies have been carried out on *Macrocystis pyrifera*, obtaining a net annual productivity of 0.0013 t C m^{-2} (Wheeler & Druehl, 1986). Furthermore, the influence of physical parameters, such as temperature, on carbon capture has been described; for example, *Laminaria hyperborea* forests in warm regions of the Northeast

Atlantic capture less carbon (3.09 t C ha^{-1}) than in cold areas (9.72 t C ha^{-1}) (Pessarrodona et al., 2018). Similarly, several studies have investigated the accumulation of carbon in the biomass of red algae, such as the study by Rozaimi et al. (2024), in this study, species from the Florideophyceae family, collected from a tropical seagrass meadow, were evaluated, including *Gracilaria blodgettii, Gracilaria coronopifolia, Gracilaria fisheri* and *Gracilaria textorii*, two zones were sampled: in the Northeastern zone, the carbon values were 0.44 g C m^{-2}, 8.84 g C m^{-2}, 1.78 g C m^{-2}, and 0.57 g C m^{-2}, respectively; in the Southwestern zone, the values were 0.20 g C m^{-2}, 14.07 g C m^{-2}, 0.0045 g C m^{-2}, and 0.013 g C m^{-2}, respectively, the results indicated that biological and spatial factors significantly influence carbon sequestration, however, they do not include anthropogenic effects in their results. Furthermore, has been evaluated the carbon sequestration capacity of red algae *Sarcodia suae* cultivated, varied considerably with the season: winter/spring (2.1-3.9 g C m^{-2} d^{-1}) and summer (0.09 g C m^{-2} d^{-1}) (Weerakkody et al., 2023). Despite this, studies are limited and most information regarding carbon stock is focused on seagrasses and mangroves (Donato et al., 2011; Ricart et al., 2020).

In the South American Pacific, carbon capture studies have been carried out on populations of *Lessonia nigrescens* and *Lessonia trabeculata* in Chile (during spring was estimated at 11.46 g C m^{-2} d^{-1} and 2.46 g C m^{-2} d^{-1} respectively; in autumn to 0.66 g C m^{-2} d^{-1} and C m^{-2}, respectively) (Tala & Edding, 2007). In Peru, greenhouse gas emissions were 210 404.42 Gg CO2eq in 2019, with CO_2 accounting for 75.76 % of the total emissions, or 159 395.34 Gg CO2eq (Ministerio del Ambiente [MINAM], 2019). Therefore, it is crucial to analyze nature-based solutions that can mitigate the future impacts of these significant CO_2 emissions. While there is a recognized need for accurate mapping and effective quantification of the carbon sequestered by algal meadows in terms of their contribution to blue carbon (McKinley et al., 2019), few studies have been conducted on this subject. Regarding scientific articles, there is only the research by Aller-Rojas et al. (2020) in *Lessonia trabeculata* forests in San Juan de Marcona, in which the carbon capture potential of *L. trabeculata* is highlighted by presenting a capture of 4.31 ± 1.56 t C ha^{-1}. Another study by Cevallos et al. (2024) also in *L. trabeculata* in the Reserva National San Fernando in which the carbon capture potential of *L. trabeculata* is 1.2-3.5 t C ha^{-1}. These studies suggest that further research on the carbon dynamics of marine algal ecosystems in the Humboldt Ecoregion.

Chondracanthus chamissoi is a benthic marine red macroalga that is located between Paita, Peru (5 °S) to Ancud, Chile (42 °S) (Wang et al., 2012), with a distribution from the lower intertidal zone, up to 15 m deep (Bulboa & Macchiavello, 2006). This species is considered one of the most important due to its potential use to obtain carrageenan (Bulboa et al., 2005). In the Ica region, mainly in shallow areas of the coast, its extraction is carried out by artisanal fishermen as an economic sustenance activity, with biomasses of 180 t, 30.1 t, and 2.1 t having been reported for the Atenas, Puerto Nuevo, and Lobería beaches, respectively (autumn of 2010) and registered reductions in the last two prairies compared to 2007 due to the intensification of extractive activity (Flores et al., 2015). Laguna Grande coastal lagoon is one of the main extraction sites of *C. chamissoi*. Intensified and disorderly extraction is the potential cause of resource decline, and this may be aggravated by the effects of climate change and phenomena such as “El Niño” and “La Niña” (Vivanco et al., 2014). The reduction of algal biomass affects carbon capture in ecosystems (Macreadie et al., 2013) and, thus, the carbon cycle; for this reason, it is essential to ensure sustainable use of the resource that allows maintaining the ecosystem services that algal meadows provide (McKinley et al., 2019). In this context, the objective of this research was to describe the distribution of algal biomass in algal meadows in *C. chamissoi* between August 2021 and September 2022 and to estimate its biomass per unit area and carbon capture as standing stock biomass, it also relates these results with climatic seasons and anthropogenic extractive

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processes, in the Laguna Grande coastal lagoon (Ica-Peru) located within the Paracas Protected Natural Area, zone protected by the Peruvian state, which is one of the areas of high interest as it serves as the primary extraction center for this species. The results of carbon capture may provide potential mitigation strategies for climate change (Cuba et al., 2022).

MATERIALS AND METHODS

Study area: The study was conducted in Ica-Peru in the province of Pisco, located South of Lima (Fig. 1). The research focused on the Laguna Grande coastal lagoon, which has a semi-enclosed formation that covers 299.29 ha (Quispe et al., 2010). Four sampling zones were chosen for the main extraction points of *C. chamissoi*: Bocana, La Isla, Bajada de León, and Criadero. This area presents a textured bottom of the coarse sand type, with rock fragments, shell remains, and fan shells (Velazco & Solís, 2000), which allow the fixation of *C. chamissoi*. Criadero, Bocana, and La Isla are shallow areas with depths between one and three m, while Bajada de León is an area with a depth between four and eight meters (Quispe et al., 2010).

The study was conducted between August 2021 and September 2022, performing monthly sampling (except for July and August 2022, when logistical conditions did not allow sampling).

The distribution and area of each sampling zone: Each sampling zone was delimited according to the presence of *C. chamissoi* and a motorboat was used to delimit every contour. Furthermore, a freediver validated the presence or absence, and the limits were georeferenced with the help of a GPS (Garmin model GPSMAP 64sx) receiver. Finally, considering these limits, polygons were built, and then the area of each sampling zone was calculated using QGIS Desktop 3.16.5 software (Sherman, 2022).

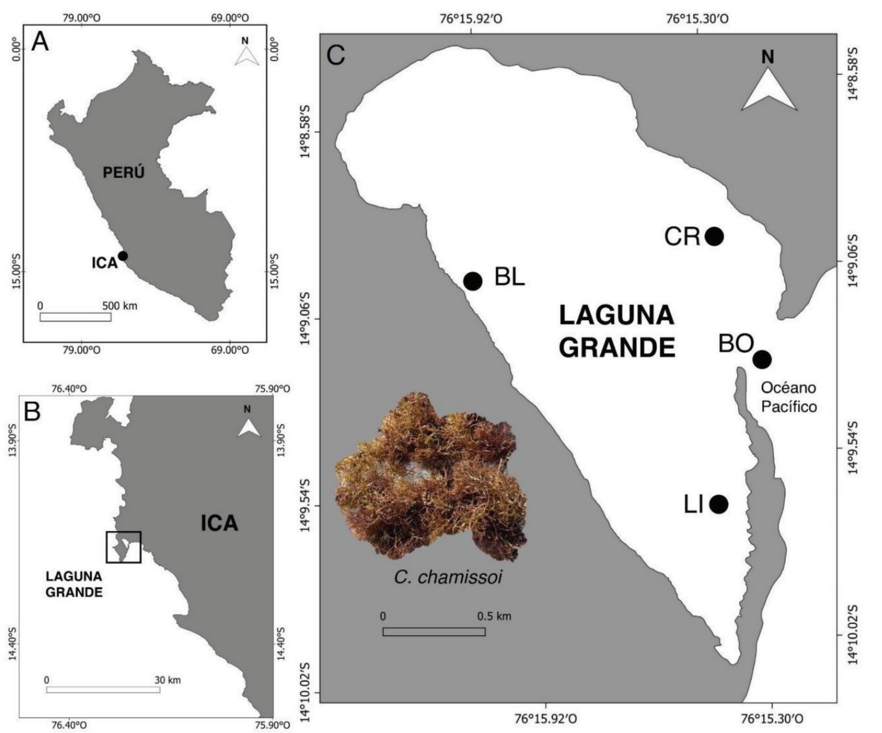

Fig. 1. The location of Laguna Grande in **A.** Peru and **B.** the Ica Region. In **C.**, the sampling area is shown, indicating the four sampling zones: Bocana (BO), La Isla (LI), Bajada de León (BL), and Criadero (CR).

Biomass in each sampling zone: To determine the biomass in each sampling zone, a transect was carried out parallel to the coast that crossed the *C. chamissoi* population through the central part and from end to end. The length of each transect was determined with GPS and was conditioned to biomass variations (increase or decrease over time). Algal biomass was recorded in PVC quadrats of 25 x 25 cm, randomly placed along each transect by a scuba diver. Since the area of each sampling zone differed, between 12 and 32 points were made for each transect, verifying that it was representative of the population using a performance curve (Elzinga et al., 1998). In each quadrant, the algae were extracted from the substrate and excess water was removed with blotting paper. Subsequently, the biomass was weighed on an electronic balance (FERRAWYY brand model BAG030-YJ; 5 g precision). This procedure was carried out in each month evaluated. Finally, each month the values of the sampling zones were added to determine the biomass of the total monthly algal population.

Percentage of dry biomass and percentage of carbon: To calculate the dry weight percentage, three samples of *C. chamissoi* were taken to the Algaex S.A. laboratories and weighed (wet weight). They were subsequently dried in a dehydrator at 38 °C for 48 hours. A moisture analyzer (MX-50, 0.005 g precision) was used to verify that the moisture percentage was null. The difference between the wet and dry weights indicated the percentage of dry biomass (DB), corresponding to the average results obtained from the three samples.

Three additional samples were collected and processed in the ELTRA CS-2000 elemental analyzer in the Soldexa S.A. laboratories to know the percentage of carbon in the biomass. The elemental analyzer measures the carbon concentration through combustion in an induction furnace and the subsequent analysis of the gaseous combustion products carbon dioxide and sulfur dioxide. The average result in the three samples was used as the carbon percentage of the biomass.

Calculation of carbon capture in each sampling zone: To calculate the average carbon capture in each sampling zone (C), the average biomass of the quadrats of each population (B) was multiplied by the percentage of dry biomass (% DB) and by the percentage of carbon in the biomass (% C), following formula 1:

$$C = B \times \% DB \times \% C \qquad (1)$$

This value was multiplied by the area of each sampling zone, showing the total carbon capture of each sampling zone in each month evaluated. Finally, the values obtained for each sampling zone were added to determine the total carbon capture of each month in the study area. This study refers to carbon captured as standing stock biomass.

Statistical analysis: Descriptive statistical analysis (means and standard deviations) was performed for the biomass values of the plots in each sampling zone. Graphs and tables were made with these values. All this was done in Excel software (Microsoft Corporation, 2021). To compare the carbon capture of each sampling zone over time, a PERMANOVA test was carried out. This test allows evaluating the dependent variable (carbon capture as standing stock biomass) based on two or more independent variables (in this case, the sampling area, and the sampling month), verifying the relationship between the dependent variable and the interaction between the independent variables. This test was chosen since the dependent variable did not meet the normal distribution ($p < 0.05$ for the Shapiro-Wilk test). This analysis was performed in the PAST 3.17 software (Hammer et al., 2001).

RESULTS

Distribution and area of each sampling zone: The locations of the sampling areas were the same in August and September 2021 (Fig. 2A). In October 2021 (compared to September), an increase in area was evidenced in 64 % and 29 % of the sampling areas of Criadero and

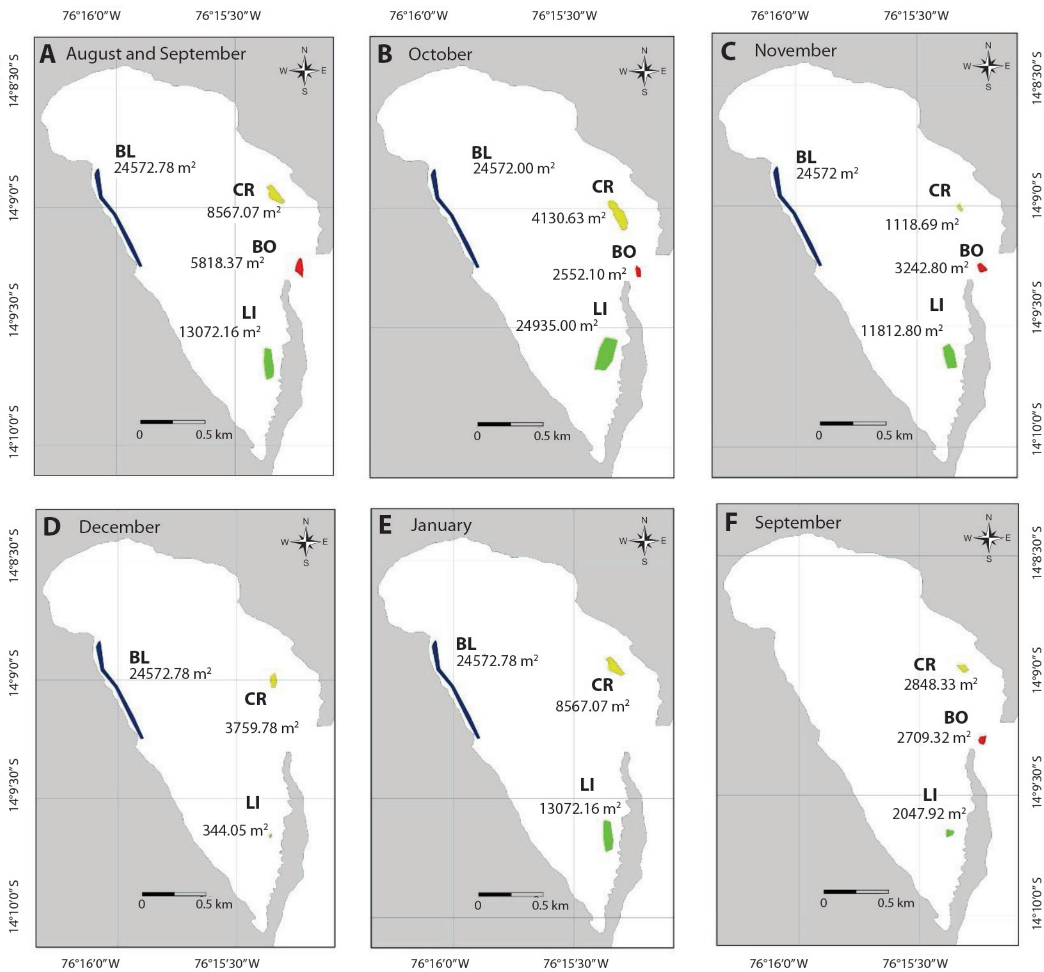

Fig. 2. Distribution and area of the orange Bocana (BO), green La Isla (LI), blue Bajada de León (BL), and yellow Criadero (CR) sampling zones. **A.** Sampling of August and September 2021. **B.** Sampling of October 2021. **C.** Sampling of November 2021. **D.** Sampling of December 2021. **E.** Sampling of January 2022. **F.** Sampling of September 2022. The samplings that do not appear in the figures are those without algal biomass.

the Island respectively, while the area in Bocana decreased by 57 % and the area in Bajada de León was maintained (Fig. 2B and MST 1). On the other hand, in November 2021 (compared to October), the sampling areas of Criadero and La Isla, decreased by 93 % and 53 %, respectively, while Bocana increased by 27 % and the area in Bajada de León was maintained (Fig. 2C and MST 1). In the December 2021 sampling, the Criadero sampling zone increased by 236 % and La Isla decreased in area by 98 %, while the Bocana algal population disappeared (Fig. 2D and MST 1). In the sampling of January 2022, the distribution of the sampling areas of the first sample was used (the low density did not allow clearing the established limits). In that month, there was no record of algal biomass in Criadero (Fig. 2D and MST 1). There was no record of algal biomass in February, March, April, May, June, or July 2022. Finally, in the September 2022 sampling, only the La Isla, Criadero, and Bocana patches were identified, with the distribution and areas being different from those found in September 2021 (Fig. 2E and MST 1).

Biomass in each sampling zone: The average wet biomass in the Bocana algal population was higher in November 2021 with 4.44 ± 2.33 kg m^{-2} with an estimated this biomass of 14 389.38 kg. Between December 2021 and June 2022, there was no algal recorded. Regarding the algal population of La Isla, the highest wet biomass was also recorded in November 2021 with 4.85 ± 2.96 kg m^{-2} and an estimated total biomass of 57 258.51 kg, with no record of algal biomass between February and June 2022. Regarding Bajada de León, in September 2021, the highest value of wet biomass was obtained with 15.52 ± 7.91 kg m^{-2} and an estimated total biomass of 38 1431.62 kg. This value was the highest achieved compared to the remaining sampling areas. Finally, like Bajada de León, Criadero registered the highest wet biomass in September 2022 with 6.20 ± 3.65 kg m^{-2}, and an estimated total biomass of 53 109.60 kg. January was the month with the lowest registered wet biomass in all the sampling areas with zero kg m^{-2}, 0.17 ± 0.89, 0.12 ± 0.17 and 0.16 ± 0.1 for Bocana, La Isla, Bajada de León, and Criadero, respectively (Fig. 3).

Carbon capture in the sampling zone and statistical analysis: The general average of % DB was ten ± 0.01 and the % C was 25.83 ± 0.57. The highest value of DB was found in September 2021 (in an area of 52 030.4 m^2) with a value of 50.42 t and a carbon capture of 13 t C (47.58 t CO_2) with an equivalence of 7.46 t C ha^{-1} and the lowest non-zero value in January 2022 (in an area of 52 030.4 m^2) with a value of 6.6 t and a carbon capture of 0.17 t C (6.22 t CO_2) with an equivalence of 0.12 t C ha^{-1} (Fig. 4 and MST 1). In addition, the results indicate a peculiarity, where in September 2022, biomass as high as September 2021 is not reached. In addition, it was noted that the biomass obtained in September 2022 was not as high as that achieved in September 2021.

On the other hand, the most significant extraction of *C. chamissoi* occurred between July and October (cold months) while between January and May (warm months), the activities ceased.

The extraction cycle is directly related to the maximum algal biomass reached by *C. chamissoi* during winter and spring (Fig. 4). Furthermore, the maximum biomass is directly proportional to carbon capture (Fig. 4).

There were significant differences in carbon capture between the sampling areas, months, and the interaction between these last two variables (PERMANOVA, area: $F(3) = 6.28$, $p = 0.0003$; month: $F(6) = 55.24$, $p = 0.0001$; interaction: $F(3.6) = 8.98$, $p = 0.0001$) on analyzing the carbon capture of the four sample areas studied (Bocana, La Isla, Bajada de León, and Criadero) and the months studied.

DISCUSSION

Distribution and area of each sampling zone: The differences registered in the distribution and area of the algal population during the sampling months (Fig. 3) are related to bathymetric factors and extraction of the resource. Criadero, Bocana, and La Isla are shallow areas, while Bajada de León is a deeper area (Quispe et al., 2010). The characteristics of the latter area make it less accessible; therefore, compared to the other areas, its extraction is less intensive, and the area is maintained over time. In contrast, Bocana, which is a few meters from the shore, has more significant extractive pressure, and therefore, its area decreases monthly from August 2022 until it disappears. La Isla and Criadero are at a midpoint regarding access to extraction, which makes them moderate regions chosen for extraction purposes.

Percentage of dry biomass and percentage of carbon: No similar studies regarding the % DB and % C of *C. chamissoi* are available. However, the results of the present study are similar to those registered in the macroalgae *L. trabeculata* in which the % DB is 12.99 ± 0.65 and the % C is 28.84 ± 4.59 (Aller-Rojas et al.,

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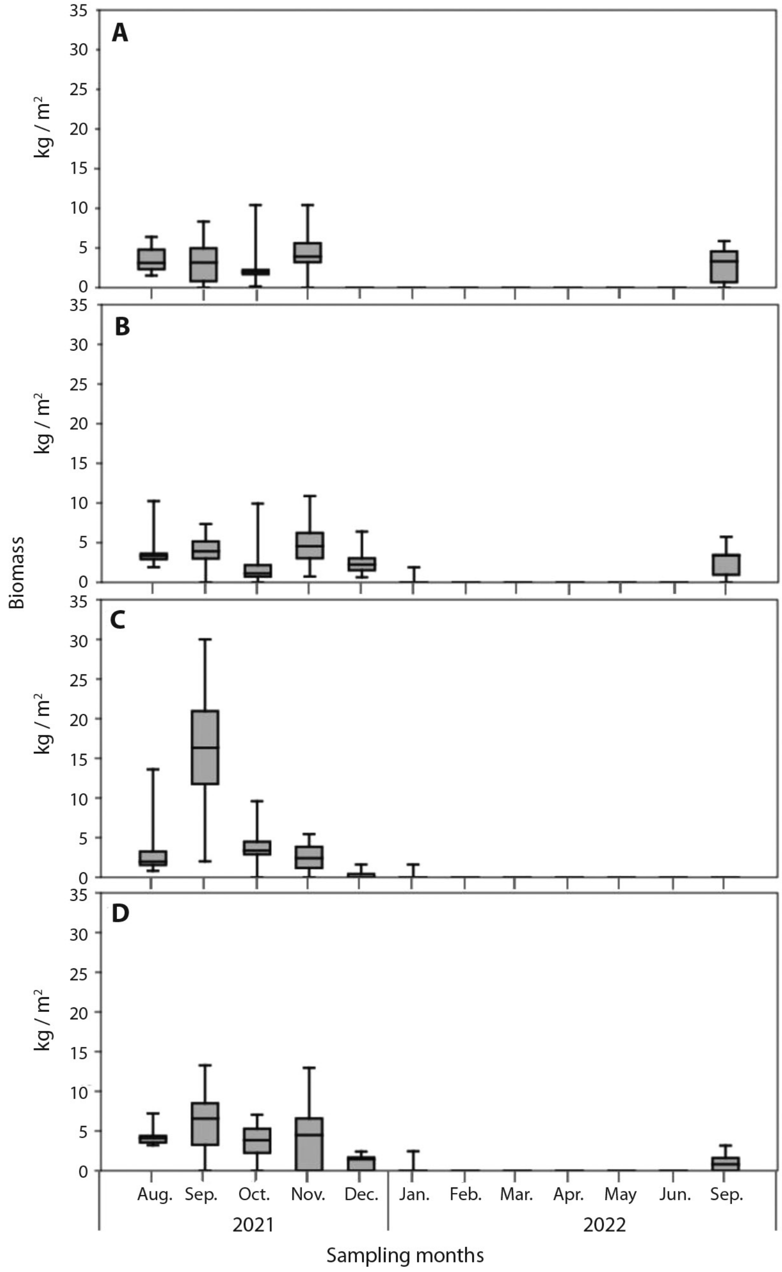

Fig. 3. Boxplot chart of the wet biomass (kg/m^2) was found in the four sampling areas. **A**. Bocana. **B**. The Island. **C.** Bajada de León. **D.** Criadero. Error bars indicate standard deviation.

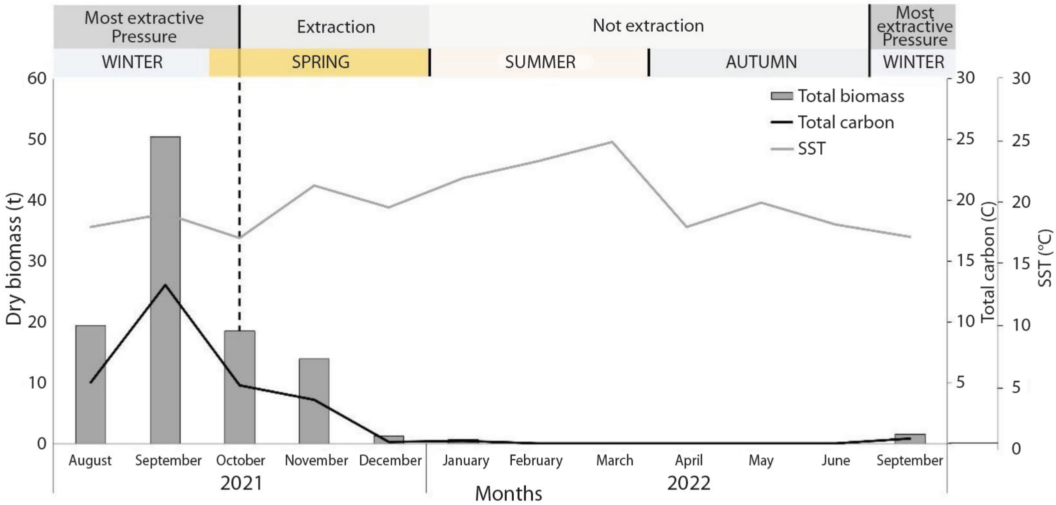

Fig. 4. Total carbon capture (t C), dry biomass (t) of *C. chamissoi* and its relationship with the seasons of the year, the extractive processes of the resource, and the sea surface temperature (SST).

2020) and in *L. nigrescens* in which the % C = 27.23 ± 1.07 in spring and % C = 23.44 ± 1.92 to 22.32 % in Autumn.

In relation to other species of vegetated marine-coastal ecosystems, the % C values reported for *C. chamissoi* are lower than those reported for the seagrass *Thalassia testudinum* with which % C is equal to 35 % (Acosta-Chaparro et al., 2022) or for wetland species with a % C of 33.77 % ± 7.05 having been recorded in succulent plants, 39.25 % in floating aquatic plants and 48.97 % ± 9.32 in amphibian herbs (Aldave & Aponte, 2019).

These results could be related to the fact that most woody and slow-growing plants require a greater investment of C at the cellular level to synthesize lignin (a polymer that allows the formation of support structures such as thallus) (Nielsen et al., 1996; Ma et al., 2018). In contrast, species with a high growth rate and less complex structures lead to less demand for C (Johnson et al., 2007), as is the case of *C. chamissoi.*

Biomass of each sampling zone and carbon capture: Temperature fluctuations could explain the differences between sampling areas and their relationship with specific months. It has been shown that temperature is a controlling factor for *C. chamissoi* growth (Bulboa & Macchiavello, 2001). This is attributed to the fact that lower temperatures favor *C. chamissoi* growth in situ (Bulboa & Macchiavello, 2001), while during the warm months, there is an increase in grazing, epiphyte proliferation, and excess radiation, which generate bleaching, detachment, and destruction of fronds (Macchiavello et al., 2006), further studies considering epiphytes could help understand their effect on the growth of this species (Uribe et al., 2020). This would explain the highest biomass recorded in September 2021, the month with the lowest recorded sea surface temperatures (18.9 °C), and the zero-biomass recorded in March 2022 (24.8 °C), the month with the highest recorded temperature.

Oceanographic conditions could also have contributed to the differences in biomass and carbon capture between September 2021 and 2022. In May 2022, shallow subtropical waters appeared near the coast between Pisco and San Juan de Marcona (Instituto del Mar del Perú

[IMARPE], 2022), potentially causing stratification, changes in settlement, and alterations in biomass growth.

Extraction pressure and its relationship with bathymetry also seem to be key factors explaining the differences between sampling areas (Quispe et al., 2010; Flores et al., 2015), as explained in the section on the distribution and area of each sampling zone. No carbon capture occurs during the warm months because maximum biomass extraction happens in winter-spring, a pattern also observed in *C. chamissoi* meadows in La Libertad (Uribe et al., 2020). When algae are completely extracted from the area, no biomass remains during the summer months until new recruitment and germination occurs in winter-spring (Pariona & Gil-Kodaka, 2011). These factors also influence carbon capture, as algae biomass is harvested along with carbon.

However, something peculiar occurs with Bajada de León has lower extraction pressure and is the deepest zone, and in some cases, its average biomass per unit area is lower than that of other sampling zones. This may be due to its greater depth, which results in reduced light availability, thus limiting the algae's proliferation and photosynthetic activity (Yu et al., 2013). These results coincide with similar studies that described a decrease in biomass at greater depth, demonstrating the growth preference for *C. chamissoi* at depths between one and four meters (Bulboa et al., 2005; Macchiavello et al. 2018), and at high levels of irradiance (Bulboa & Macchiavello, 2001).

Species from various coastal marine ecosystems have been studied, reporting carbon captures of 3.09 t C ha^{-1} for the macroalgae *L. hyperborea* in warm regions and 9.72 t C ha^{-1} in cold regions (Pessarrodona et al., 2018), 4.31 ± 1.56 t C ha^{-1} for the macroalga *L. trabeculata* (Aller-Rojas et al. 2020) and 1.2-3.5 t C ha^{-1} in another population of *Lessonia trabeculate* (Cevallos et al., 2024), while the seagrass *Thalassia testudinum* recorded a capture between 4.6 t C/ ha^{-1} and 3.5 t C ha^{-1} (Acosta-Chaparro et al., 2022). On the other hand, the carbon captures of coastal wetland species, such as *Schoenoplectus californicus* "totora" were 28.9 t C ha^{-1}, 18.6 t C ha^{-1} for *Scirpus americanus* "junco", 17 t C ha^{-1} for *Paspalum vaginatum* "grass salt" stores and 6.1 t C/ha for *Salicornia fruticosa* "salicornia" (Contreras & Carranza, 2007). According to our study, *C. chamissoi* had a maximum potential catch of 1.86 t C ha^{-1}, a value lower than that found in the species mentioned above and the dynamics of which differ from our species, since the above species do not present extraction cycles.

In Peru, *C. chamissoi* is periodically extracted, with the capture of carbon over a period (related to its life cycle, maturity, and extraction). Despite this, they do not contribute to carbon sequestration since this element does not end up on the seabed. In this context, it is important to study the carbon transport that was once part of the macroalgae biomass. Currently, there is no industrial use of this algae, as there are no companies extracting carrageenan; therefore, it is exported as raw material and imported in the form of carrageenan (Arbaiza et al., 2019). In 2020, Peru exported 97.95 t of *C. chamissoi* (dry biomass) for industrial purposes, (mainly carrageenan extraction), with the United States, France, and Canada being the main destinations. Likewise, 5.3 t of DB were exported for direct human consumption, with the main destinations being China, Taiwan, and Japan (Avila-Peltroche & Villena-Sarmiento, 2022). Locally, this resource is in high demand as it has been part of the Peruvian diet since pre-Inca times (Acleto, 1986) and is a main component of highly consumed seafood dishes in the country (Diaz et al., 2021).

The carbon captured by *C. chamissoi* returns to us either converted into carrageenan or through direct consumption. Subsequently, due to our physiological processes, it is eliminated as CO_2 into the atmosphere, returning to the carbon cycle. Then, the algal populations or other ecosystems that serve as a carbon sink fix the CO_2 again, thus generating a cycle that is repeated periodically. After this process, it is no longer considered blue carbon.

Currently, there is a Fisheries Management Regulation for macroalgae, but there is no specific regulation for *C. chamissoi*. The results of this study can help evaluate the sustainability of this resource, considering its availability and use (Magill et al., 2019). The Ministry of Production, along with the Regional Directorate of Production of Ica and the Institute of the Sea of Peru, can use these findings to develop sustainable extraction schemes, particularly in the Protected Natural Area of Paracas.

This study explores the potential of algal meadows in carbon capture as a mitigation measure against climate change (Cuba et al., 2022). Non-extracted algal populations could be included in future carbon inventories prepared by the Ministry of the Environment of Peru. This inclusion will be conditioned by the limited and sustainable resource extraction, as well as the quantification of algae extraction and its reincorporation in the calculation. This research responds to strategies previously identified for the development of the blue economy in Peru (McKinley et al., 2019), and the data will be added to those recently obtained in other vegetated marine-coastal ecosystems (Aller-Rojas et al., 2020) for the better understanding of these ecosystems.

The methodology used in this study did not differentiate between reproductive phases and sizes when calculating biomass and carbon capture. It assumed that the carbon percentage remains constant throughout the year, without considering seasonal influences (such as environmental variables). It has been confirmed that there are significant differences in density and weight between vegetative plants and those with carpospores (Uribe et al., 2020). Additionally, it has been observed that environmental variables influence carbon storage in kelp beds (Aller-Rojas et al., 2020). Therefore, future studies should consider factors such as plant height, sexual proportions, and physical parameters. This study is the first to characterize the algal population and carbon capture of *C. chamissoi* under the context of massive extraction dynamics in Peru, laying the groundwork for future investigations.

In conclusion, the distribution and area of each sampling zone identified varied monthly. The highest algal biomass was reported in September 2021 with 504.2 t of wet biomass, with the % DB being 10 ± 0.01 and the % C was 25.83 ± 0.57. The Laguna Grande coastal lagoon presents a dynamic in which the cyclical processes of total extraction of the algal biomass explain the carbon capture, which was highest in September 2021 with 13 t C. Significant differences were found in the capture of carbon, between the sampling areas, months of the year and the interaction between these last two variables.

The results of this study enable us to assess the availability of the resource over the course of one year and propose sustainable extraction schemes. These results highlight the interaction between the anthropogenic extraction of *C. chamissoi* and seasonal environmental changes, alongside the net contribution of macroalgal biomass. Additionally, estimating carbon as a permanent stock within this resource could redirect interest in this alga, promoting its inclusion in regional strategies for climate change adaptation and mitigation, provided that the long-term sustainability of the ecosystem is carefully evaluated. Overall, this study enhances our understanding of how physical, environmental, and anthropogenic processes can influence both the biomass and carbon capture, as standing stock, of algal meadows with economic value.

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See supplementary material
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