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Analysis of the red seaweed *Gelidium corneum* harvest in the Cantabrian Sea and its influence on resource sustainability

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ABSTRACT

The exploitation of *Gelidium corneum* (Hudson) J.V. Lamouroux in the Cantabrian Sea has an important economic and cultural component. Through the extraction methods of hand plucking underwater and collection of cast seaweed, this seaweed contributes to the livelihoods of many individuals within the region. This species is an international commodity harvested for the production of agar and agarose. The aim of this study was to examine the sustainability of the *G. corneum* hand plucking method by comparing natural standing biomass with exploited biomass using landings and biomass data available from the Centro de Experimentación Pesquera in Asturias, Spain.

In order to assess the effect of exploitation on *G. corneum* biomass along the Asturian coastline of the Cantabrian Sea, two research questions were posed. Firstly, the change in *G. corneum* biomass along the coast during the years 1987–2021 was examined in exploited and non-exploited sectors. It was hypothesized that over time, if unsustainable, exploited sectors would show a decrease in total biomass compared to non-exploited sectors. Secondly, the change in *G. corneum* biomass due to summer extraction was assessed. It was hypothesized that the summer *G. corneum* harvest would negatively affect the following seasons standing stocks. The results illustrate the sustainability of the resource in exploited populations, and suggest that the strength of exploitation of *G. corneum* does not severely affect its biomass and distribution along the Asturian coast. In order to accurately assess the sustainability of extractive methods, targeted study and management plans are recommended.

1. Introduction

Gelidium spp. (Rhodophyta) are red algae commercially exploited for the production of bacterial agar and agarose (Melo, 1998). *Gelidium* spp. are highly prized in the agar industry for their consistent gelling strength, electronegative stability and low sulphate percentage (Armisén, 1991; McHugh, 1991). Agar extraction from *Gelidium* spp. originated in Japan in the early 20th century, and expanded into an international commodity in the 1950s, when countries such as Spain, Portugal, Morocco, Mexico and South Korea entered the market (Santos and Melo, 2018). Global *Gelidium* landings peaked at 60,000 t year^{-1} in the 1960s, and maintained those levels until the 1990s, when socio-economic factors shifted the market from a multi-species production to mainly *Gelidium corneum* production (Santos and Melo, 2018). This particular species has been found to produce the highest quality agar (Armisén, 1991; Fernández, 1991). *G. corneum* from Morocco now represents ~82% of production of raw material for the agar industry (Santos and Melo, 2018). However, mismanagement of this natural resource in Morocco and climatic shifts over the past decades have led to worldwide shortages of agar and agarose, with global production decreasing to 25,000 t year^{-1} (Santos and Melo, 2018). Demand for *Gelidium*-based agar and agarose has surpassed global supply in recent decades, with price fluctuations leading to an unstable market (Callaway, 2015). As international *Gelidium* stocks face sustainability problems due to extraction and climate changes, regional assessments must be made in order to maintain the sustainability of the resource.

Gelidium spp. are found along the coast of northern Spain, in the provinces of Asturias, Cantabria, Basque Country and Galicia (Sosa et al., 2006, Fig. 1). The exploitation of *Gelidium* began in the 1940s and peaked in the late 1980s at ~10,000 t year^{-1} (Fernández, 1991). *G. corneum*, commonly known as “ocle” in Asturias, is the main species found and harvested in Spain, producing agar yields of 15–17% (Santos

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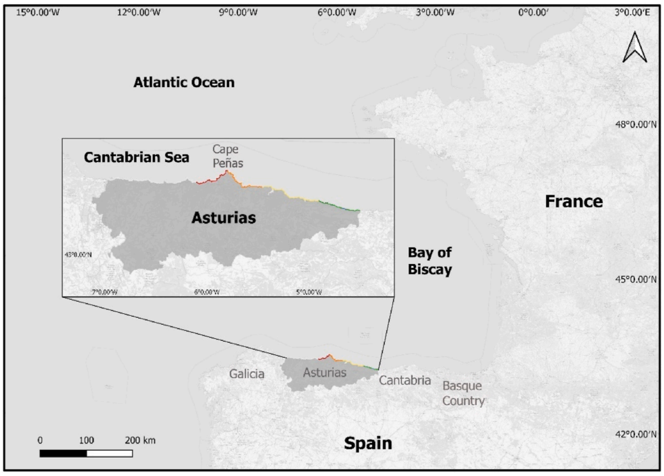


Fig. 1. Map showing the study area of Asturias, in the western Cantabrian Sea. The colored lines along the coastline represent the four harvest zones.

and Melo, 2018). However, climatic shifts in this region can affect *G. corneum* growth because there the species encounters its maximum temperature thresholds (Luning, 1990; Voerman et al., 2013). It has been found that if irradiance exceeds 250 μmol $m^{-2}s^{-1}$ at 22 °C, *G. corneum* photosynthesis is diminished; which can be surpassed in the summer months in the Cantabrian Sea (Torres et al., 1991). Sea surface temperatures in this region have risen 0.1–0.25 °C per decade since the 1980s (Chust et al., 2022). Since the 1990s, a distributional shrinkage of 7% has been observed across the Iberian Peninsula, particularly concentrated in *G. corneum* fields in the easternmost Cantabrian Sea (Casado-Amezúa et al., 2019). Studies along the northern coast of Spain have shown that *G. corneum* cover and biomass has been steadily decreasing in the Basque Country over the past 20 years due to increased wave energy and decreased irradiance throughout the winter-spring growing season (Borja et al., 2018).

The province of Asturias represented 50% of the total Spanish *Gelidium* production in the beginning of the 21st century (Melo, 1998). *Gelidium corneum* is the primary algal species exploited in Asturias, with standing stock estimations of up to ~12,000 t (Llera Gonzalez et al., 1990; Sosa et al., 2006). *G. corneum* can mainly be found to the east of Cape Peñas in large fields typically between 0 and 20 m depth (Fernández, 1991, Fig. 1). A projected 60–70% of total *G. corneum* biomass is lost during the fall-winter storm season in the Cantabrian Sea, and much of that biomass gets washed onto the shore from October to February (Gorostiaga, 1994). During the winter-spring growing season, the *G. corneum* compensates for this massive loss with turnover rates of 150–180%, contributing to its renewability (Borja, 1994a; Gorostiaga, 1994).

G. corneum harvest is performed in Asturias by two methods, hand plucking by divers and cast seaweed collection. The hand plucking method occurs by divers plucking or cutting individual *G. corneum* stalks under the water and bringing them up to the surface (Juanes and Borja, 1991). *G. corneum* production by hand plucking has maintained fairly stable values in the last few years, with total recorded landings of 3843–4426 t from 2017 to 2020, respectively (Centro de Experimentación Pesquera, personal communication, May 10, 2021). This method is practiced in the Cantabrian region as well as in other countries such as Portugal, Mexico and Morocco (Hernández-Guerero et al., 1999; Santos et al., 2003; Givernaud et al., 2005). Cast seaweed collection is a more artisanal method, where individuals collect *G. corneum* that has washed onto the shore after storms with rakes, nets or tractors, to sell in bulk (Sosa et al., 2006). Only 18–35% of *G. corneum* that is detached by storm action is estimated to reach the shore for collection (Borja, 1987). This method is employed in Cantabria and the Basque Country, although in the latter province, collection is performed by boat with the use of suction pumps (Sosa et al., 2006). In Asturias, hand plucking is prevalent in dispersed fields along the entire coastline, and cast collection where the beaches are accessible to equipment (Juanes and Borja, 1991). In both cases, the *G. corneum* is sold as a raw product to processing companies in Spain which produce the agar themselves or export it to other countries such as Japan, South Korea or USA for refinement (Sosa et al., 2006). It is important to note, however, that local regulations regarding collection of cast landing data are not enforced, leading to reporting errors both regionally and internationally (Santos and Melo, 2018).

The Asturian coastline is divided into four harvest sectors which have been discontinuously exploited by cast seaweed collection since exploitation of the resource began in 1945, and hand plucking since 1972 (Ministerio de Comercio, 1955, 1972). The fourth sector, the easternmost part of the Asturian coastline, was closed to hand plucking from 1991 to 2017, while cast seaweed collection has been conducted since 1945 (Principado de Asturias, 2017). *G. corneum* fields across all sectors have been mapped at various times in the past decades, with 2017 being the most recent (Fig. 2). Harvest strength by hand plucking in each sector has been recorded using GPS systems since 2017, allowing for more accurate data collection on extraction effects. Total yield by hand plucking has fluctuated across all sectors since 1972, so these GPS data allow the fisheries agency, the Centro de Experimentación Pesquera, to identify precisely where exploitation occurs most (Ministerio de Comercio, 1972). It has been shown that limited exploitation by hand plucking or cutting methods allows *G. corneum* to regenerate within one year, allowing for a sustainable harvest (Borja, 1994a). In exploited areas in the Basque Country, production and turnover rates were found to be 1.4 and 2.5x higher than non-exploited areas, respectively, in less than one year (Borja, 1994a).

The main objectives of this study were to analyze the effects of the hand plucking extraction method on the biomass of *G. corneum* along the Asturian coast. Firstly, the change in *G. corneum* biomass along the coast during the years 1987–2021 was examined in exploited and non-exploited sectors. It was hypothesized that over time, if unsustainable, exploited sectors would show a decrease in total biomass compared to non-exploited sectors. Secondly, the change in *G. corneum* biomass due to summer extraction was assessed. It was hypothesized that the summer *G. corneum* harvest would negatively affect the following quarters' biomass. Long-term studies such as these are able to reveal historical trends in the data to assess actual exploitation effects on *G. corneum* biomass. A deeper understanding of *G. corneum* in the Asturian province and how it is affected by consistent exploitation is vital to the management and sustainability of this resource.

2. Materials and methods

2.1. Study area

The Asturian coast is located along the western Cantabrian Sea, between 43° 20′–40′N latitude and 7° 2′/4° 30′W longitude, in the southwestern part of the Bay of Biscay (Domínguez-Cuesta et al., 2018). This 570 km coastline is mainly characterized by rocky intertidal shores and wave heights between 2 and 7 m (Domínguez-Cuesta et al., 2018). Here, oceanographical conditions form a transitional zone, where colder, nutrient-dense water from the Atlantic Ocean meets warmer water from the eastern Bay of Biscay (Sosa et al., 2006). Sea surface temperature (SST) ranges from 11 to 23 °C, generating a temperature limit for *G. corneum* growing conditions (Quintano et al., 2013). The majority of *G. corneum* found along the Asturian coast can be found east of Cape Peñas, typically in the sublittoral zone between 0 and 20 m depth (Fernández, 1991). The study area consists of a 150 km range between western Cape Peñas and the Asturias-Cantabria border in the east (Fig. 1).

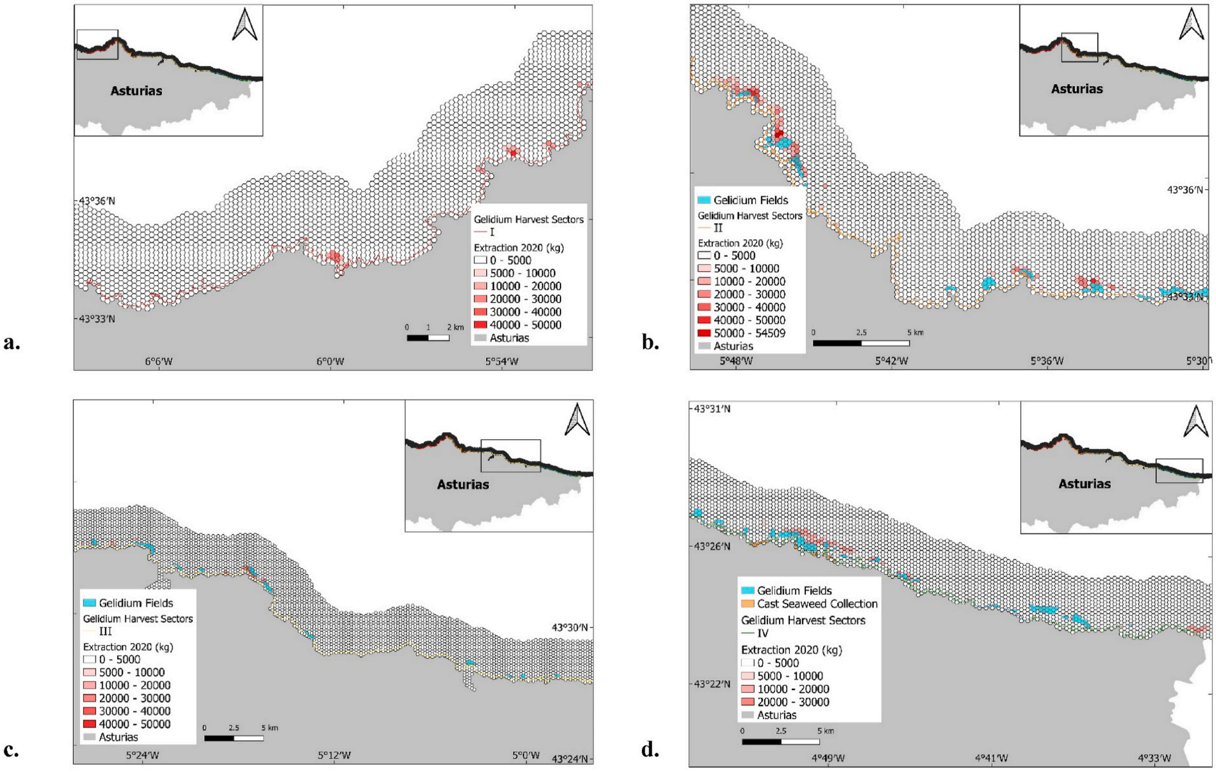


Fig. 2. (a) GIS rendering showing sector I on the Asturian coast, strength of 2020 harvest and mapped *G. corneum* fields from 2017. (b) GIS rendering showing sector II. (c) GIS rendering showing sector III. (d) GIS rendering showing sector IV.

2.2. Environmental variables

G. corneum growth is affected by several known factors including SST, light availability, depth, nutrients and wave exposure (Díez et al., 2012; Borja et al., 2018). *G. corneum* is relatively sensitive to temperature, with productivity decreases shown above temperatures of 20 °C (Rico and Fredriksen, 1996). From 1982 to 2012, SST along the northern Spanish coast has shown a significant increase in the number of days above 20 °C, shifting certain algal distributions westward, towards cooler summer temperatures (Voerman et al., 2013). Decreased irradiance has been noted along the Basque coast over the past 20 years, which could cause a shift in *G. corneum* depth distribution in the next few decades (Borja et al., 2018). It has been suggested that *G. corneum* frond size increases with depth to increase light harvesting efficiency (Quintano et al., 2018). *G. corneum* cover has been found to increase in areas with higher nutrient supply, which coincides with its occurrence mainly in areas of strong wave exposure (Miguel-Vijandi et al., 2010). Wave heights of at least 5 m have been found to be the threshold for *G. corneum* frond detachment during winter storms, while allowing regrowth to previous biomass levels within one year (Borja, 1994b). However, increased wave regimes in the Bay of Biscay since 2006 are believed to have lowered the *G. corneum's* ability to regrow to its previous biomass each spring in the region (Borja et al., 2018). Clearly, a combination of natural and anthropogenic factors contributes to *G. corneum* biomass, but while natural processes have been the focus of many *G. corneum* studies along the northern coast of Spain, anthropogenic effects are less studied (Borja et al., 2013).

2.3. Sampling

Sampling for *G. corneum* took place from 2017 to 2021 on a quarterly basis by the Centro de Experimentación Pesquera (Gobierno del Principado de Asturias, 2018). Algal samples were taken from exploited and non-exploited fields along the entire study area, spanning 48 fields in total. To generate higher sampling precision, 5-ha hexagons were used as spatial distribution units along the entire coastline, yielding a total of 157 sampled hexagons, or sites (Fig. 3). At each site, teams of professional divers placed 40 × 40 cm quadrats in spots where there was representative algal coverage of the surrounding area to yield three replicates. Because calculations were carried out by weight/area, it was not necessary to know the exact coverage percentage per quadrat. All of the algae within each quadrat were hand plucked, regardless of the species. Individuals were plucked at the root and placed into separate bags by replicate. Samples were either processed fresh the following day, or frozen at −20 °C until processing. In the laboratory, the samples

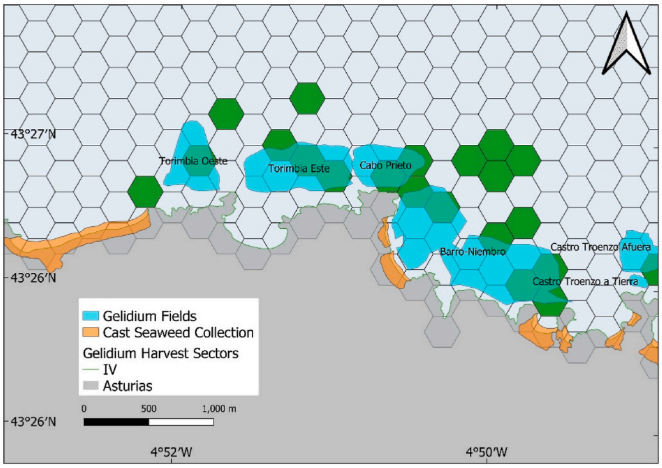


Fig. 3. GIS rendering depicting sampling effort by hexagon in a section of sector IV from 2017 to 2020 (green hexagons). Mapped *G. corneum* fields (2017) are shown in blue with their respective names. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

were examined by first weighing each replicate separately after centrifuging out the seawater for 5 min. The coordinates, depth, time taken and temperature of each replicate were noted as well. All of the epiphytes and accompanying algae species within each replicate were then separated and weighed individually. These data were used to calculate the proportion of each species per replicate. Biomass was calculated from the wet weight of each sample in units of g m^{-2}. The sampling methods used in this study followed those of Llera Gonzalez et al. (1990), in order to create a consistent sampling protocol from 1987 to 2021. Because historical hand plucking data from 1987 to 2016 used *G. corneum* fields rather than hexagonal units as sampling sites, the following results will therefore refer to *G. corneum* fields for spatial units when comparing data from 1987 to 2021, while referring to hexagons for spatial units when comparing data from 2017 to 2021.

2.4. Statistical analysis

The hand plucking data from 2017 to 2021 was entered into Microsoft Access databases and later combined into Microsoft Excel files which contained historical data from 1987 to 2016, in order to accurately analyze both datasets. A total of 762 observations from 2017 to 2021 were combined with 2499 observations from 1987 to 2016, yielding 3261 replicates over the entire period. One-way ANOVA tests were performed to determine if yearly *G. corneum* biomass changes were general or sector-dependent. Beginning in 2017, during the hand plucking harvest season each year, daily extraction values (kg) and GPS data were obtained from each boat to identify the exact harvest strength and location within each 5-ha hexagon. Simple linear regression analyses were calculated to determine the effect of summer extraction on the following *G. corneum* biomass per quarter, until the next harvest season.

3. Results

3.1. Biomass changes between exploited and non-exploited sectors from 1987 to 2021

A time series of *G. corneum* biomass from 1987 to 2021 was graphed for exploited and non-exploited sectors. Sectors I–III have been continuously harvested by hand plucking during all sampling years, and each sector has shown fairly consistent biomass over time and among sectors (Fig. 4). Data points are shown from quarters 1 and 3 (including the month of June), to depict the maximum and minimum biomass values each year. Sector IV began to be exploited by hand plucking in 2017, however *G. corneum* biomass did not show noteworthy changes after that point (Fig. 5). The one-way ANOVA test comparing sector IV biomass before and after exploitation began showed no significance at the $p < .05$ level between years ($F(1, 90) = 0.04$, $p = .84$). A one-way ANOVA test was performed to compare the changes in biomass over the years between all sectors. There was no significant effect of exploitation on *G. corneum* biomass over time at the $p < .05$ level between sectors ($F(3, 511) = 1.79$, $p = .15$). *G. corneum* minimum and maximum standing stocks by sector were calculated from 1987 to 2021 (Table 1). The range of values was calculated using the first and last years' values that were sampled per sector. Again, minimum values correlate with quarter 1 and maximum values correlate with quarter 3 of each year. It must be noted that the first sampling years are different according to sector and quarter, presumably due to varying sampling efforts by the agency in that time frame. Over the entire time period, minimum standing stock for sectors I, II and IV increased 227.3, 117.8 and 416.4 g m^{-2}, respectively. Minimum standing stock for sector III decreased 203.5 g m^{-2} during this time frame. The ranges of maximum standing stock values varied much more over time, with sectors I and II increasing by 958.8 and 7.4 g m^{-2}, respectively, and sectors III and IV decreasing by 470.0 and 652.2 g m^{-2}, respectively.

3.2. Effect of quarter 3 extraction on following quarters' biomass from 2017 to 2021

Simple linear regressions were calculated to describe *G. corneum* biomass based on extraction strength from 2017 to 2020 (Fig. 6). *G. corneum* biomass per hexagon (kg) was plotted against extraction per hexagon (kg) to determine how extraction affected quarterly changes in biomass each year. Extraction occurs during quarter 3 each year. A significant regression equation was found for the following quarter 4 ($F(1, 31) = 16.51$, $p = .0003$), with an $R^2 = 0.347$. Predicted quarter 4 biomass per hexagon is 79, 300, 000–1041.7(extraction) grams. *G. corneum* biomass in quarter 4 decreased 1041.7 kg per kilogram extracted in quarter 3. A significant regression equation was also found for the next year's quarter 1 ($F(1, 36) = 4.15$, $p = .049$), with an $R^2 = 0.104$. Predicted quarter 1 biomass per hexagon is 55, 600, 000–370.1 (extraction) grams. *G. corneum* biomass in quarter 1 decreased 370.1 kg per kilogram extracted in quarter 3. *G. corneum* harvest effects on the following years' biomass in quarters 2 and 3 did not produce significant relationships. Further analyses were performed for each extraction year, to illustrate the effects on *G. corneum* biomass in the following quarters from individual harvests. The slope values for each regression are shown in Table 2. *G. corneum* biomass in the following quarters 4 and 1 showed a negative relationship with extraction for all sampled years. However, extraction showed a positive relationship with *G. corneum* biomass every year by quarter 3, and by quarter 2 in 2019, indicating full biomass recovery in each sampled year.

4. Discussion

4.1. Exploitation effects on Gelidium corneum biomass

The results from this study illustrate that *G. corneum* biomass along the Asturian coast has maintained stable levels from 1987 to the present, among all harvest sectors, regardless of exploitation strength. It was

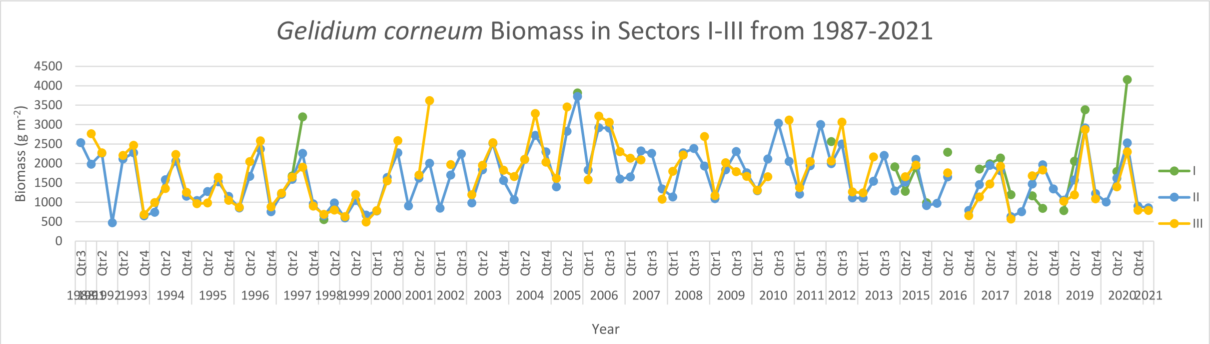


Fig. 4. Time series data showing *G. corneum* biomass in sectors I–III from 1987 to 2021.

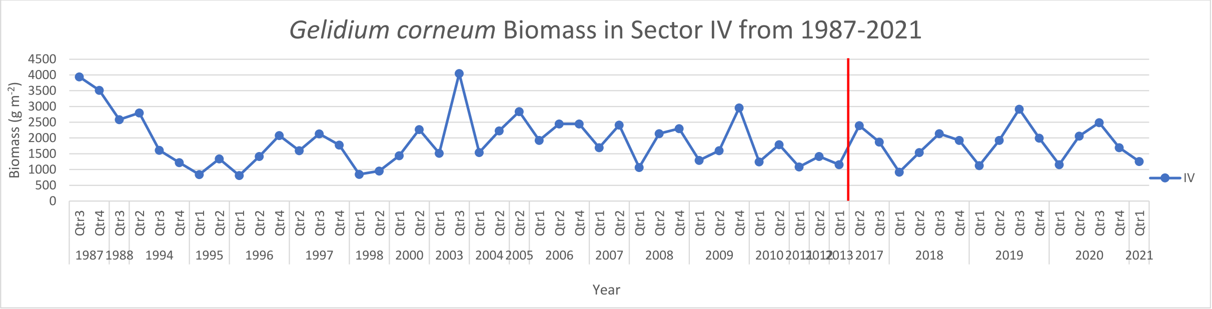


Fig. 5. Time series data showing *G. corneum* biomass in sector IV from 1987 to 2021. (Red vertical line represents when hand plucking exploitation began in sector IV: 2017). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Minimum and maximum standing stock values from 1987 to 2021 by sector.

Sector	Minimum (g m^{-2})	Year	Maximum (g m^{-2})	Year
I	556.2–783.5	1998–2019	3197.5–4156.3	1997–2020
II	740.8–858.3	1994–2021	2535.1–2527.7	1998–2020
III	992.3–788.8	1994–2021	2766.3–2296.3	1991–2020
IV	838.7–1255.1	1995–2021	3138.4–2486.2	1987–2020

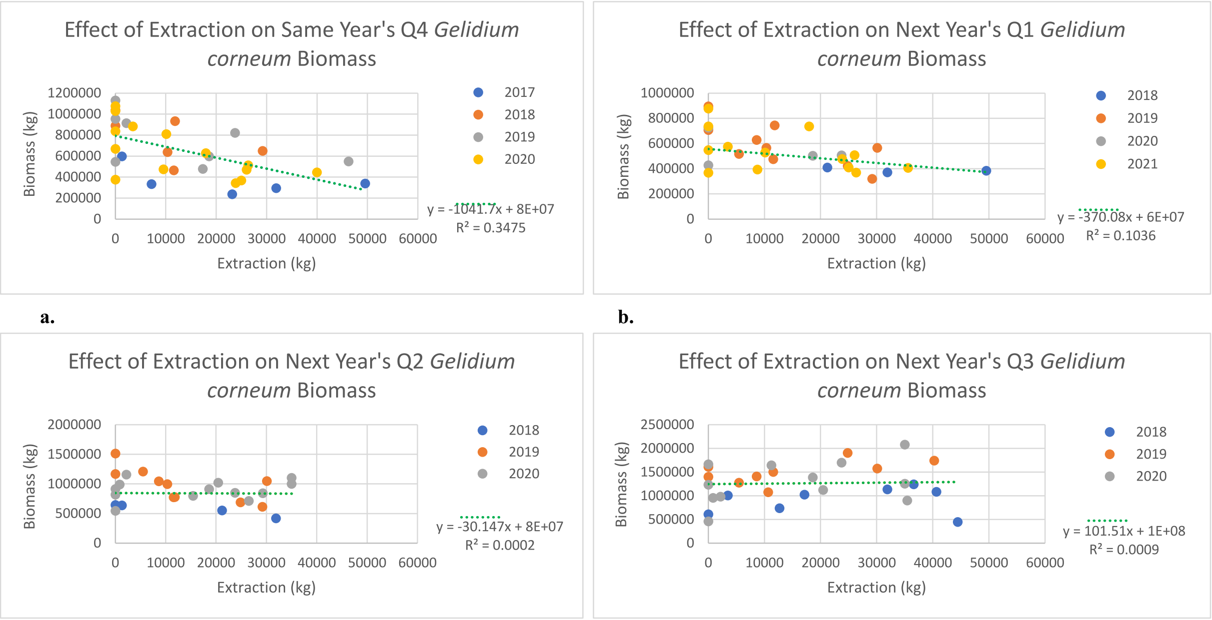
Note: Minimum values were taken in quarter 1 of the corresponding year range and maximum values were taken in quarter 3 of the corresponding year range.

hypothesized that lower *G. corneum* biomass would be found in exploited sectors than non-exploited sectors, but results show that biomass among all sectors is non-distinguishable over the study period (Figs. 4 and 5). As well, the start of exploitation in sector IV in 2017 did not significantly affect biomass values in the following years. The lack of significant differences among per-sector biomass values indicates that the current harvest strength by hand plucking is sustainable. Fluctuations in winter to summer biomass are shown to be consistent among years and sectors from 2017 to 2021, indicating full biomass recovery each year. While the negative relationship between quarter 3 extraction and the following quarters 4 and 1 biomass showed significance ($p = .0003$, $p = .049$), the biomass recovery in the following two quarters before the next year's harvest makes up for these losses (Fig. 6). These data are consistent with the literature, which notes that 3–4 months after exploitation is the most important period for *G. corneum* biomass recovery (Borja, 1994a). *G. corneum* biomass increases have been shown to continue until October even after July exploitation, aiding the growth process before the winter-spring reproductive season, thus recovering full biomass losses after one year (Juanes and Borja, 1991). Notably, September exploitation has been found to give less time for biomass recovery, yielding a two-year gap until full biomass was recovered (Juanes and Borja, 1991). While the *G. corneum* harvest season in Asturias runs from July 1-September 30, typically the quotas assigned to

Table 2
Effect of extraction on Gelidium corneum biomass from 2017 to 2021.

Extraction Year	Q4	Q1	Q2	Q3
2017	−393.4	−73.2	−649.0	+279.2
2018	−1114.0	−1057.7	−1705.1	+1002.7
2019	−774.3	−334.6	+221.6	+1052.3
2020	−1215.1	−590.2		

Note: Numbers indicate individual slope values for the regression analysis of effects of extraction each year on the following quarters' biomass. Extraction takes place in quarter 3 each year.



a. b. c. d.

Fig. 6. (a) Scatter plot depicting the regression between quarter 3 exploitation and the following quarter 4 *G. corneum* biomass. (b) Regression between quarter 3 exploitation and the following quarter 1 *G. corneum* biomass. (c) Regression between quarter 3 exploitation and the following quarter 2 *G. corneum* biomass. (d) Regression between quarter 3 exploitation and the following quarter 3 *G. corneum* biomass.

each sector are reached before the final date; for example, in the 2020 season, September 9 was the final harvest day (Peón Torre, 2020). Furthermore, regulations stating that *G. corneum* cannot be harvested in areas where cover is less than 70% and that divers must leave at least 25% of the initial biomass found after plucking contribute to the *G. corneum's* ability to recover each year (Peón Torre, 2020).

In the eastern Cantabrian Sea, natural *G. corneum* biomass losses by mid-autumn have been shown to be 40–60%, increasing to 60–70% by winter (Gorostiaga, 1994). In turn, G. corneum biomass grew 15% by the springtime (compared to winter biomass) and full biomass recovery was found by the summer season (Gorostiaga, 1994). The results from this study show that biomass losses per quarter after 2017–2020 exploitation also yield negative slopes, while recovery occurs by the summer in each study year (Table 2). Furthermore, maximum standing stock values per sector from 1987 to 2020 are relatively consistent, indicating that exploited sectors are able to recover biomass just as efficiently as non-exploited sectors (Table 1).

Hand plucking has been shown to be a sustainable exploitation method in a previous study, where *G. corneum* biomass was able to recover to 153% of its original biomass in 2 years, when cut 8 cm from the base (Gorostiaga, 1990). Also, the methodology proposed by expert assessment demonstrates that hand plucking scores well in a sustainability scale, especially when compared to cast-collecting (APROMAR, 2017; Pérez del Molino, 2017). More severe methods of intensive plucking and intensive cutting (2 cm from the base), were found to allow *G. corneum* biomass recovery of 115% and 110%, respectively, after 2 years (Gorostiaga, 1990). It has been theorized that because divers using the hand plucking method typically select for larger fronds (above ~10 cm) and leave smaller fronds that may become fertile during the reproductive season, this allows exploited *G. corneum* fields to more easily recover (Juanes and Borja, 1991). The results of this study indicate that exploitation by hand plucking in Asturias has allowed *G. corneum* biomass to recover consistently over an extended time period. It is important to note, however, that *G. corneum* resilience to climate change has been negatively correlated with extraction in the eastern Cantabrian (Borja et al., 2013). Because *G. corneum* fields meet their upper temperature threshold in this region, its ability to adapt to natural and anthropogenic pressures are lowered (Gorostiaga, 1994; Borja et al., 2013). Based on these results, the current and historical strength of hand plucking in each sector has maintained the biomass of *G. corneum* populations in Asturias, but future resilience in the face of climate change is yet unknown.

4.2. *Recommendations for management*

With regards to hand plucking, policies such as total and per-sector quotas, minimum coverages in harvest spots and yearly biomass assessments have aided in the successful management of this exploitation method and its sustainability long-term Llera Gonzalez et al., 1990; Peón Torre, 2020). However, it must be noted that the current maps that the fisheries agency uses to designate *G. corneum* fields are not necessarily accurate, based on GPS data of where divers harvest underwater. When georeferencing the divers' coordinates to the distributional hexagons along the coast, it is apparent that harvesting occurs outside of the *G. corneum* fields that have been mapped to varying capacities in 1990 and 2017 (Llera Gonzalez et al., 1990; Gobierno del Principado de Asturias, 2017). Not only can this cause issues when creating harvest quotas because the full area of *G. corneum* fields in each sector is unmapped, but it makes any study of environmental variable effects not possible, because current field distribution and depth data is not precise. The lack of exact depth data could be a cause for management concern because it has been found that *G. corneum* detachment decreases with increasing depth, with losses from 80% to 64% from 0 to 5 m and 10–15 m depths, respectively (Borja, 1987). If there have been any distributional shifts in the *G. corneum* population along the Asturian coast, such as is the case with other macroalgal species in the region, shifts towards deeper depths could have an effect on both exploitation methods (Casado-Amezúa et al., 2019; Ramos et al., 2020). Priority should be placed within the fisheries agency on creating updated maps of all *G. corneum* fields within each sector. Macroalgal distribution has been mapped off the coast of Cantabria in recent years, increasing ecological knowledge of the subtidal communities, particularly those of *G. corneum*, in that region (Guinda et al., 2012). Utilizing those same techniques would greatly enhance knowledge of *G. corneum* coverage at varying locations and depths along the Asturian coast, as well as knowledge of other accompanying algal species. A secondary recommendation would be to use the depth records from each boat, which state the depth at which they harvested when they declare their *G. corneum* landings each day at the port, to create updated bathymetric maps using each hexagon that is exploited. In this way, the fisheries agency could analyze the exploitation strength of *G. corneum* by depth as well as identify any distributional changes over time.

While not assessed in this study, cast collection data is a large information gap concerning *G. corneum* exploitation in Asturias. With no regional policies regarding total and per-sector cast collection quotas, nor for reporting of harvest data, knowledge about this method is poor. The most obvious concern is the lack of landing data, which makes total exploitation statistics for the region inaccurate (Peón Torre, 2020). This problem is amplified into inaccurate international reports by entities such as the FAO (Santos and Melo, 2018; Araujo et al., 2021). Efforts have been made to estimate cast data from 2013 to 2017 through interviews with processing companies in Spain, with 2700–4200 t reported, but enforcement of regulations would make data collection much more accurate (Centro de Experimentación Pesquera, personal communication, May 10, 2021). Proper data on cast collection yields will allow the fisheries agency to accurately examine all *G. corneum* exploitation in Asturias, as well as avoid conflicts between both harvesting groups. At present, cast collectors believe that summer hand plucking decreases winter cast yields due to biomass decreases leading to less displaced *G. corneum*. However, this conflict cannot be rectified, because without accurate cast landing data, no comparative analysis can be performed, as shown by this study. Furthermore, no examination of which shorelines receive displaced *G. corneum* from which fields has been performed, so again, direct analyses are not possible at this time. Because cast seaweed washing onto the shore holds an important ecological role in beach habitats, further investigation on its contribution to the Asturian coastline is imperative (Zemke-White et al., 2005). Environmental analyses such as these can only improve the efficacy of *G. corneum* management in Asturias, while also ensuring that both exploitation methods are truly sustainable.

5. Conclusions

Based on the results of this study, the level of hand plucking in Asturias has maintained *G. corneum* biomass over the time period of exploitation. Long-term biomass fluctuations from extraction have been shown to be insignificant among and within harvest sectors. Exploited and non-exploited areas are both able to recover their biomass within one year, regardless of varying harvest strength. While summer exploitation does negatively affect the following fall-winter biomass, spring-summer recovery before the next harvest season has been shown to be consistent. Additional study in Asturias regarding the effects of other environmental variables, such as depth, nutrients and light availability on *G. corneum* biomass could be useful for future management. Lastly, from this study alone, comprehensive statements on current *G. corneum* exploitation in Asturias cannot be made, due to the lack of data regarding an entire exploitation method: cast collection. Recommendations to improve regional knowledge include updated bathymetric maps of *G. corneum* fields in each sector, enforcement of cast collection regulations for reporting purposes and further investigation regarding cast seaweed ecology. The results shown by this study will hopefully serve as a stepping stone to further ecological research and management techniques regarding *G. corneum* along the Asturian coast. Deeper understanding of all aspects of *G. corneum* ecology and subsequent exploitation will allow the resource to be effectively and sustainably managed in Asturias.

CRediT authorship contribution statement

Jaclyn Higgins: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Paloma Peon Torre:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Jose M. Rico:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

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