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Analysis of ocle (*Gelidium corneum*) extraction along the Asturian coast and its influence on the sustainability of the resource

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Abstract

The exploitation of ocle (*Gelidium corneum*) along the Asturian coast has an important economic and cultural component. Through the extraction methods of hand plucking underwater and collection of cast seaweed, the ocle 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 *Gelidium corneum* hand plucking by comparing natural standing biomass with exploited biomass using landings and biomass data available from the Centro de Experimentación Pesquera in Asturias.

In order to assess the effect of exploitation on ocle biomass along the Asturian coastline, three research questions were posed. Firstly, the change in ocle 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 ocle biomass due to summer extraction was assessed. It was hypothesized that the summer ocle harvest would negatively affect the following quarters' biomass. Thirdly, the change in sea surface temperature (SST) during the sampling period was compared against ocle biomass changes. It was hypothesized that increased SST, as a proxy for environmental change, could have an effect separated from exploitation. The results illustrate the maintenance of the resource in exploited populations, and suggest that the strength and method of exploitation of ocle affects its biomass and distribution along the Asturian coastline. In order to accurately assess the sustainability of extractive methods, targeted study and management plans regarding each technique are recommended.

Keywords: Algae, Exploitation, Seaweeds, Seaweed harvesting, Biomass, Landing statistics

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, as countries such as Spain, Portugal, Morocco, Mexico and South Korea entered the market (Santos & Melo, 2018). Global *Gelidium* landings peaked at 60,000 t year^{-1} in the 1960s, and maintained those levels until the 1990s, when socioeconomic factors shifted the market from a multi-species production to mainly *Gelidium corneum* production (ibid). This particular species has been found to produce the highest quality agar, due to low sulphate contents (Armisén, 1991; Fernández, 1991). *Gelidium corneum* from Morocco now represents ~82% of production of raw material for the agar industry (Santos & 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} (ibid). Demand for *Gelidium*-based bacterial agar and agarose has increased in recent decades, however, from 250 and 15 t to 700 and 50 t, respectively (Santos, 1993). 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, Pinchetti & Juanes, 2006). The exploitation of *Gelidium* began in the 1940s and peaked in the late 1980s at ~10,000 t year^{-1} (Fernández, 1991). *Gelidium corneum*, commonly known as "ocle" in Asturias, is the main species found and harvested in Spain, producing agar yields of 15-17% (Santos & Melo, 2018). *Gelidium corneum* from Spain have been described to yield the highest quality agarose, due to the water conditions where they grow, leading to low sulphate content and high gel strength (J. M. Rico, pers. comm). However, climatic shifts in this region can affect *Gelidium corneum* growth because there the species lies at its northern physiological limit (Luning, 1990; Voerman, Llera & Rico, 2013). It has been found that if irradiance exceeds 250 µmol m^{-2}s^{-1} at 22ºC, ocle photosynthesis is diminished; which can be surpassed in the summer months in the Cantabrian Sea (Torres, Niell

& Algarra, 1991). Sea surface temperatures in this region have risen 0.3-0.8ºC per decade since the 1950s (Lima & Wethey, 2012). Since the 1990s, a distributional contraction of 7% has been observed across the Iberian Peninsula, particularly concentrated in ocle fields in the easternmost Cantabrian Sea (Casado-Amezúa et al., 2019). Studies along the northern coast of Spain have shown that ocle 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 the area, with standing stock estimations of up to ~12,000 t (Llera et al., 1990; Sosa, Pinchetti & Juanes, 2006). Ocle production by hand plucking has maintained fairly stable values in the last few years, with total recorded landings of 3,843-4,426 t from 2017-2020, respectively (CEP, unpublished data). The ocle can mainly be found to the east of Cape Peñas in large fields typically between 0-20 m depth (Fernández, 1991). A projected 60-70% of total ocle 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 ocle compensates for this massive loss with turnover rates of 150-180%, contributing to its renewability (Borja, 1994a; Gorostiaga, 1994).

Ocle 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 ocle stalks under the water and bringing them up to the surface (Juanes & Borja, 1991). This method is practiced in the Cantabrian region as well as in other countries such as Portugal, Mexico and Morocco (Hernández-Guerero, Casas Valdez, & Ortega-Garcia, 1999; Santos, Cristo & Jesus, 2003; Givernaud et al., 2005). Cast seaweed collection is a more artisanal method, where individuals collect ocle that has washed onto the shore after storms with rakes, nets or tractors, to sell in bulk (Sosa, Pinchetti & Juanes, 2006). Only 18-35% of ocle 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, Pinchetti & Juanes, 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 & Borja, 1991). In both cases, the ocle is sold as a raw product to processing companies in Spain who create the agar themselves or ship it to other countries such as Japan, South Korea or USA for refinement (Sosa, Pinchetti & Juanes, 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 & Melo, 2018).

The 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 1991-2017, while cast seaweed collection has been conducted since 1945 (Principado de Asturias, 2017). Ocle fields across all sectors have been mapped at various times in the past decades, with 2017 being the most recent (Figure 1). 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 capture by hand plucking has fluctuated across all sectors since 1972, so this GPS data allows 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 ocle 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 (ibid).

The main objectives of this study were to analyze the effects of the hand plucking extraction method on the biomass of *Gelidium corneum* along the Asturian coast. Firstly, the change in ocle 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 ocle biomass due to summer extraction was assessed. It was hypothesized that the summer ocle harvest would negatively affect the following quarters' biomass. Thirdly, the change in sea surface temperature (SST) during the sampling period was compared against ocle biomass changes. It was hypothesized that increased SST, as a proxy for environmental change, could have an effect separated from exploitation. Long-term studies such as these are able to reveal historical trends in the data to assess actual exploitation effects on ocle biomass. A deeper understanding of *Gelidium 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 2-7 m (ibid). Here, conditions form a transitional zone, where colder, nutrient-dense water from the Atlantic Ocean meets warmer water from the eastern Bay of Biscay (Sosa, Pinchetti & Juanes, 2006). Sea surface temperatures range from 11-23ºC, generating a northern limit for *Gelidium corneum* growing conditions (Quintano et al., 2013). The majority of ocle found along the Asturian coast can be found east of Cape Peñas, typically in the sublittoral zone between 0-20 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 (Figure 2).

2.2 Environmental variables

Gelidium corneum growth is affected by several known factors including sea surface temperature (SST), light availability, depth, nutrients and wave exposure (Díez et al., 2012; Borja et al., 2018). The ocle is relatively sensitive to temperature, with decreases in productivity shown past temperatures of 20ºC (Rico & Fredriksen, 1996). From 1982-2012, SST along the northern Spanish coast has shown a significant increase in the number of days above 20ºC, shifting certain algal distributions westward, towards cooler summer temperatures (Voerman, Llera & Rico, 2013). Decreased irradiance has been noted along the Basque coast over the past 20 years, which could cause a shift in ocle depth distribution in the next few decades (Borja et al., 2018). It has been suggested that ocle frond size increases with depth to increase light harvesting efficiency (Quintano et al., 2018). Ocle cover has been found to increase in areas with higher nutrient supply, which coincides with its occurrence mainly in areas of strong upwelling

(Miguel-Vijandi et al., 2010). Depleted nitrate availability in certain parts of the eastern Cantabrian Sea has been suggested as a factor in the decreased ocle density in that region (Díez et al., 2012). In addition, the ocle is found primarily in regions with high wave exposure. Wave heights of at least 5 m have been found to be the threshold for ocle 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 ocle'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 ocle biomass, but while natural processes have been the focus of several *Gelidium corneum* studies along the northern coast of Spain, anthropogenic effects are less studied. In order to compare human exploitation and environmental variabilities as factors affecting ocle biomass, SST was investigated as a potential variable that could contribute to noteworthy biomass changes over time via natural processes. This variable was chosen due to the availability of long-term data which overlapped with the study sampling period, making comparisons between SST and exploitation effects reasonable.

2.3 Sampling

Sampling for *Gelidium corneum* took place from 2017-2021 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-hectare hexagons were used as spatial distribution units along the entire coastline, yielding a total of 157 sampled hexagons, or sites (Figure 3). At each site, teams of professional divers placed 40x40 cm quadrats where there was 100% algal coverage to yield three replicates. 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 were examined by first weighing each replicate separately after centrifuging out the seawater for five minutes. 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. This data was 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 et al., in order to create a consistent sampling protocol from 1987-2021 (1990). Because historical hand plucking data from 1987-2016 used ocle fields rather than hexagonal units as sampling sites, the following results will therefore refer to ocle fields for spatial units when comparing data from 1987-2021, while referring to hexagons for spatial units when comparing data from 2017-2021.

2.4 Statistical analysis

The hand plucking data from 2017-2021 was entered into Microsoft Access databases and later combined into Microsoft Excel files which contained historical data from 1987-2016, in order to accurately analyze both datasets. A total of 762 observations from 2017-2021 were combined with 2,499 observations from 1987-2016, yielding 3,261 replicates over the entire period. One-way ANOVA tests were performed to determine if yearly ocle 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 procured from each boat to identify the exact harvest strength and location within each 5-hectare hexagon. Simple linear regression analyses were calculated to determine the effect of summer extraction on the following ocle biomass per quarter, until the next harvest season. SST data from eastern Asturias was procured and plotted against the biomass data for the sampling period to determine if this natural variable could be correlated with biomass values (OMA, unpublished data).

3. Results

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

A time series of ocle biomass from 1987-2021 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 (Figure 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 ocle biomass did not show noteworthy changes after that point (Figure 5). The one-way ANOVA test comparing sector IV biomass before and after exploitation began showed no significance at the $p < 0.05$ 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 ocle biomass over time at the $p < 0.05$ level between sectors ($F(3, 511) = 1.79$, $p = .15$). Ocle minimum and maximum standing stocks by sector were calculated from 1987-2021 (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 2017-2021

Simple linear regressions were calculated to describe ocle biomass based on extraction strength from 2017-2020 (Figure 6). Ocle biomass per hexagon (kg) was plotted against extraction per hexagon (kg) to determine how extraction effected 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. Ocle 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. Ocle biomass in quarter 1 decreased 370.1 kg per kilogram extracted in quarter 3. Ocle 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 ocle biomass in the following quarters from individual harvests. The slope values for each regression are shown in Table 2. Ocle 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 ocle biomass every year by quarter 3, and by quarter 2 in 2019, indicating full biomass recovery in each sampled year.

3.3 Biomass changes versus sea surface temperature (SST) from 1997-2019

Sea surface temperature data from the La Franca area of eastern Asturias was used for comparison, and morning and evening values from 1997-2019 were averaged to create one temperature per day during the entire period (OMA, unpublished data). The previous time series data regarding ocle biomass per sector was plotted against average SST values to compare the fluctuations between both variables and among sectors (Figure 7). Biomass fluctuations for each sector closely followed the pattern of SST fluctuations for the entire period. However, after regression analysis, there was no significant relationship between maximum SST and maximum biomass in the following year ($F(1, 19) = 106.8$, $p = .43$), with an $R^2 = 0.033$. Predicted maximum biomass across all sectors is 1827.98+106.8(temperature) g m^{-2} when SST is measured in ºC. Maximum ocle biomass increased 106.8 g m^{-2} in the following year per degree rise in SST in the previous year.

4. Discussion

4.1 Exploitation effects on ocle biomass

The results from this study illustrate that *Gelidium 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 hypothesized that lower ocle 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 (Figures 4 & 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 2017-2021, 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 (Figure 6). These data are consistent with the literature, which notes that 3-4 months after exploitation is the most important period for ocle biomass recovery (Borja, 1994a). Ocle 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 & 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 (ibid). While the ocle harvest season in Asturias runs from July 1-September 30, typically the quotas assigned to 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 ocle 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 ocle's ability to recover each year (ibid).

In the eastern Cantabrian Sea, natural ocle biomass losses by mid-autumn have been shown to be 40-60%, increasing to 60-70% by winter (Gorostiaga, 1994). In turn, ocle biomass grew 15% by the springtime (compared to winter biomass) and full biomass recovery was found by the summer season (ibid). 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 1987-2020 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 ocle biomass was able to recover to 153% of its original biomass in 2 years, when cut 8 cm from the base (Gorostiaga, 1990). More severe methods of intensive plucking and intensive cutting (2 cm from the base), were found to allow ocle biomass recovery of 115% and 110%, respectively, after 2 years (ibid). 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 ocle fields to more easily recover (Juanes & Borja, 1991). The results of this study indicate that exploitation by hand plucking in Asturias has allowed ocle biomass to recover consistently over an extended time period. It is important to note, however, that ocle resilience to climate change has been negatively correlated with extraction in the eastern Cantabrian (Borja et al., 2013). Because the ocle resides at its northern limit 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 ocle populations in Asturias, but future resilience in the face of climate change is yet unknown.

4.2 Relationship between SST and ocle biomass

The results show that while there is a clear trend of biomass fluctuations following SST fluctuations from 1997-2019, these factors are not directly correlated (Figure 7). No significance was found in the relationship between maximum SST in the eastern Cantabrian Sea and maximum ocle biomass in the following year. While contrary to the original hypothesis that SST would show a separated effect from biomass, these data do agree with the literature. Algal biomass decreases and distributional shifts have been shown to be directly caused by an excess and higher frequency of extreme temperatures across northern Spain (Voerman, Llera & Rico, 2013; Casado-Amezúa et al., 2019). However, in the case of *Gelidium corneum*, study has shown that wave action and light availability could explain more variability in biomass (Borja et al., 2013; 2018). From 2006-2016, a 41% increase in the frequency of waves over 5 m, which mark the ocle's typical detachment threshold, coincided with a 45% decrease in ocle biomass in the southeastern Bay of Biscay (Borja et al., 2018). Regression models combining decreased irradiance with such wave increases accounted for 37% of the variability (ibid). Irradiance has been shown to have conflicting effects on algal biomass, because although increased light availability has a positive relationship with productivity, too much light can result in photodamage and mortality of algae fronds (Díez et al., 2012; Quintano et al., 2017). The positive or negative effects of irradiance appear to be a function of the depth at which the ocle is found; with shallower fields exhibiting higher photodamage and deeper fields exhibiting enhanced light-harvesting techniques (Quintano et al., 2017; 2018). Study of the depth distribution of mapped ocle fields over time would be a potential way to identify which of these environmental factors contributes the most to biomass variability among Asturian fields. In addition, other environmental data such as nutrient and light availability could be recorded to assess their role in ocle sustainability along the Asturian coast. It is likely, however, that a combination of these natural factors with anthropogenic factors is more relevant to yearly biomass fluctuations than any specific variable in the case of the Asturian region.

4.3 Alternate exploitation methods in Asturias

Cast collection of ocle in Asturias has a large cultural component. Historically, traditional harvest techniques such as raking and the use of nets were employed by collectors, but modern technology has increased yields through the use of cranes and tractors (Sosa, Pinchetti & Juanes, 2006). In the Basque Country, collection is done by boat using suction pumps to pull the ocle out of difficult to reach, rocky areas (ibid). Cast collection was the only exploitation method performed in Asturias from 1945 until 1972 (Ministerio de Comercio, 1972). Until the 1990s, 80-90% of *Gelidium* landings came from cast collection (Sosa, Pinchetti & Juanes, 2006; Santos & Melo, 2018). However, the purity and quality of the agar produced from cast ocle is lower than that of hand plucking or cutting, because the *Gelidium* is not separated from the epiphytes and accompanying species that get displaced alongside it (Juanes & Borja, 1991). It has been estimated that only 60% of Spanish seaweeds sold as *Gelidium* are actually pure *Gelidium* (McHugh, 1991). This has consequences for the manufacture of agar and agarose products as well as the exports of cast seaweed in the marketplace. High quality agarophyte seaweeds are measured based on their gelling strength, electronegative stability and low oligomer and protein content (Armisén, 1991). Because *Gelidium*-based agar is used primarily in the bacteriological industry, the mixing of other algal or epiphytic species that do not possess these traits into agar products can impact biotechnological work (ibid). For instance, *Gracilaria spp*., another red alga exploited for the production of agar, is only considered a food-grade agar due to poor gelling strength (McHugh, 1991). For these reasons, hand plucked ocle that is free of contaminants attains prices 2-3x higher than cast ocle from manufacturers (Sosa, Pinchetti & Juanes, 2006).

While hand plucking or cutting methods generate a higher quality product, cast collection has a cultural component in the region of Asturias that maintains its prominence. However, in addition to quality concerns, yield fluctuations due to changing storm and wave regimes in the past decades have created problems in an industry with increased demand (Santos & Melo, 2018). Management concerns are impounded by a lack of knowledge on yearly cast collection landings and data on which fields the cast ocle gets displaced from (Peón Torre, 2020). Socioeconomic factors have contributed to this investigative gap, because cast collectors in Asturias do not cooperate with regional authorities to reveal their yearly landings although there are regulations in place to collect this data (Principado de Asturias, 1988). To that effect, regional and country-level data on *Gelidium* landings is not necessarily accurate. For example, in 2020, 20 boats in sectors I-III and 8 boats in sector IV obtained licenses to hand pluck ocle with a total quota of 4,600 t for the season (Peón Torre, 2020). Daily GPS data was obtained by the Asturias fisheries agency to identify in which 5-hectare hexagon each boat was harvesting, and how many kilograms they harvested per day. This data was categorized per sector and compared against pre-harvest biomass in each area to decide when each sector's quota was fulfilled and when to end the harvest season; which ended with 4,426 t hand plucked in total. However, in the same year, other than the sale of 146 cast collection licenses, no data was obtained by the agency on the number of tons harvested via cast collection (CEP, unpublished data). Information gaps like these about an entire exploitation method in Asturias make it difficult to advise about the sustainability of ocle exploitation overall in the province. While cast collection does not directly affect ocle biomass regrowth each year, cast seaweeds do impact the surrounding environment by providing a food source for microorganisms and invertebrates and releasing nutrients into their surrounding habitat (Zemke-White, Speed & McClary, 2005). It is imperative to further scientific inquiry about this harvest method along the Asturian coastline, to ensure that natural processes are not being impeded by overexploitation.

4.4 Recommendations for management

This study has identified several knowledge gaps regarding the exploitation of *Gelidium corneum* in Asturias. 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 et al., 1990; Peón Torre, 2020). However, it must be noted that the current maps that the fisheries agency uses to designate ocle 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 ocle fields that have been mapped to varying capacities in 1990 and 2017 (Llera et al., 1990; Gobierno del Principado de Asturias, 2017). Not only can this cause issues when creating harvest quotas because the full area of ocle 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 ocle detachment decreases with increasing depth, with losses from 80% to 64% from 0-5 m and 10-15 m depths, respectively (Borja, 1987). If there have been any distributional shifts in the ocle 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 ocle 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 *Gelidium corneum*, in that region (Guinda et al., 2012). Utilizing those same techniques would greatly enhance knowledge of ocle 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 ocle 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 ocle by depth as well as identify any distributional changes over time.

Cast collection data is the primary knowledge gap concerning ocle exploitation in Asturias. Policies regarding total and per-sector cast collection quotas should be put into place, for both reporting, conflict management and environmental purposes. 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 & Melo, 2018; Araujo et al., 2021). Efforts have been made to estimate cast data from 2013-2017 through interviews with processing companies in Spain, with 2,700-4,200 t reported, but enforcement of regulations would make data collection much more accurate (CEP, unpublished data). Proper data on cast collection yields will allow the fisheries agency to accurately examine the sustainability of ocle 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 ocle. 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 ocle from which fields has been performed, so again, direct analyses are not possible at this time. Because cast seaweed has an important ecological role in beach habitats, further investigation on its contribution to the Asturian coastline is imperative (Zemke-White, Speed & McClary, 2005). Environmental analyses such as these can only improve the efficacy of ocle management in Asturias, while also ensuring that both exploitation methods are truly sustainable.

Conclusions

Based on the results of this study, the level of hand plucking in Asturias has maintained *Gelidium 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. Furthermore, although SST and biomass fluctuations by season follow a similar pattern, they are not significantly correlated. Additional study in Asturias regarding the effects of other environmental variables, such as depth, nutrients and light availability on ocle biomass could be useful for future management. Lastly, from this study alone, comprehensive statements on the current sustainability of ocle 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 ocle 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 *Gelidium corneum* along the Asturian coast. Deeper understanding of all aspects of ocle ecology and subsequent exploitation will allow the resource to be effectively and sustainably managed in Asturias.

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Tables and figures

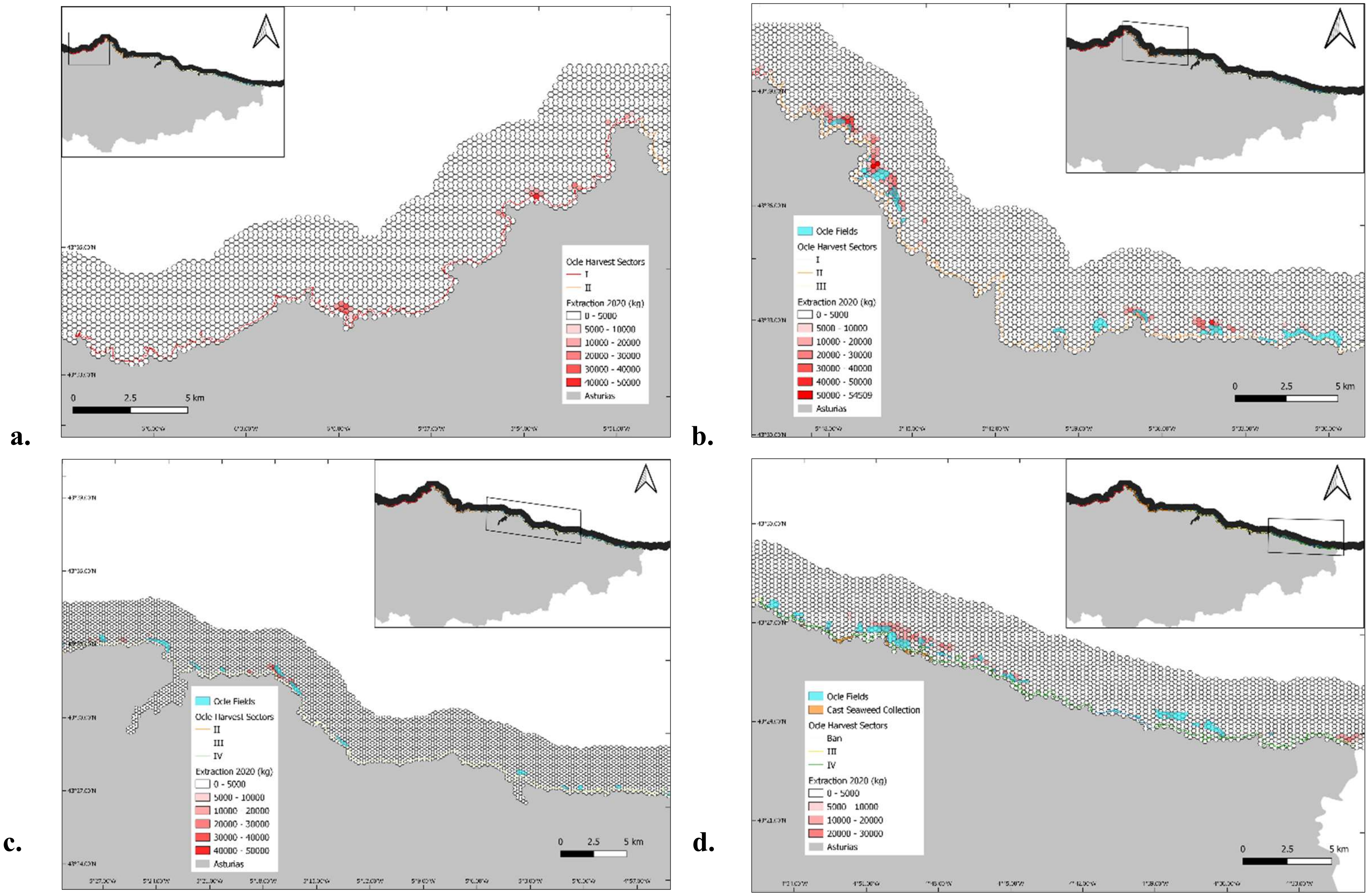


Figure 1: (a) GIS rendering showing sector I on the Asturian coast, strength of 2020 harvest and mapped ocle fields. (b) GIS rendering showing sector II. (c) GIS rendering showing sector III. (d) GIS rendering showing sector IV.

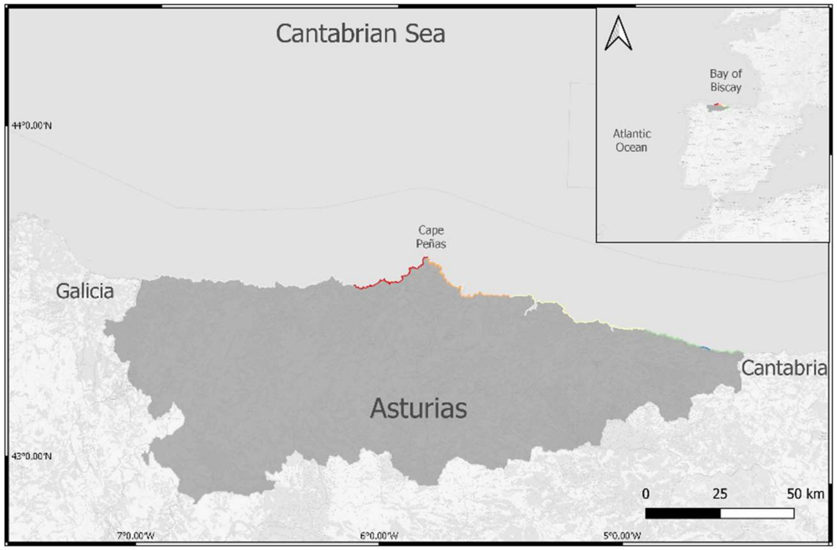


Figure 2: Map showing the study area of Asturias, in the western Cantabrian Sea. The colored lines along the coastline represent the four harvest zones.

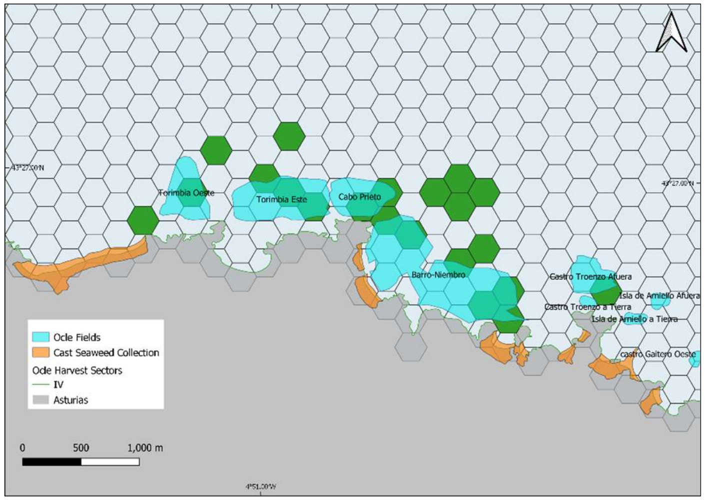


Figure 3: GIS rendering depicting sampling effort by hexagon in a section of sector IV from 2017-2020 (green hexagons). Mapped ocle fields (2017) are shown in blue with their respective names.

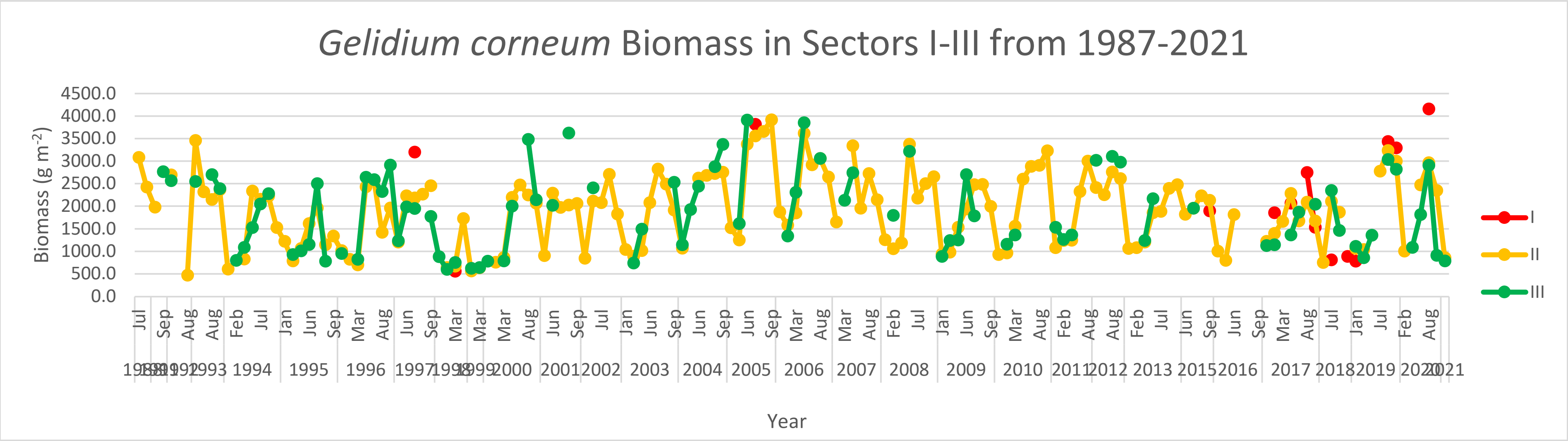


Figure 4: Time series data showing *Gelidium corneum* biomass in sectors I-III from 1987-2021.

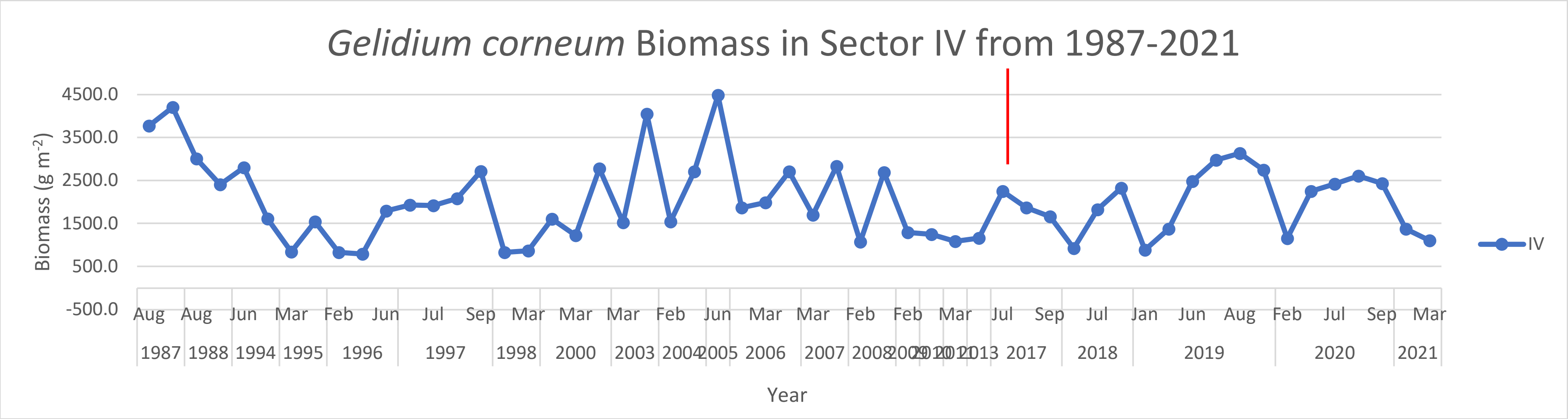


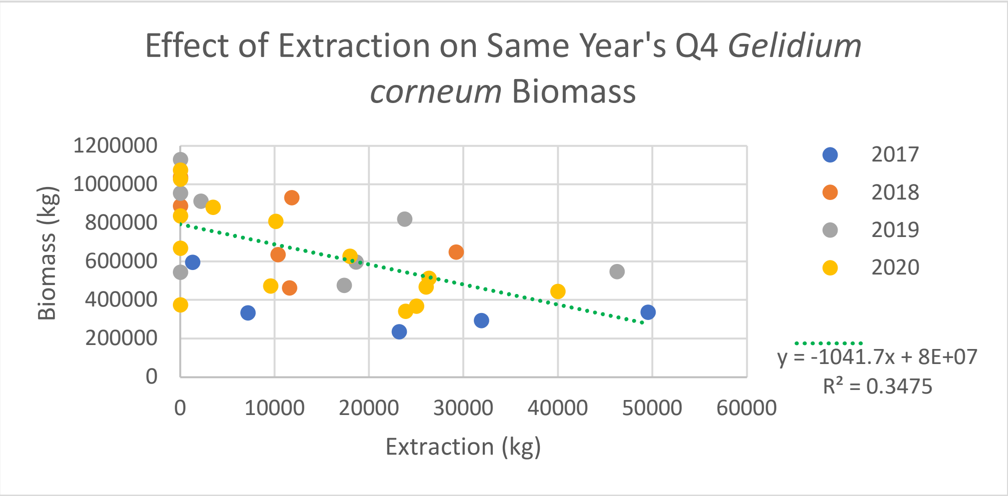
Figure 5: Time series data showing *Gelidium corneum* biomass in sector IV from 1987-2021. Red vertical line represents when hand plucking exploitation began in sector IV (2017).

Table 1

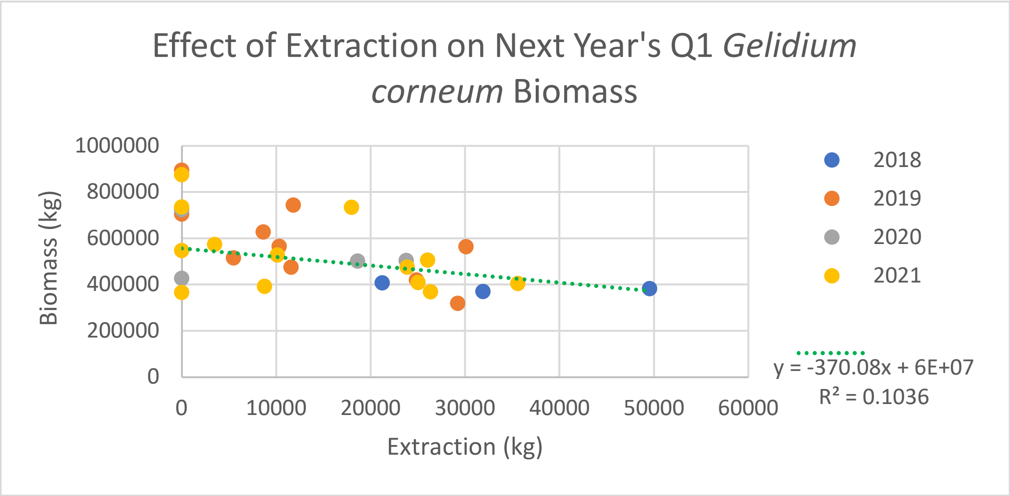
Minimum and Maximum Standing Stock Values from 1987-2021 by Sector

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.



a.



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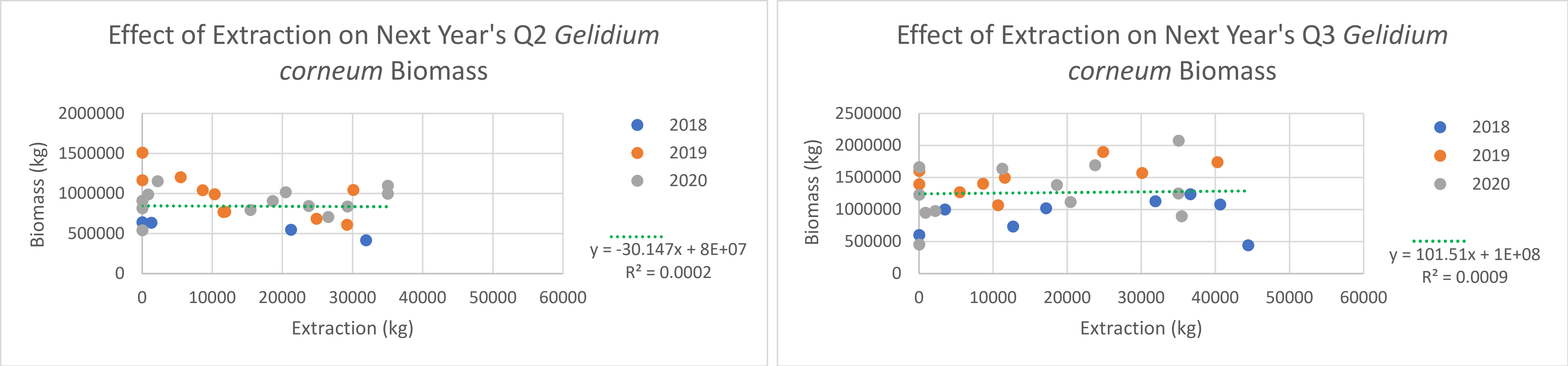

c.

d.

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

Table 2

Effect of Extraction on Gelidium corneum Biomass from 2017-2021

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.

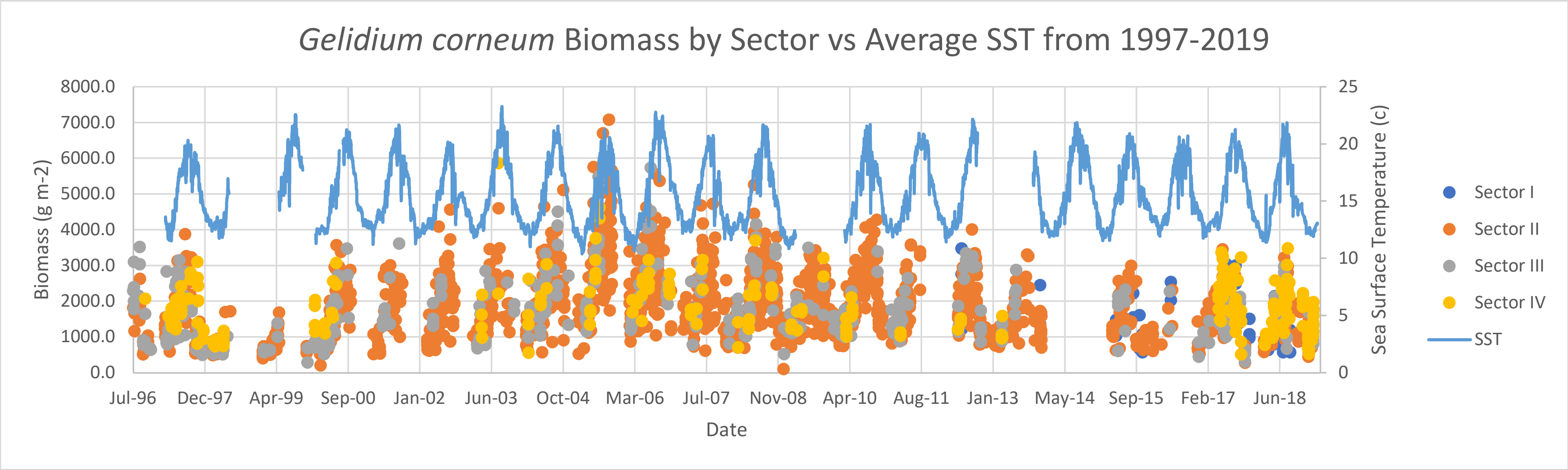

Figure 7: Time series data showing *Gelidium corneum* biomass by sector against sea surface temperature (SST) in eastern Asturias from 1997-2019.