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Review

Chilean Antarctic krill fishery (2011-2016)

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ABSTRACT: Antarctic krill (*Euphausia superba*) is a key resource in the Antarctic region, as it is the primary food source for fish, whales, seals, flying birds, penguins and cephalopods. The high concentrations of the species and its possible uses -food for human and animal consumption and in the production of industrial, pharmaceutical and dietetic products- generates interest in the fishing industry. Its relevance motivated the implementation of administrative measures and international regulations for this fishery, which are summarized in this review. Chile is the only South American fishing country that has shown interest in participating in Antarctic krill fishery. Thus, between 1983 and 1994, the Fisheries Development Institute and some companies carried out fishing activities mainly aimed at prospecting and researching this species. However, starting in 2011, the factory trawler FV Betanzos began sustained commercial krill fishing aimed at krill meal production. This document analyzes the information collected by said vessel between 2011 and 2016, including areas of operation, fishing depth catches and CPUE obtained. Also, the main challenges faced by this fishery and the actions planned as solutions are assessed.

Keywords: *Euphausia superba*; krill; fishing operations; CPUE; Conservation Measures; Antarctic region

INTRODUCTION

The ocean that surrounds the Antarctic continent is well-known for its high primary productivity generated by phytoplankton (Pakhomov *et al*., 2002; Atkinson *et al*., 2008). These unicellular algae provide sustenance for krill, a species of small crustaceans that live in open waters. The most common and abundant krill species in Antarctic waters is *Euphausia superba* (hereafter referred to as 'krill'). The word *Euphausia* derives from Greek for good or true, combined with *phausia* for shining or light emitting, and the word "krill" was first used in this sense by Norwegian whalers who applied it to the swarming little fish (krill) which signaled whale feeding grounds (Guglielmo *et al*., 2015).

These great aggregations have also draw human interest in using the abundant krill as a source of protein and sub-products. Hence, this resource is exploited for the elaboration of krill pastes for human consumption, krill oil and krill meal for balanced animal feed, as well as derivative products such as omega-3 tablets and dyes (Budzinski *et al*., 1985; Nicol *et al*., 2000; Burri & Johnsen, 2015).

The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), an international organization forming part of the Antarctic Treaty System with headquarters in Hobart, Tasmania, Australia, administers this resource. This Commission aims towards conserving the marine flora and fauna of Antarctica, with particular attention focused on researching and monitoring krill fishery and its interaction with other species, due to the growing interest in krill exploitation. CCAMLR has established that krill fishery will not expand further without scientific data, indicating that said expansion is not competitive with natural predators of krill, including fish, whales, seals, flying birds, penguins and cephalopods.

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A total of five countries currently catch krill in the Southern Ocean (CCAMLR Secretary), being Chile the only Latin American one, with sporadic activities carried out since 1970. Thereby, from 2011 to 2016, the factory trawler FV Betanzos was used for the extraction of this resource for meal production. Since December 2017 another Chilean ship (FV Antarctic Endeavour), built especially for fishing and processing krill, has replaced it in these tasks.

The importance of this resource in the Antarctic ecosystem and the growing fishery interest motivated by its abundance encourages the need to research krill biology, behavior and status, in order to have up-to-date scientific information to define and regulate its exploitation. This document contributes to this by presenting the results of five years of commercial krill fishing, the main characteristics associated with Antarctic krill fishery regulation, and its predictable future.

THE ANTARCTIC KRILL RESOURCE

These small crustaceans are distributed around the entirety of Antarctica; however, their main distribution is located in statistical area 48 established by the Food and Agriculture Organization of the United Nations (FAO), an oceanic region to the south and east of Cape Horn in the extreme south of the American continent. The main concentrations are found south of the South American continent and in the Atlantic Ocean (Statistical Area 48 of the FAO), subdivided into Subareas 48.1 (West Antarctic Peninsula, Bransfield Strait, Gerlache Strait, South Shetland Islands and Elephant Island), 48.2 (South Orkney Islands), and 48.3 (South Georgia Island), while the remaining subareas (48.4, 48.5 and 48.6) record no relevant catches (Fig. 1).

Krill will cluster in enormous concentrations of millions of individuals, weighing hundreds and even thousands of tonnes, and covering great extensions. These dense swarms can be found from near the surface to several hundred meters deep (up to 600 m) (Miller & Hampton, 1989; Watkins, 2000). Krill display massive daily vertical migrations making a significant amount of biomass available as food for predators near the surface at night and in deeper waters during the day (Everson, 2000). The distribution pattern of the population can be affected by currents, bottom topography, food distribution and the presence of predators.

The distinctive characteristics of *Euphausia superba* are: i) eyes spherical, somewhat larger in males than in females; ii) rostrum short, triangular, and truncated, slightly shorter in males than in females; iii) distal segment of mandibular palp long and slender, seven times as long as broad; iv) first segment of antennular peduncle bearing a wide lappet with a sinuous distal margin, which is stouter, narrower, and smaller in males than in females. The second segment is bearing a dorsal lappet, which is wider and larger in females - abdominal segments without mid-dorsal spines. The sixth segment as long as high; v) proximal process of petasma without keel; terminal process curved and pointed, not cleft in two; lateral process without a secondary tooth (Antezana *et al.*, 1976; Antezana, 1985; Guglielmo *et al*,, 2015).

Although marine waters host a great variety of euphausiid species, the most relevant is the *Euphausia superba*, which is also one of the largest, growing to a larger size (3-7 cm) and weigh (up to 2 g) (Siegel, 1992; Nicol & Endo, 1997; Arana & Rolleri, 2012). Differences between species of the *Euphausia* genus are determined mainly according to the shape of the distal projection of the first antennular segment, the shape of the petasma, the presence of spines on the abdominal segments and the shape of the rostrum (Antezana *et al.*, 1976).

The main spawning season of the species is from January to March, mostly above the continental shelf (Perry *et al*., 2019). A condition considered favorable for a successful spawning is the extension, temporal and spatial, of the sea ice cover that occurs during winter (Perry *et al*., 2019). Females lay 6,000-10,000 eggs at one time in the first 100 m of the water column. The 0.6 mm fertilized eggs move with the current into the open ocean and descend for a short period to depths of 1,000 to 3,000 m for their embryonic development. The egg hatches as a nauplius larva; once the individuals have molted into a metanauplius, and next to the young animal starts to move towards the surface in a migration known as "developmental ascent" (Hempel & Hempel, 1986). Later, they go through larval stages know consecutively as calyptopis and furcilia. Krill larvae emerge from the pack ice in spring more advanced than in autumn. It is probably at this point that they begin to exhibit schooling behavior and as they develop into juveniles over their second summer this behavior becomes more pronounced (Nicol & Endo, 1997). At 15-20 mm, the juvenile krill resembles the general aspect of the adults and has adopted the adult habits, with a preferred distribution over the continental shelves. The proportion of krill measuring less than 30 mm could be used to derive as a recruitment index.

As planktonic organisms, their behavior is passive, and they are dragged along by marine currents. Fach & Klinck (2006) suggest that krill populations off South Georgia in the eastern Scotia Sea could be subject to an

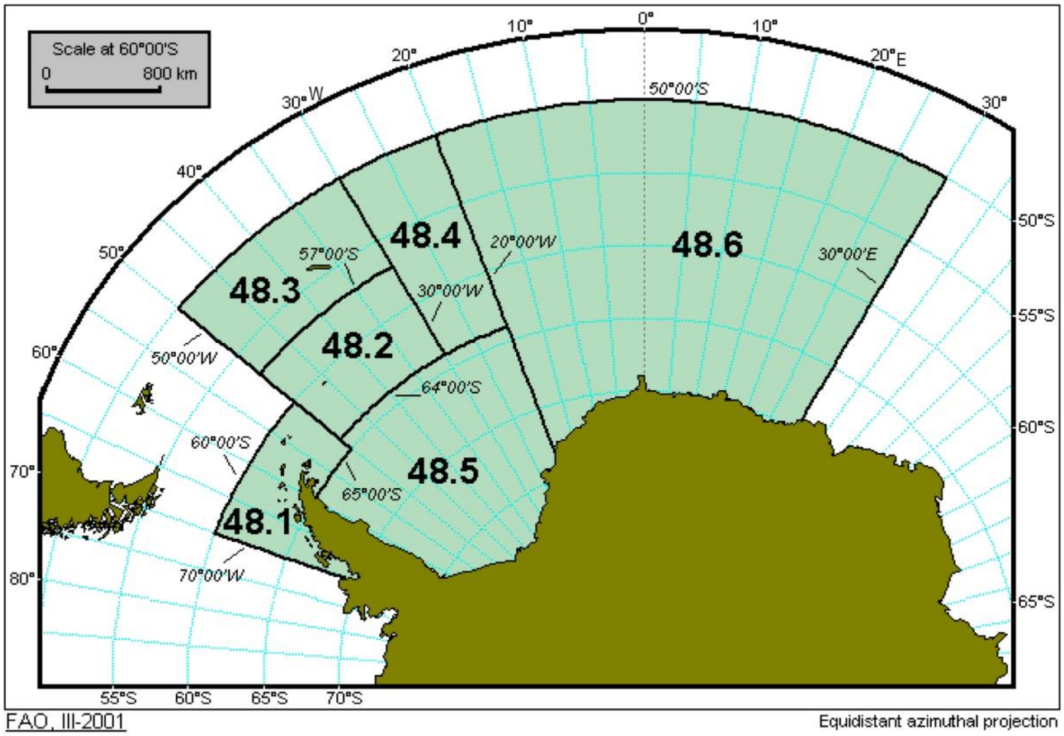

Figure 1. Major fishing statistical subareas established by FAO in the South Atlantic Ocean. From: FAO Fisheries and Aquaculture Department [online].

import of individuals from upstream regions, such as the western Antarctic Peninsula. Another possibility is that aggregations of Antarctic krill are displaced by local currents from the Bransfield Strait towards the north, between the South Sandwich Islands, thus producing a circulation (retention) effect of at least a portion of the population of this species in Subarea 48.1. Thus, the combined effects of the Coastal Current, the Bransfield Current and the northern South Shetland Current comprise a sort of clockwise circulation pattern in the region (Dotto *et al*., 2016; Moffat & Meredith, 2018; Trathan *et al*., 2019). Oceanographic models indicate that the influence of these features would have particular relevance in krill distribution and possibly in the development of the egg and larval stages as well (Perry *et al*., 2019). Likewise, the models support the possibility that large aggregations of this species occur in the mentioned regions, providing krill-dependent animals extended periods with the availability of this resource for their feeding.

Juvenile growth is estimated to be slow in winter and rapid in spring-summer, displaying a lower growth rate at higher latitudes, which corresponds to cooler waters (Candy & Kawaguchi, 2006; Constable & Kawaguchi, 2017). Also, Antarctic krill has been observed to molt approximately every 20-30 days (Nicol & Endo, 1997). Krill reach maturity between 40-50 mm, when they are in the open ocean; females become sexually mature as age class 2+, while males become mature as age class 3+ (Siegel & Loeb, 1994). The average individual lifespan varies from two to seven years (Nicol & Endo, 1999; Constable & Kawaguchi, 2017), although they can live up to 11 years (Ikeda, 1985).

Their diet consists mainly of phytoplankton (microscopic plants in suspension such as flagellates and diatoms) and algae that live under the surface of the ice (Zhu *et al*., 2019). This species can withstand long periods without feeding (Nicol & Endo, 1997; Meyer, 2012).

KRILL FISHERY

Krill fishing began with exploratory purposes in 1961-1962, in little relevant quantities (<500 t), mainly carried out by ships of the former USSR (Nicol & Endo, 1997). The CCAMLR database holds data on krill catches starting in 1973 (CCAMLR Secretariat).

After 1977, catches increased rapidly, surpassing 100,000 t yr^{-1}, although with fluctuating values between years, reaching in 1986 a maximum of 425,867 t. After 1993, catch figures show a sharp decline, maintaining values varying between 80,800 and 156,000 t yr^{-1} until

2012 (CCAMLR, Statistical Bulletin). As of 2010, a gradual increase has been observed in Antarctic krill catches, reaching a total of 390.135 t in 2019 (CCAMLR, 2019), an amount that could tend to increase in the coming years.

Several countries have ventured in this fishery, with the most relevant and persistent being Chile, China, Japan, Republic of Korea, Poland, Ukraine, USSR and the Russian Federation, although its permanence over time has varied throughout time. During the period registering the largest landings (1980-1992), vessels from the USSR and Japan registered the highest catches; nevertheless, between 1987 and 1992, the USSR vessels were replaced by ships chartered by the Russian Federation, as Japan remained the most important country in krill fishing. Regarding fishing volumes, between 2000 and 2009 records show that Japan, Republic of Korea, Norway, Ukraine and Poland were the main countries operating in the fishery. A significant fact in the history of this fishery is the withdrawal in 2005 of Japanese vessels and the entry of ships from Norway, quickly positioning the latter as the leading country in the extraction of this resource, registering around 50% of the total catch obtained in Subarea 48. For the period 2019-2020 are authorized vessels from Chile (1), China (4), Republic of Korea (3), Norway (4), and Ukraine (1) (CCAMLR Secretariat).

The vessels operating in this fishery have used traditional midwater trawls (Boopendranath *et al*., 2010). However, the Norwegian ships introduced continuous trawl fishing, in which the gear is deployed and trawls continuously for an extended period (hours or days), while the krill is continuously pumped from the cod end to the deck of the ship (Davis *et al*., 2009).

Krill is mainly processed into a variety of products for direct human consumption (*e.g*., paste, frozen tails, sticks) given their high protein value and low-fat content, for animal feed (*e.g*., fish farming, poultry, products for pets), and for use as bait for sport fishing (dehydrated or frozen). The rapid decomposition of the unprocessed material results in a large portion of the krill extracted being destined *in situ* to the manufacture of oil and meal, the latter mostly used for animal feed, as well as the production of dyes (astaxanthin) and the elaboration of diverse dietetic (*e.g.*, omega 3 polyunsaturated fatty acids) and pharmaceutical products (Budzinski *et al*., 1985; Nicol *et al*., 2000; Burri & Johnsen, 2015).

Biomass and total allowable catch (TAC's)

Since the start of the exploration of krill as a resource, there has been speculation about the real magnitude of its biomass. Assessing this information is hindered by various factors, given the vastness of the area the species inhabits around Antarctica, the seasonality of its abundance, the movement of the waters that transport them and the climate. Since the 1970s, a wealth of data has been collected to help on the estimation on the species abundance. These include a series of large-scale, semi-synoptic surveys that have been used to determine the distributions of krill, including, for example, FIBEX 1981 (El-Sayed, 1994); BIOMASS-1981 (Trathan *et al.*, 1995); SIBEX 1984-85 (Siegel, 1986); CCAMLR 2000 (Constable *et al.*, 2000); Southern Ocean GLOBEC 2001-2005 (Skjoldal *et al.*, 2013); US AMLR 2011 (Walsh, 2014); Palmer LTER (Saba *et al.*, 2014); and others minor relevant national or international surveys. The most significant research evaluating krill biomass corresponded to the CCAMLR Krill Survey-2000. It consisted of an international effort based on hydroacoustic research that used four vessels and covered an area of approximately 2×10^6 km^2; the results determined total biomass of around 60.3 million t in Subareas 48.1, 48.2, 48.3 and 48.4 combined (Constable *et al.*, 2000; Trathan *et al.*, 2001; Hewitt *et al.*, 2002, 2004; Watkins *et al.*, 2004; Hill *et al.*, 2016).

Based on that research, a maximum catch limit of around 5.61 million t was established per season for these subareas as a protection measure (CCAMLR, 2010). This catch limit was based on the biomass previously indicated with a survey coefficient of variation (CV) of 12.8%, and a fraction of the population referred to as γ (gamma) estimated using the generalized yield model (GYM) of 0.093 (CCAMLR, 2017a,b; CCRVMA, 2018a). However, given this species' key role in the Antarctic ecosystem, a maximum of 620,000 t of the total annual catch has been set as a precautionary measure (approximately 1% of the estimated unexploited biomass), established as a trigger catch level. The maximum registered annual catch level of 390,135 t in 2019 constitutes approximately 0.62% of the estimated total krill biomass. Currently, the fishery does not exploit the total trigger level, and for this reason, is considered to be precautionary and sustainable (Hill *et al.*, 2016). Additionally, so as to avoid concentrating the fleet operation in one area, the trigger level for *E. superba* catch establishes that no more than the following percentages of the maximum annual catch (620,000 t) can be taken from the nominated Statistical Subareas: 25% from Subarea 48.1, 45% from Subarea 48.2, 45% from Subarea 48.3, and 15% from Subarea 48.4 (CCAMLR, Conservation Measure 51-07, see Table 1).

In order to update the distribution and biomass of krill resource in the current fishing zones, in the austral summer of 2019, a large-scale survey was carried out

Table 1. Summary of current CCAMLR Conservation Measures (CM) in force for the krill *Euphausia superba* fishery in Subareas 48.1, 48.2, 48.3, and 48.4 (CCAMLR, 2020).

Topic	Measure	Conservation Measure or Resolution
Target species	*Euphausia superba* and any others species is bycatch.	
Season	1 December to 30 November of the following year.	CM 51-01 (2010)
Vessel	All fishing vessels to operate in the Convention Area must be marked in such a way that can be readily identified.	CM 10-01 (2014)
Vessel Monitoring Sytems	Al vessel must be equipped with a satellite-based monitoring system (VMS). For krill fisheries, the system must transmit data every four hours, to charge to every hour commencing 1 Decenber 2019.	CM 10-04 (2018)
Fishing gears	Trawling only, with midwater trawls; conventional trawl, continuos fishing system, pumping to clear codend. The use of net monitor cables on vessels is prohibited.	CM 21-03, Annex A (2019) CM 25-03 (2019)
Notification of intent to participate in the fishery	All Members intending to fish for krill for the coming season must notifify the Commission, using the pro formas for that (21-03A and 21-03B), not later than 1 June. Product types and methods for direct estimation of green weight of krill caught is required. A vessel on Illegal, Unreported or Unregulated (IUU) Vessel List shall not permitted to participate in krill fisheries.	CM 21-03 (2019)
Catch limit	The total combined catch of *Euphasia superba* in Statistical Subareas 48.1, 48.2, 48.3 and 48.4 shall be limited to 5.61 million tonnes in any fishing season. Nevertheless, the total combined catch in these subareas shall be further limited to 620,000 t in any fishing season.	CM 51-01 (2010)
Trigger level by subarea	The distribution of the trigger level by subarea will be: 48.1-25% (155,000 t); 48.2-45% (279,000 t); 48.3-45% (279,000 t) and 48.4-15% (93,000 t). No more than 75% of the catch limit shall be taken within 60 nautical miles of known breeding colonies of land-based krill-dependent predators. The Scientific Committee shall provide advice to the Commission regarding progress towards the development of the risk assessment framework, feedback management and the spatial allocation of catch no later than the end of the 2020/7021 fishing season, at which time this conservation measure will expire.	CM 51-07 (2016)
Move-on rule	No move-on rules in this fishery.	
Minimisation of the incidental mortality of seabirds and marine mammals	Various measures are specified to reduce the incidental mortality of, or injury to, seabirds and marine mammals during trawl fishing. The use of marine mammals exclusion device on trawls is mandatory. The discharge of offal and discards (wholw fish or other organisms) shall be prohibited during the shooting and hauling of trawl gear. Nets shall be cleaned prior to shooting to remove items that might attract birds.	CM 25-03 (2018) CM 51-01 (2018)
Data	Catches shall be reported monthy. However, when the total reported catcg is greater than, or equal to, 80% of the trigger levels, catches shall be reported in accordance with the five-day catch and effort reporting.	CM 23-06 (2012)
Scientific data reported by the CCAMLR Scheme of international Scientific Observation	Haul-by-haul catch, effort data and total green weight of krill caught and brought on board shall be reported. The systematic observer coverage scheme shall entail: a target coverage rate of no less than 50% of vessels during the 2018/17 and 2017/18 fishing seasons; no less than 75% of vessels during the 2018/19 and 2019/20 fishing seasons; and 100% coverage in sunsequent fishing seasons.	CM 51-06 (2019)
Exploratory fishery for krill	Defines the general measure for the exploratory fisheries of krill in the Convention Area.	CM 51-04 (2019)
Environmental protection	Several conservation measures to minimise possible effects on the marine environment arising from fishing-related activities in the context of mitigating incidental mortality of non-target species and protecting the marine environment. Prohibition of discharge oil, garbage, baits, any product from the processing, by-catch, etc.	CM 26-01 (2019)
Tariff classification	Urges the contracting parties to introduce into their domestic law, an appropiate tariff classification in order to improve knowledge of the volume and trade of Antarctic krill.	Res. 27/XXVII (2016)

in Area 48, coordinated by Norway scientists engaging international partners and CCAMLR scientific working groups (Macaulay *et al*., 2019). The design and sampling protocol used was similar to the ones used in the CCAMLR-2000 Survey in order to allow comparing the results obtained in this cruise with those previously obtained (Knutsen *et al*., 2018; Kraff, 2018a,b). The survey involved co-operative fishing vessels of the Association of Responsible Krill Fishing Companies (ARK: seven companies integrated by Chile, China, Republic of Korea, and Norway) and Ukraine, and scientific ships from Norway and the United Kingdom. The krill biomass estimate from International Large-Scale Synoptic Krill Survey in Area 48 was 62.6 million tonnes with a coefficient of variation (CV) of 13% (CCAMLR, 2019).

Conservation measures

Since the CCAMLR came into force (1982), this organization has been particularly concerned about regulating krill fishing operations, given its importance in the Antarctic trophic web and the fact that krill is one of the primary resources exploited around the continent, using an "ecosystem approach". The essence of the "ecosystem approach" to management can be found in Article II of the Convention, which spells out the management goals in following general terms: 1. The objective of this Convention is the conservation of Antarctic marine living resources; 2. For the purposes of this Convention, the term "conservation" includes rational use; and, 3. Any harvesting and associated activities in the area to which this Convention applies shall be conducted in accordance with the provisions of this Convention and with the following principles of conservation: a) prevention of decrease in the size of any harvested population to levels below those which ensure its stable recruitment. For this purpose its size should not be allowed to fall below a level close to that which ensures the greatest net annual increment; b) maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and the restoration of depleted populations to the levels defined in sub-paragraph above; and c) prevention of changes or minimization of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, taking into account the state of available knowledge of the direct and indirect impact of harvesting, the effect of introduction of alien species, the effects of associated activities on the marine ecosystem and the effects of environmental changes, with the aim of making possible the sustained conservation of Antarctic marine resources.

During the annual meeting of this organization (November 2019), the current conservation measures are revised and updated to then be applied for the following fishing season. These measures correspond mainly to regulating the maximum captures by subarea, mitigating the possible incidental capture of birds and mammals, protecting the environment, regulating measures to ships' operation and having mandatory scientific observers onboard the ships (see Table 1).

In parallel, CCAMLR is studying the establishment of several Marine Protected Areas (MPAs) in the Antarctic region, most of them in areas where krill is currently being fished, in order to contribute to the its protection and to avoid its extraction to compete with natural krill predators. Example of this MPAs are the two already established: the first in the southern shelf of the South Orkney Islands (CCAMLR Conservation Measures 91-03/2012) and the second in the Ross Sea (CCAMLR Conservation Measures 91-05/2016), while others are proposed in the east Antarctica, in the Weddell Sea (Domains 3 and 4) and in the Antarctic Peninsula region (Domain 1) (CCAMLR, 2019).

While the possible establishment of these MPAs is under analysis, the Association of Responsible Krill Harvesting Companies (ARK), formed by the leading companies that exploit this resource, established a voluntary agreement stating that, as of January 1, 2019, they will restrict extractive operations from October to March to a distance greater than 40 km off the coast in penguin breeding areas in the Antarctic Peninsula, South Shetland Islands and Gerlache Strait (ARK, 2018).

CHILEAN KRILL EXPLOITATION (2011-2016)

In virtue of the proximity of its ports to the Antarctic continent and the areas where the main concentrations of krill are found, between 1974 and 1984, the Chilean government promoted the research of this resource organizing expeditions in Antarctic waters, carried out by the Institute of Fisheries Development (IFOP) and the development of various works with the collaboration of numerous researchers and national institutions (Lillo & Guzmán, 1982; Guzmán, 1985). The purpose of these expeditions was to research this resource and determine the possibility of exploitation and use for human consumption (Eberhard, 1982, 1983). Although these actions did not lead to the development of this fishery, they allowed for several attempts to extract this species over short periods, which were soon abandoned.

More recently, given the decrease in abundance of fish species traditionally extracted in Chilean jurisdictional waters, the fishery company Pesca Chile S.A., followed by Antarctic Sea Fisheries S.A., grew interested in developing krill fishery. Thus, from 2011 to

2016, the FV Betanzos (72 m in length and 1,439 gross registered tonnage) was used to extract *E. superba*. At the same time, these expeditions allowed gathering information on the resource and on the characteristics of these fishing operations; a description of the analysis of such data is provided below.

Analyzed information

In this document, we report on the analysis of data from the vessel logbooks, which include information on the location of fishing hauls, as well as records of effort, catch, and the general characteristics of each haul (geographical position, depth (m), duration of trawl (h) and catch (kg)). The FV Betanzos carried out the extractive operations between 2011 and 2016 in Statistical Subareas 48.1, 48.2, and 48.3. Also, reports provided by the National Scientific Observers who worked permanently aboard the ship were used. This information was registered in Excel files provided by the CCAMLR to be filled *in situ*, according to its Scientific Observers Manual (CCAMLR, 2011).

The operation of the FV Betanzos in the krill fishery was authorized each year by the Chilean Undersecretariat of Fisheries of the Chilean government and by CCAMLR.

An annual summary was made detailing the number of trips, the date and days of the fishing operations, as well as the totals per year, subarea, and the total number of hauls with and without catch carried out by the vessel. Along with this, we present the depth distribution frequencies in which the trawls were carried out, by year and subarea. Maps of the catches were made per year and fishing subarea (48.1, 48.2 and 48.3) using the Surfer geostatistical software to visualize the haul's geographical location carried out during the study period.

The total Antarctic krill catches obtained in the successful hauls were added by year and by subarea. Also, to facilitate the interpretation of these results, additional box-and-whisker diagrams or boxplots are provided (Chambers *et al.*, 1983), describing the range observed in the catches per haul and the average value, and ± 1 standard deviation concerning the respective average value is included as a measure of dispersion. The catch per unit of effort (CPUE) calculation was established globally for the entire study period in each subarea using the relative frequency distribution using the logarithmic function of CPUE (log of catch per minute of fishing (kg min^{-1})) at intervals of 0.1 (CCAMLR, 2016).

Operational results

Number of trips and duration of fishing efforts

The number of trips carried out per year varied between 3 and 5, with 2013 presenting the highest amount and 2011, 2015 and 2016 the lowest (Table 2). However, the fishing days fluctuated between 14 and 58 days, with the highest number of days by year was registered in 2012 (175 days). Later, the duration of the fishing days remained around 150 days, decreasing markedly in 2016 (72 days), the last year of operation of this ship (Table 2).

Hauls

The total number of hauls carried out during the 2011-2016 period (n = 3,257) reveals that the largest amount was registered in Subarea 48.1, accounting for 1,928 hauls, and far exceeding the remaining subareas; 840 in Subarea 48.3 and 489 in Subarea 48.2 (Table 3). As a global average, 96% of the hauls were successful, so a similar situation is observed when considering hauls with a yielded catch (n = 3,129), with 1,890 hauls in Subarea 48.1, 776 hauls in Subarea 48.3, and 463 hauls in Subarea 48.2. Regarding trawls per year, the largest number was carried out in 2014 (749 total hauls, of which 738 yielded catch), and the lowest amount in 2016 (252 total hauls of which 239 yielded catch).

Fishing depth

The depth at which the fishing trawls were carried out varied according to the subarea (Fig. 2). In Subarea 48.1, the hauls were mainly carried out between 0 and 120 m of depth, with an annual average varying during the different years between 31 and 66 m. In Subarea 48.2, the trawls were carried out between 20 and 140 m of depth, with annual averages between 54 and 115 m. In Subarea 48.3 the trawls were carried out at a deeper range, mostly between 40 and 200 m of depth, with interannual means between 93 and 138 m.

Catch

The amount of catch per year and subarea varied considerably throughout the investigated period (Table 2). In 2011, the total catch reached approximately 3,827 t. In the following years, it increased irregularly, with amounts that fluctuated between 7,200 and 9,600 t yr^{-1}, finally falling in 2016 to 3,700 t. The catch registered by FV Betanzos represented between 2 and 6% of total annual Antarctic krill catches in Area 48.

The conversion factor from green weight (fresh wet weight of captured krill) to fishmeal was between 7.0 and 8.0%.

Regarding the catch by subarea, the most substantial amount was obtained in Subarea 48.1, contributing to a large part of the catches in 2013. The maximum amount of catch (6,800 t) was obtained in 2014. In Subareas 48.2 and 48.3, the volumes were relatively low, being under 2,300 t per year (Fig. 3).

Table 2. The number of trips, fishing period, fishing days and catch performed by FV Betanzos in the krill *Euphausia superba* fishery (2011-2016).

Year	Trip	Period	Fishingn days	Total (days)	Catch per trip (t)	Annual catch (t)
2011	1	Jun 25 - Aug 04	41	84	1,811.04	3,827.15
	2	Aug 27 - Sept 09	14		558.00	
	3	Dec 11 - Jan 08	29		1,458.11	
2012	1	Jan 18 - Feb 29	43	175	2,120.27	7,275.53
	2	Mar 12 - Apr 22	42		1,697.39	
	3	May 02 - June 12	42		2,287.60	
	4	June 22 - Aug 27	48		3,290.54	
2013	1	Jan 08 - Jan 28	21	135	1,182.30	7,242.32
	2	Mar 23 - Apr 17	26		1,601.28	
	3	May 01 - June 09	40		1,797.90	
	4	June 29 - July 28	30		2,085.12	
	5	Aug 21 - Sept 07	18		575.72	
2014	1	Dec 29 - Feb 16	50	154	2,807.66	9,603.67
	2	Mar 03 - Apr 10	39		2,350.42	
	3	Apr 23 - June 01	39		2,868.80	
	4	Aug 14 - Sept 08	26		1,576.79	
2015	1	Jan 27 - Mar 18	51	153	2,537.49	7,277.62
	2	Mar 31 - May 27	58		2,507.90	
	3	June 18 - July 31	44		2,232.23	
2016	1	Feb 02 - Mar 01	29	72	1,148.55	3,707.12
	2	Mar 14 - Apr 22	40		2,373.80	
	3	May 12 - May 15	3		184.77	
Total						38,993.41

Table 3. Total hauls and hauls with catch recorded in Subareas 48.1, 48.2, and 48.3 during the 2011-2016 period by FV Betanzos in the krill *Euphausia superba* fishery.

Subarea	Year						Total
	2011	2012	2013	2014	2015	2016	
Total hauls							
48.1	149	276	344	526	431	202	1.928
48.2	9	279	0	95	56	50	489
48.3	227	151	158	128	176	0	840
Total	385	706	502	749	663	252	3.257
Hauls with catch							
48.1	135	269	339	525	424	198	1.890
48.2	3	271	0	92	56	41	463
48.3	186	151	142	121	176	0	776
Total	324	691	481	738	656	239	3.129

Catch per unit of effort (CPUE)

In terms of catch per haul, Subarea 48.1 registered averages showing gradual growth until 2013, when it reached an average close to 15 t haul^{-1}, which then decreased between 2014 and 2015, and increased again in 2016 to 16.11 t haul^{-1}, corresponding to the highest record of the period (Fig. 4). In Subarea 48.2, an irregular behavior was observed, with a steadily increase from 2011 to 2014, with an average of 12 t haul^{-1} in the last, to subsequently decline in 2015 and another increase in 2016. Subarea 48.3, despite achieving the highest average catch volumes in 2012 (21.79 t haul^{-1}), in addition to being the subarea with the highest average extraction values, experienced a constant decrease in said amount from 2013, with an average of 12.63 t haul^{-1} in 2015.

When analyzing the catch per unit of effort, transformed to log CPUE min^{-1}, a unimodal distribution

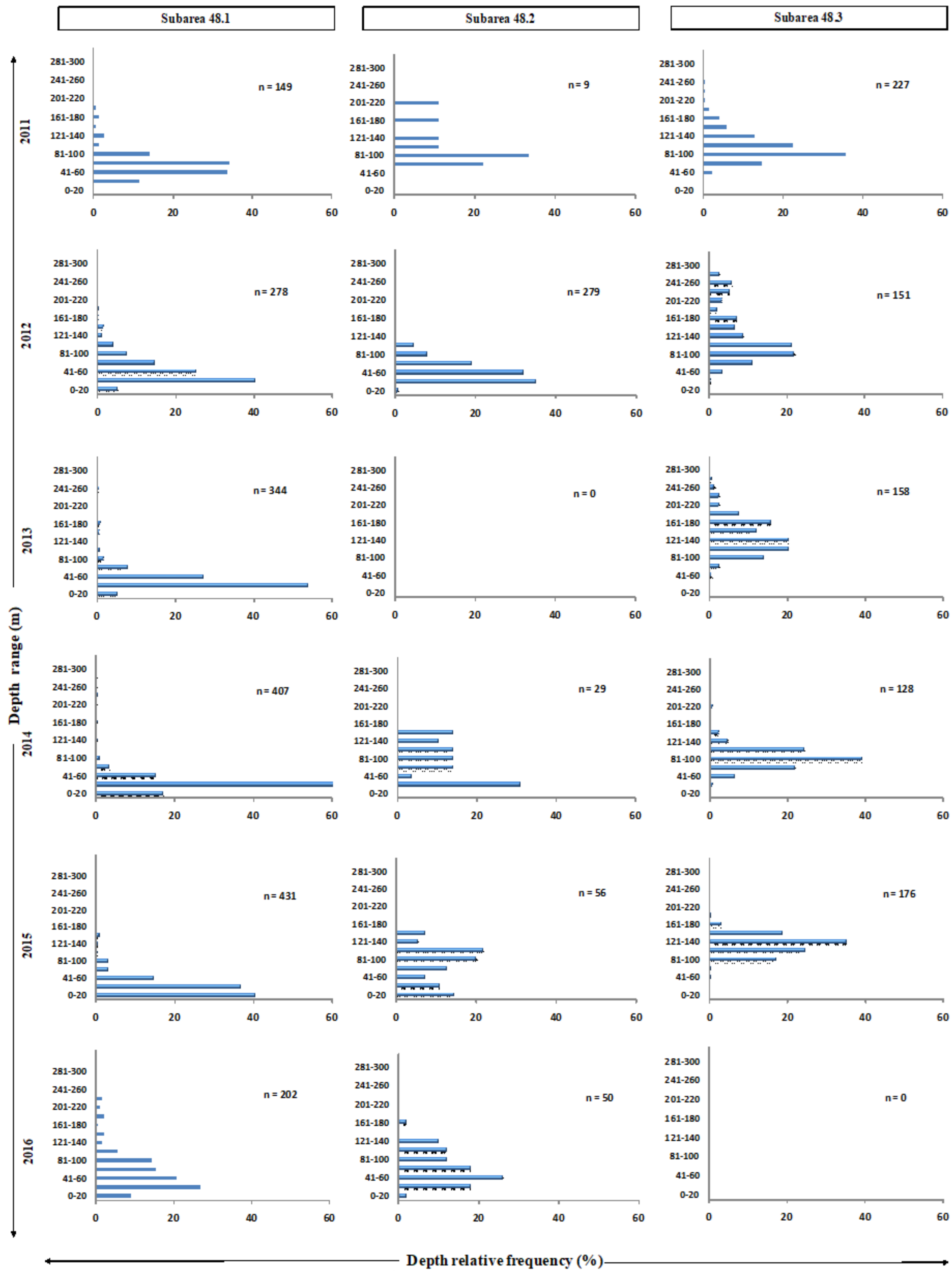

Figure 2. Depth frequency distribution for krill *Euphausia superba* fishery performed by FV Betanzos in subareas 48.1, 48.2, and 48.3.

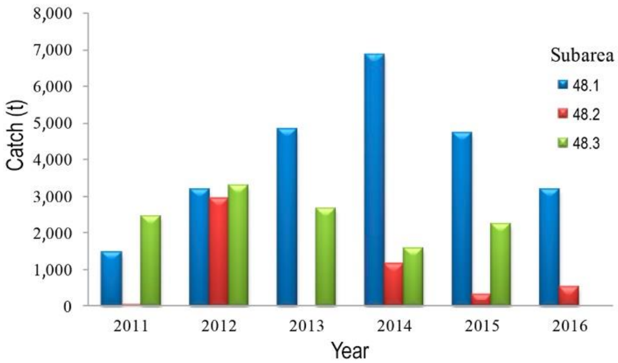

Figure 3. Annual krill *Euphausia superba* catch between 2011 and 2016 by FV Betanzos in subareas 48.1, 48.2 and 48.3.

is observed in the different fishing subareas, with the mode around log 2 kg min^{-1}. The range observed in Subarea 48.1 shows an approximately symmetric distribution with extreme values of 0.5 to 3.0 kg min^{-1} ($\bar{x}$ = 1.79 ± 0.35 kg min^{-1}) while in Subareas 48.2 and 48.3 these distributions present greater dispersion, with mean values of 1.78 ± 0.39 and 1.95 ± 0.41 kg min^{-1}, respectively (Fig. 5). In the case of the first subarea, it is more likely to obtain lower than the average high catch values, while in Subarea 48.3, the probability is shared in obtaining higher or lower values of log CPUE per minute.

Hauls distribution per subarea

Within each subarea, the distribution of the hauls varied during the analyzed period (Figs. 6-8). In Subarea 48.1, the hauls carried out were mainly located in the Bransfield Strait in 2011; in the following years, fishing operations north of the South Shetland Islands were incorporated, and, in 2015, operations were extended to the north-west of Elephant Island, albeit in smaller numbers (Fig. 6).

In general, in Subarea 48.2, a significant number of hauls was carried, although in 2013 there was no fishing operations. For the most part of this subarea, the operations took place in the northwest of the South Orkney Islands, with a reduced number of hauls to the southwest of these islands in 2016 (Fig. 7).

In Subarea 48.3, the fishing activities were only carried out between 2011 and 2015, focused mainly to the northeast of South Georgia Island (Fig. 8). In the northwest area, the number of hauls gradually decreased, with no activity at all in 2015.

GENERAL COMMENTS

Because of the considerable biomass that this species presents and the proximity of the fishing areas to Chilean ports, this species has been considered as a potential resource since the 70s, as it could diversify the country's fishing activity and become an operationally and economically viable activity. Although there is interest in krill fishery from Chile since the 1970, some factors delayed to start as such activity. Among these factors, we can cite the availability of vessels with the necessary characteristics to operate in Antarctic waters, the rapid decomposition of the raw material and uncertainty regarding the use and sale of the production. All these factors implied that Chilean participation in the krill fishery represented a complex, risky and expensive endeavor. As of 2010, relying on larger factory vessels with improved technology, coupled with the decrease in the abundance of some fish species in the southern-austral region of Chile, this

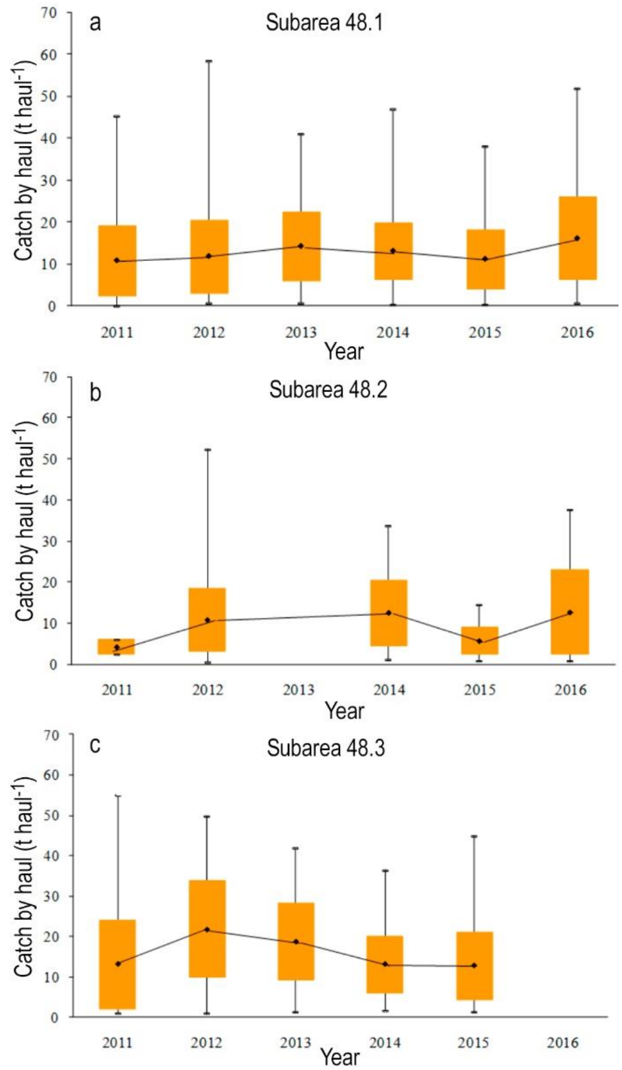

Figure 4. Annual krill *Euphausia superba* catch by haul (t haul^{-1}) between 2011 and 2016 carried out by FV Betanzos. a) Subarea 48.1, b) Subarea 48.2, and c) Subarea 48.3.

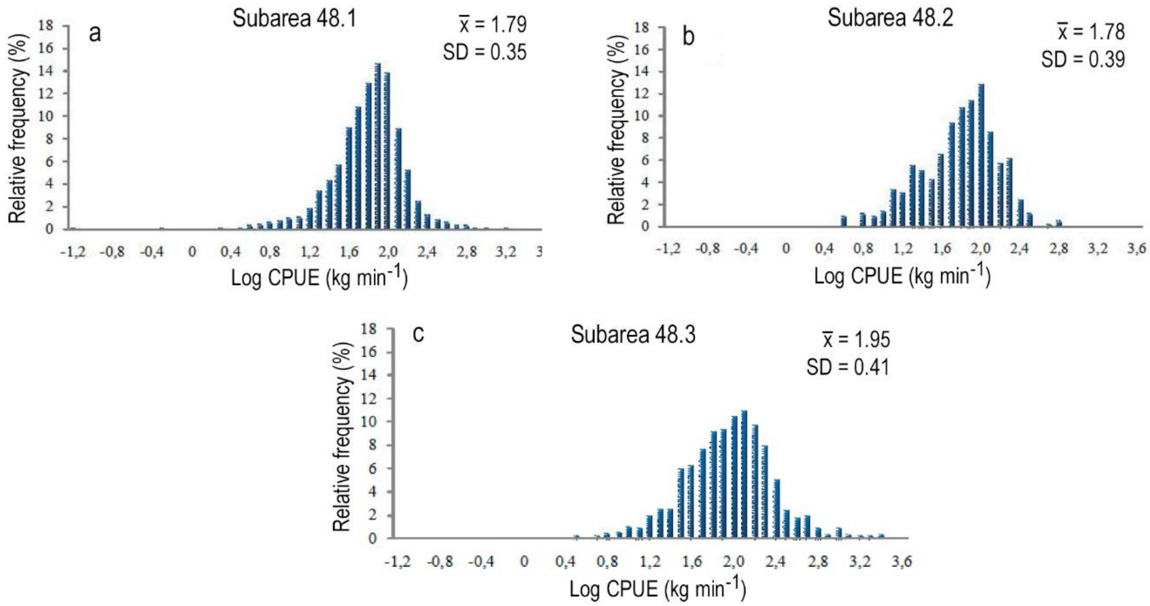

Figure 5. log CPUE (kg min^{-1}) relative frequency distribution for krill *Euphausia superba* carried out by FV Betanzos during the 2011-2016 period. a) Subarea 48.1, b) Subarea 48.2, and c) Subarea 48.3.

risk was finally assumed by two Chilean companies that then promoted the development of this activity positioning Chile as the only Latin American country to participate in this fishery. The six years (2011-2016) of Chilean krill fishery data analyzed demonstrate that successful and economically viable exploitation of this resource is feasible by Chile. Considering the increasing in the demand of krill in recent years due its different uses, the investment of this country in the described activity might be profitable.

The results obtained by data on krill fishery from the FV Betanzos allowed defining the operation of the ship in the different subareas used by CCAMLR to manage the activity. During the period analyzed, the operation of the ship was recorded in certain defined areas, such as the Bransfield Strait and north of the South Shetland Islands (Subarea 48.1), northwest of the South Orkney Islands (Subarea 48.2) and northeast of South Georgia Island (Subarea 48.3) (Figs. 6-8). The persistence in the use of these areas throughout the studied year's evidence that they represent habitual Antarctic krill concentration areas where CPUE values are satisfactory to fish this resource.

The results show the variability in the yields obtained per haul, although this is not a matter of concern as the successful hauls exceeded 96%. Also, it is evident that the most recurrent depths for the fishing of this species ranged between 20 and 120 m in Subareas 48.1 and 48.2, while in Subarea 48.3 the concentrations of *E. superba* were found in deeper waters, trawling as far as 280 m in depth (Fig. 2).

Antarctic krill possibly represents one of the most studied species, with more than 1,000 articles available regarding different aspects of it. In recent decades various multi-disciplinary studies have been performed, using technological developments and new modeling approaches. However, many details remain unknown; the views on these topics have not changed too much (Meyer, 2017). The complexity of the study associated with this resource and its fishery implies, at the very least, considering five fundamental aspects: a) the marine ecosystem as a whole, including its requirement by natural predators, b) the climate-induced variability in its biomass, c) the exact determination of the krill catch (green weight) by fleets belonging to different countries, d) the available scientific knowledge, and e) the human intervention in the Antarctic.

CCAMLR from 1973 has compiled information provided by vessels regarding their fishing operations, including the location of catches, the quantities extracted and the characteristics of the hauls and the fishing gear used. Also, the scientific observation system implemented by this Commission requires certain personnel embarked on a mandatory basis (national or international) who must collect information permanently aboard the vessels, including the collection of biological records based on samples obtained from krill catches, which are mainly directed to register frequency distributions of lengths, sex, and the presence of by-catch (species other than krill). These tasks can be helpful in providing information for

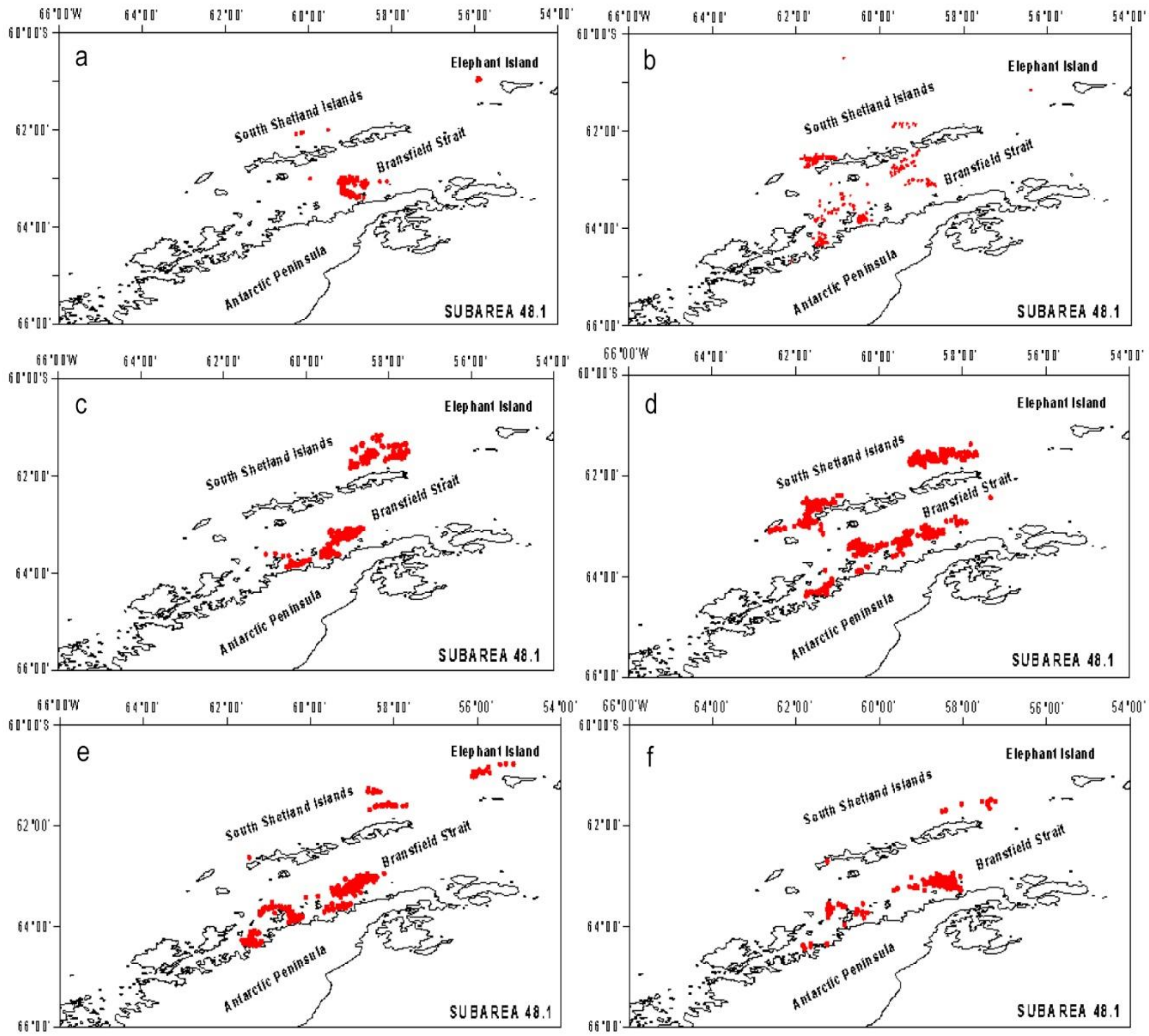

Figure 6. Geographic distribution of krill *Euphausia superba* fishing hauls carried out in Subarea 48.1. a) 2011, b) 2012, c) 2013, d) 2014, e) 2015, and f) 2016.

the investigation of possible interactions occurring between fishing operations and marine birds or mammals that are krill-dependent species.

In recent years, scientists and non-governmental organizations have become very concerned that the distribution of fishing efforts has tended to concentrate on some specific regions of the Bransfield Strait, where a large number of Antarctic species that feed on krill coexist. Several factors have contributed to the current concentration of fishing efforts in the same specific areas in this strait. Such factors include regulatory dispositions (*e.g.*, national or international regulations, licensing fees at South Georgia), environmental (*e.g.*, changing sea-ice conditions, weather conditions), economic (*e.g.*, subsidies, operational vessel costs, costs of searching and processing capacity), fleet dynamics (*e.g.*, Olympic fishing, voluntary coastal closures adopted by ARK, vessel cooperation, the experience of the skipper), and available sites for protection during adverse weather conditions.

For these reasons, the scientific community must focus on determining the real status of this resource and adopt conservation measures compatible with the krill exploitation, avoiding any potential impact on the remaining species that make up the Antarctic ecosystem, especially in those areas where fishing efforts have become concentrated. Some environmental organizations and NGOs are concerned about the development of this fishery and the impact that extraction could have on the communities that feed on this species. However, according to numerous specia-lists, there is no evidence of a decline in krill density

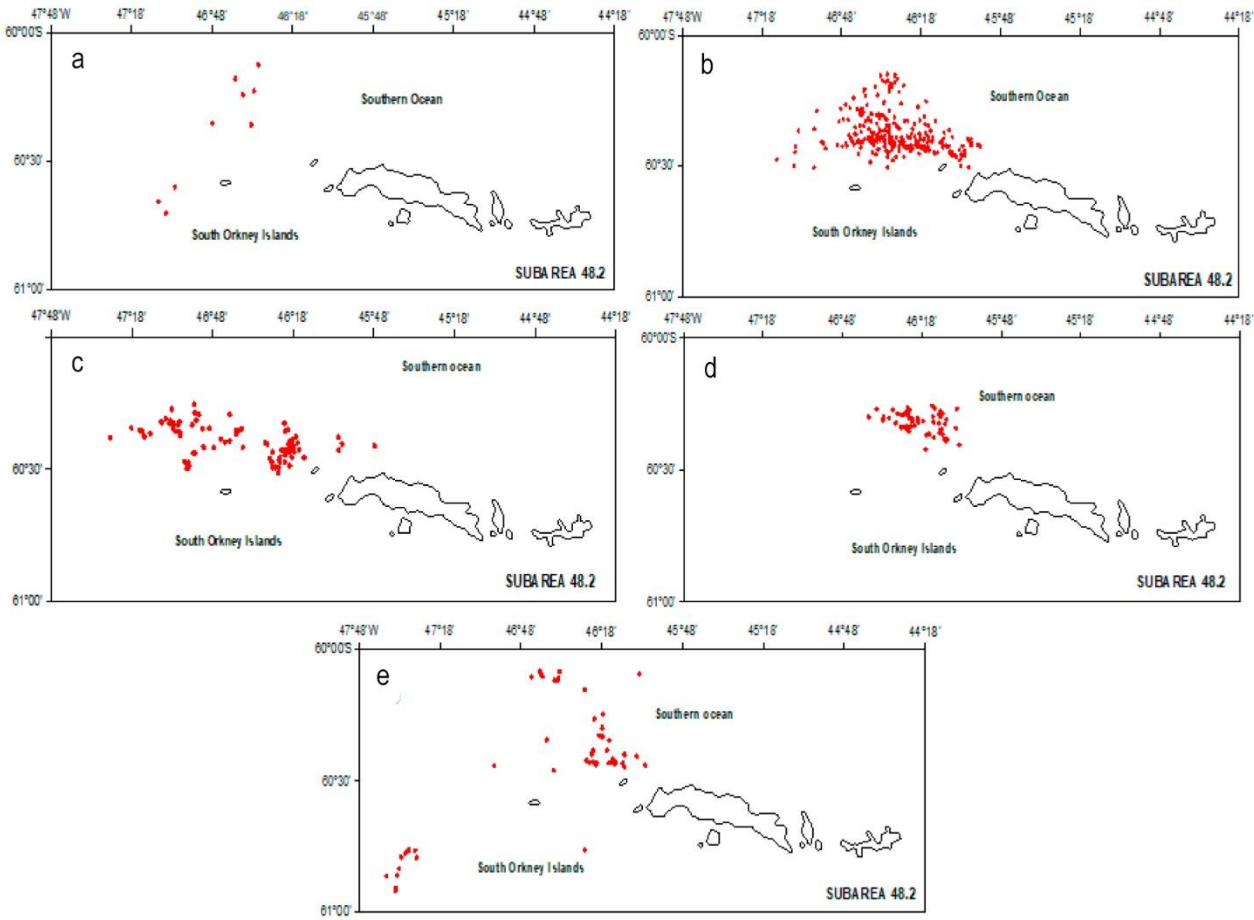

Figure 7. Geographic distribution of krill *Euphausia superba* fishing hauls carried out in Subarea 48.2. a) 2011, b) 2012, c) 2014, d) 2015, and e) 2016.

over the last 40 years. Krill density in the SW Atlantic in the said period has fluctuated, but there is no overall decreasing trend (Hill, 2016; Cox *et al.*, 2017, 2018). However, other evidence also exists showing a late-twentieth-century decline in Antarctic krill density (Loeb *et al.*, 1997; Atkinson *et al.*, 2004, 2014, 2019; Watters *et al.*, 2013; Hill *et al.*, 2019a). Nevertheless, it is essential to recognize that estimates of krill stock status based on currently available data will carry substantial uncertainties, and therefore require substantial precaution (Hill *et al.*, 2019b).

The results of the International Large-Scale Synoptic Krill Survey in Area 48, led by Norway, are expected to contribute towards developing integrated methods and estimates of *E. superba* biomass and distribution in Statistical Area 48 and at a subarea scale (*e.g.*, Bransfield and Gerlache Straits). Also, a regular synoptic assessment of Antarctic krill every five to ten years would help monitor any changes that occur in the population of this species, as well as in the different species that consume it and, in the environment (*e.g.*, global warming, changing climate), which would allow time to adapt management measures.

A precautionary and ecosystem approach to fisheries management has been adopted by CCAMLR (Table 1). According to current knowledge regarding Antarctic krill, the conservation measures implemented are considered adequate for the protection of this resource. However, due to the tendency of krill to predictably aggregate in specific locations, the krill fishery and krill predators may overlap in space and time, increasing the risk of severe impacts on some predators. Consequently, CCAMLR has recognized that additional mechanisms are required to mitigate the risk of interactions, leading to a risk-based approach to distributing the krill trigger catch limit in subareas 48.1, 48.2 and 48.3 (Constable, 2016; Kelly *et al*., 2017).

Another management option for the Antarctic krill fishery aimed at establishing the most convenient distribution of the trigger level in the different subareas

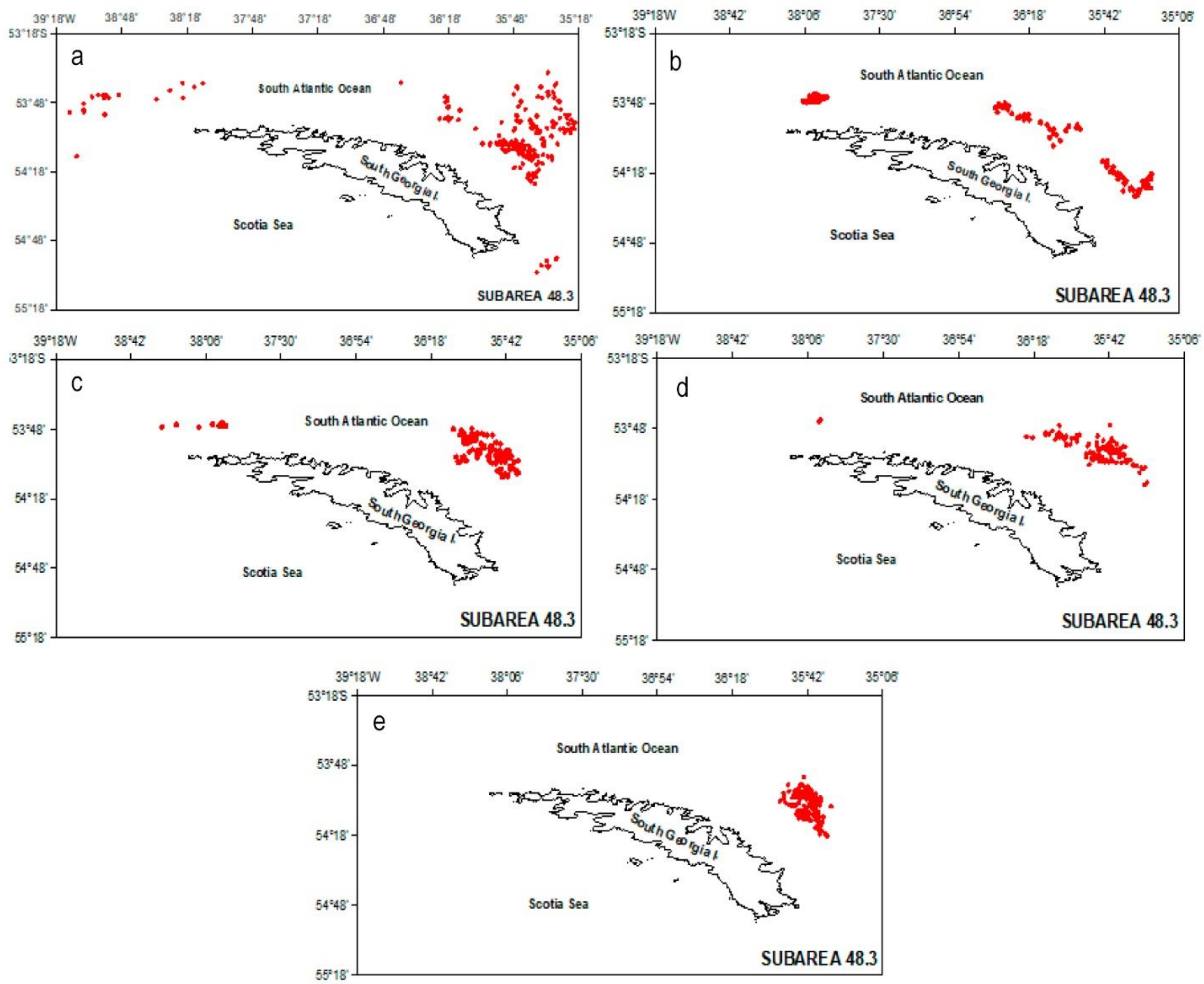

Figure 8. Geographic distribution of krill *Euphausia superba* fishing hauls carried out in Subarea 48.3. a) 2011, b) 2012, c) 2013, d) 2014, and e) 2015.

is called Feedback Management (FBM), which considers the use of the following information sources for its implementation: a) basic quantitative knowledge of the relationship between krill and its predators; b) historic information about spatial and temporal krill catch distribution patterns; c) intermittent data collection quantifying predator colony size and food requirement including routine data collection from the Ecosystem Monitoring Program (CEMP) sites; and d) continuous flow of acoustic data from the fleet to be used to assess density distribution and abundance of krill in hotspots (Constable, 1992; Watters *et al*., 2016; Kraft *et al*., 2018b). FBM has been considered as an alternative approach for decades, but still lacks a plan that can be implemented in realistic cost and effort levels (CCAMLR, 2017a). The Commission shall seek to update or replace the conservation measure CM 51-07, which established the present distribution percentage of the trigger levels by subarea, in progressing feedback management, not later than the end of the 2020/21 fishing season, at which time this conservation measure will expire if an agreement has not been reached. Said impending end-date constitutes an enormous pressure for the scientific world, as it must propose a solution to this delayed commitment within the next two years.

In parallel, the proposal submitted by the Governments of Argentina and Chile to develop several Marine Protected Areas (MPAs) to conserve marine biodiversity in the CCAMLR Convention Area (CCAMLR, 2018b; Delegations of Argentina and Chile, 2018) is under study. The MPAs suggested by both countries in Domain 1 of the Antarctic region (D1MPA) would have an extension of approximately 466,000 km^2, comprising three different management zones: General Protection Zone (GPZ) in which all types of Antarctic krill fishing would be prohibited; Krill Fishery Research Zone (KFRZ), which would allow fishing under the general rules established by CCAMLR; and a Special Fishery Management Zone (SFMZ), in which it would be possible to fish under research conditions. These incorporate the conservation of different objectives, the need for a better understanding of the krill fishery activity, and the current fishery management strategy (CCAMLR, 2018b). However, this proposal has not achieved the expected progress, and its discussion possibly will be postponed in the coming years.

On the other hand, the Marine Stewardship Council (MSC) standard, to which vessels participating in the exploitation of this species are being subjected, requires that fisheries do not cause significant and irreversible harm to the ecosystems in which they operate. Currently, only two fishing companies are certified to operate in the Antarctic krill fishery: Aker Biomarine (Noruega) and Deris S.A.-Pesca Chile (Chile).

The entry of one new krill fishing vessels from China (FV Fu Yuan Yu) is proposed for the 2019-2020 period. Incorporating technological advances for detecting krill concentrations, *e.g.*, gliders and sail-buoys, which would increase the efficiency of searching for fishing grounds. It is thus expected that *E. superba* catches will increase in the next few years, although it will be difficult to quickly reach the maximum of 620,000 t of the total annual catch has been set as a precautionary measure by the CCAMLR. However, the current management approach is based on generalization at a large scale and does not include the details necessary for management at finer scales (Thathan *et al.*, 2019).

Finally, advancing research into the biological cycle of *E. superba* and into the studies that determine the effectiveness of the current conservation measures is urgent; or into defining those measures necessary to achieve an adequate balance between fishing activities and the feeding requirements of the animals that inhabit this unique Antarctic ecosystem. Also, regular acoustic surveys at different times of the year will increase understanding surrounding the seasonal krill dynamics. All this represents a significant challenge to develop a strategy to better fund and share the burden for research needed and to achieve in the shortest time possible the harmonization between the various strategies under study, such as risk assessment, FBM and MPAs. However, the level of precaution intended by CCAMLR Conservation Measure 51-07 should be retained while such investigations and solutions are agreed upon and implemented.

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