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ARTICLE

Bycatch in the Antarctic krill (*Euphausia superba*) trawl fishery

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Abstract

Bycatch of nontarget species can contribute to overfishing and slow efforts to rebuild fish stocks. Controlling bycatch is fundamental to sustainable fishing and maintaining healthy populations of target species. The Antarctic krill (*Euphausia superba*) fishery is the largest volume fishery in the Southern Ocean. Understanding the significance of bycatch and its diversity is critical to managing this keystone species. Registered bycatch data from the Antarctic krill fishery in the southwest Atlantic sector of the Southern Ocean were analysed. Observers collected data following an internationally agreed method during the 2010–2020 fishing seasons, with a 20 (±9) % coverage of fishing activity of Total catch of Antarctic krill which increased from 200,000 tonnes to 450,000 tonnes, with the greatest increase over the last 3 years. Except in 2010 (2.2%), the bycatch ratio was stable and ranged 0.1–0.3%. Fish dominated the bycatch, followed by tunicates and other crustaceans. Observer coverage was high, and bycatch levels were generally low across gear types. Given that accurate information on bycatch is important for sustaining developing fisheries, maintaining high observer coverage of this fishery will be important for detecting impacts from a warming climate and for moving back into historical fishing grounds.

KEYWORDS
crustaceans, euphausiids, icefish, fisheries management, Scotia Sea, Southern Ocean

1 | INTRODUCTION

In any type of marine resource exploitation, knowledge about total catch of a target species, and the unintended catch of undersized individuals and species, is crucial for development and sustainability of a fishery (e.g. Bastardie et al., 2021). Global fisheries bycatch is a major threat to the world's oceans, contributing to overfishing, slowing efforts to rebuild fish stocks previously depleted through overfishing, disproportionately impacting species that are endangered or through the unintentional targeting of key life history stages such as gravid females (Davies et al., 2009; Hall et al., 2000; Kelleher, 2005; Komoroske & Lewison, 2015). Appropriate monitoring and fisheries management can mitigate bycatch but require standardised bycatch data to be robustly recorded and effectively disseminated (Gilman et al., 2020). About 10.8% of contemporary global catch is discarded and is approximately half of the annual global discard rate estimated in the late 1980s (Gilman et al., 2020). Almost 60% of total annual discards globally were from combined trawl fisheries, with crustacea having the highest discard rate (32.4%; Gilman et al., 2020).

Antarctic krill (*Euphausia superba*) are an important fishery resource in the Southern Ocean, and its commercial exploitation is expected to increase as a source of protein for human and animal consumption (Kawaguchi & Nicol, 2020; Nicol et al., 2012). The fishery is managed under the Convention for the Conservation of

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Antarctic Marine Living Resources (CCAMLR), which applies a precautionary approach with a set annual catch limit for the southwest Atlantic sector of 620,000 tonnes (CCAMLR Conservation Measure 51–01) that was spatially subdivided in 2009 across Food and Agriculture Organization (FAO) Statistical Subareas 48.1, 48.2, 48.3 and 48.4 (Figure 1; CCAMLR Conservation Measure 51–07). This management approach was used to safeguard against potential detrimental effects on other ecosystem components, including the Antarctic krill population itself, from effects of localised overexploitation with insufficient knowledge (McBride et al., 2014, 2021). Biomass of Antarctic krill for the region fished commercially has been estimated to be approximately 60 million tonnes (CCAMLR, 2010; Krafft et al., 2021). Total annual catch of Antarctic krill from this region ranged 160,000–450,000 tonnes during 2010–2020 (https://fishdocs.ccamlr.org/FishRep_48_KRI_2020.pdf).

The contemporary operational pattern of the Antarctic krill trawl fishery is to begin the fishing season in November–December in Subarea 48.2 (waters adjacent to the South Orkney Islands), move to Subarea 48.1 in March–April, while maintaining some activity in Subarea 48.2, and then move to Subarea 48.3 (South Georgia Island waters) in June–September for the end of the season. This spatial distribution pattern is governed by many factors, including sea ice coverage, Antarctic krill quality and availability and other logistical factors. For example, fishing during 2010–2020 in Subarea 48.3 fluctuated between years, perhaps because the required fishing license fee leads to fishing only when opportunities in 48.1 and 48.2 are limited. This consistent pattern of distribution of the Antarctic krill fishing fleet was also reflected in the temporal distribution of bycatch among and between subareas. In terms of fishing technologies employed, two different trawling methods are employed by the fleet. The traditional (conventional) method included, as in other pelagic fisheries, large pelagic otter trawls that are towed and catch in the codend was hauled onboard, whereas the other technique included a continuous pumping of catch from the fishing depth directly to the vessel via a vacuum hose. Conventional trawlers normally operated one trawl with large meshes in the front part that gradually reduced toward the codend. Continuous trawlers operated two pelagic beam trawls with small meshes throughout the length of the trawl. Typical towing speed is 1.5–2 knots for continuous trawlers and approximately 4–5 knots for conventional trawlers.

Antarctic krill are utilised by human populations primarily in two ways, firstly in an indirect fashion as fish meal for aquaculture and secondly the oil is directly consumed by humans in health food

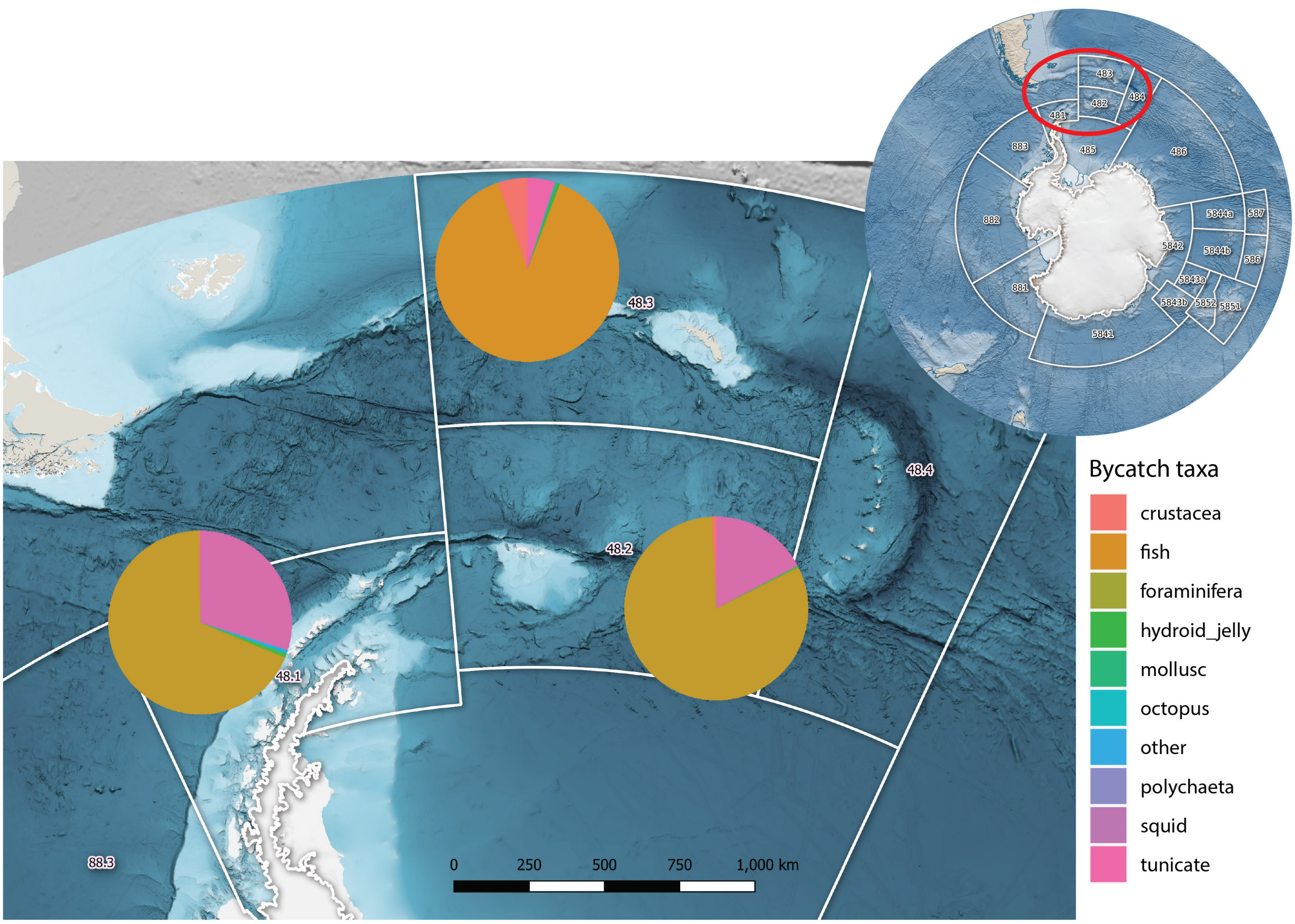

FIGURE 1 Proportional distribution of cumulative bycatch taxa recorded from the Antarctic krill fishery in subareas 48.1, 48.2 and 48.3 of the Southwest Atlantic sector of the Southern Ocean and across the Scotia Sea during the 2010–2020 fishing seasons

products such as Omega-3 oils. Given the size of the fishery, the importance of its products to human populations, the exploitation rate relative to estimated global stock size and consequently the desire to expand the fishery, understanding the degree and significance of bycatch and its impact on Southern Ocean ecosystem processes is becoming increasingly important.

The definition of bycatch used by CCAMLR includes "the incidental catch of all living and non-living material (excluding target species)" (www.ccamlr.org/node/73033). Mitigation strategies are often implemented to help reduce bycatch in fisheries (Zeller et al., 2018). However, generally bycatch data are rarely recorded or disseminated efficiently with a level of detail required (e.g., species-specific data at fine spatiotemporal resolution) to craft and implement timely and effective mitigation strategies, which further compounds this challenge (UNGA, 2015). Consequently, when available, fine-resolution bycatch data can enhance understanding of species' risk, which fisheries and gear types pose the greatest threats, and which management strategies are most effective (Cook, 2019; Jensen et al., 1988). In this context, CCAMLR developed a Scheme of International Scientific Observation (SISO), including a manual that specifies a standardised protocol for observing and recording fishing activity (CCAMLR: www.ccamlr.org/node/73033). The SISO manual contains a comprehensive range of scientific observation guidelines and reference materials and is one of the most important sources of scientific information for assessing impacts of fishing on the Southern Ocean ecosystem. Observers record information systematically on, inter alia, gear configuration, catch composition and biological measurements of target and bycatch taxa resolved in some cases to fine taxonomic resolution (e.g. Table S1). All data are submitted by observers to the CCAMLR Secretariat using standardised logbook forms designed for gear type (e.g., krill trawl). Typically, in other fisheries, the part of the target-species catch that is not landed due to damaging interactions with fishing gear is termed discards and is often thrown overboard (Gilman et al., 2020); however, fisheries operating south of 60°S are not permitted to discard unwanted catch.

Considering the importance of understanding fisheries bycatch in an ecosystem management context, our aim was to characterise the degree, significance and functional diversity of bycaught taxa within the trawl fishery for Antarctic krill. As the fishery has both a spatial and seasonal pattern of operation, we further decomposed this bycatch into its spatiotemporal distribution with the goal of providing more management-relevant information. Specifically, understanding spatiotemporal patterning of bycatch throughout the current distribution of the fishery may provide insight into potential bycatch issues should the fishery either expand into previously unfished areas or re-entering historical fishing grounds for which no information exists. To achieve this, we analysed data from the Observer Bycatch (krill) dataset of the CCAMLR C1 fisheries database for the period over which CM51-07 has been in effect (2010–2020), including registrations from the entire fishing fleet targeting Antarctic krill.

2 | MATERIALS AND METHODS

The fishery for Antarctic krill has a year-round season, starting on 1 December and ending on November 30 of the following year. Herein, each CCAMLR fishing season was designated as the year in which the fishing season began. SISO observers used two different sampling strategies during the study period. From 2010 to 2018, observers collected 25 kg sampled randomly from the trawled catch, from which taxa were sorted. After all bycatches had been sorted from 25-kg samples, observers re-examined a 10-kg subsample and two 1-kg sub-samples of each 25-kg sample. Beginning in 2018, the procedure was changed to only examine the 25-kg sample, because 98% of species present were identified from the 25-kg sub-sample (https://fishdocs.ccamlr.org/FishRep_48_KRI_2020.pdf).

During conventional fishing, the haul duration was typically 1–2 h, whereas continuous trawling could be deployed for several days. Observers sampled from each conventional haul, and for continuous trawls, a haul was defined as 2-h periods from which samples were collected. Bycatch data were logged by observers across two different tables within the broader C1 data set, with differing reporting requirements for each. These two different procedures overlapped for 4 years (2010–2014), and while we used the contemporary methodology described above, we highlight the dynamic adaptations in bycatch recording methodologies during 2010–2014. Similarly, other data exist that characterise catch in terms that are not directly incorporated into commercial product. Discards are typically reported in other fisheries as nontarget catch or damaged target species that are returned back to the sea, but this is not permitted within the Antarctic Treaty System south of 60°S. However, data on content of discards (species composition and weight) were recorded within the broader C1 fishery database. To avoid confusion in common terminology surrounding discards, we analysed and quantified observer-collected bycatch only, but presented the C1 fishery-reported discard data to describe broader taxonomic composition of nontarget species relative to damaged (or otherwise imperfect) target species (Figure S1).

For simplicity, we extracted target species catch, effort and bycatch from the C1 and associated bycatch data from the Obs_Haul_Bycatch_Krill table containing all observer-reported bycatch information throughout the study period. These bycatch data reflected individual Observer_Logbooks completed during the respective observation period. Data exploration revealed several inconsistencies within observer bycatch data, such as reporting bycatch in grams rather than kg and possible entry errors in the number of individual counts of bycatch taxa recorded. Given subsampling from the initial 25-kg sample during 2010–2018, numerous entries of the sample type (25, 10 or 1 kg) were incorrectly entered, thereby causing bycatch weights that sometimes exceeded the sample weight. In cases where a misreporting of the unit of measurement was suspected, provided the reporting error was consistent across the entire observer logbook, then the bycatch masses for that logbook were rescaled into kg. In all other cases, where the suspected entries were unverifiable, data from the entire logbook were excluded. One vessel was excluded entirely due to reporting bycatch both from sampled hauls and factory processing. Final data reflected a subset of the Obs_Haul_Bycatch_Krill table and associated records from the C1 catch and effort dataset.

Bycatch weight in each sample were expressed as bycatch-per-kg of each trawl sampled, which were then used to expand the estimated bycatch within each trawl to an estimated weight in tonnes and taxonomic composition of bycatch. For bycatch taxa, observers recorded 37 taxonomic families that were condensed into 10 functional groups (Table S1). Estimates of observed bycatch weight and taxonomic composition were grouped by fishing season and FAO statistical Subarea to describe proportions and weights of bycatch across the fishery during the 2010–2020 fishing seasons. To estimate annual bycatch at the scale of the entire fishery, the mean bycatch ratio (ratio of bycatch to total catch weight) for each year across all Subareas was multiplied with the annual catch of Antarctic krill reported during each fishing season. Analyses were conducted within the R 4.1.2 programming framework and visualised using the ggPlot2 R package (Wickham, 2016) and Quantarctica (https://www.npolar.no/quantarctica/).

TABLE 1 Fishing vessels, observed hauls, total hauls and observer coverage for the Antarctic krill fishery in subareas 48.1, 48.2 and 48.3 of the Southwest Atlantic sector of the Southern Ocean and across the Scotia Sea during the 2010–2020 fishing seasons

Year	Vessels (no)	Observed hauls (no)	Total hauls (no)	Observer coverage (%)
2010	3	138	4458	3
2011	4	422	3860	11
2012	9	904	3660	25
2013	11	706	3275	22
2014	10	1109	4630	24
2015	8	999	4816	21
2016	11	1571	5260	30
2017	8	706	4785	15
2018	8	901	5761	16
2019	9	995	4946	20
2020	11	1896	5047	38

3 | RESULTS

During the 2010–2020 fishing seasons in the southwest Atlantic sector of the Southern Ocean and across the Scotia Sea fishing only occurred in Subareas 48.1, 48.2 and 48.3 (Figure 1). Total annual fishing effort averaged 4591 hauls (SD = 734 hauls) and observer coverage averaged 20% (SD = 9.4%; Table 1). Fish dominated in the bycatch in all three areas, followed by tunicates in the 48.1 and 48.2 areas, and other crustaceans and tunicates in Subarea 48.3.

The highest weight of bycatch was during March–April in Subarea 48.1, February–March in Subarea 48.2, and June–August in Subarea 48.3 (Figure 2). Total bycatch was 25.1 (SD = 41.9) tonnes in Subarea 48.1, 14.9 (SD = 25.6) tonnes in Subarea 48.2 and 40.2 (SD = 54.8) tonnes in Subarea 48.3 (Figure 2).

Total catch of Antarctic krill more than doubled, from 200,000 tonnes to over 450,000 tonnes, during 2010–2020 (Figure 3, Table 2). Catch increased during the preceding decade but increased the most during the last 3 years (Figure 3, Table 2). Except in 2010 (2.2%), the bycatch ratio from SISO Observer logbook data ranged 0.1–0.3%. Total annual observed bycatch averaged 6.3 tonnes (±6.2 tonnes, range = 0.1–19.5 tonnes) by continuous pumping trawlers and 19.2 tonnes (±20.5 tonnes, range = 0.9–51.3 tonnes) by conventional trawlers during 2010–2020 (Figure S2).

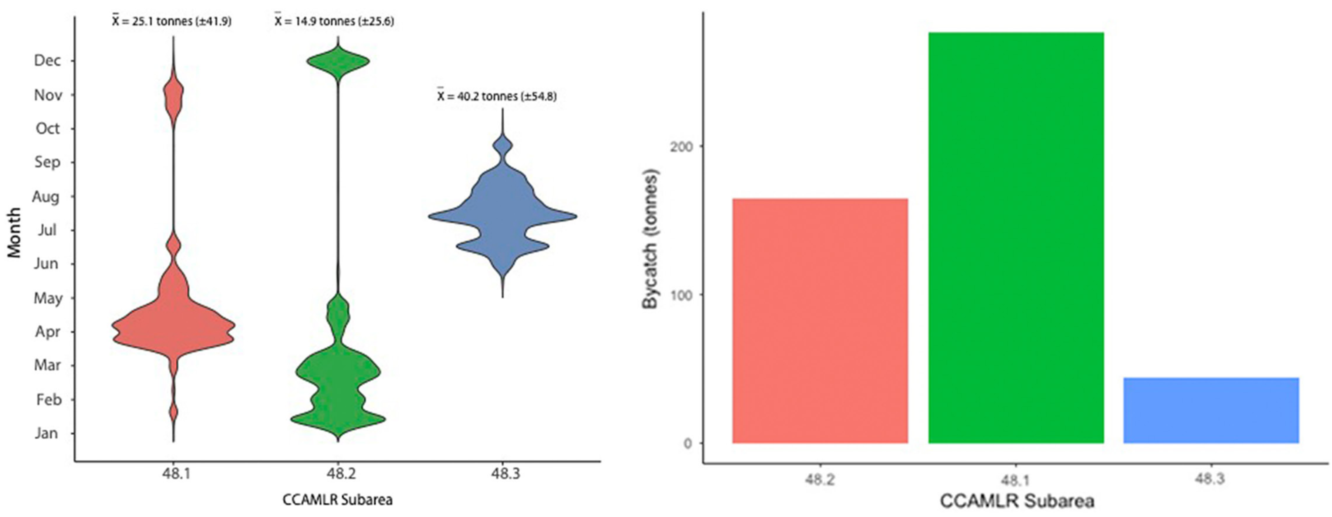

FIGURE 2 Seasonal distribution (left panel) and total distribution of bycatch (right panel) the Antarctic krill fishery in subareas 48.1, 48.2 and 48.3 of the Southwest Atlantic sector of the Southern Ocean and across the Scotia Sea during the 2010–2020 fishing seasons

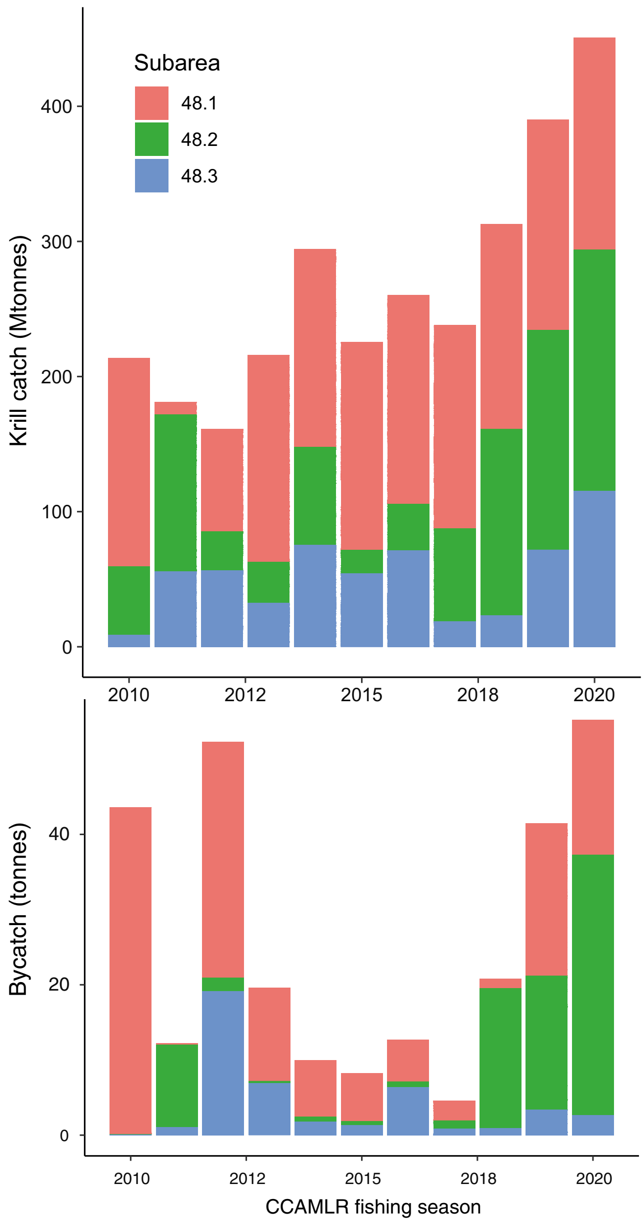

FIGURE 3 Total catch (top pane) and bycatch (bottom panel) in the Antarctic krill fishery in subareas 48.1, 48.2 and 48.3 of the Southwest Atlantic sector of the Southern Ocean and across the Scotia Sea during the 2010–2020 fishing seasons

4 | DISCUSSION

Sporadic reports representing parts of data associated with bycatch in the Antarctic krill fishery exist (e.g. CCAMLR Secretariat, 2021; Iwami et al., 2001; Iwami & Naganobu, 2008), but our study is the first time these data have been reviewed in the context of characterising their ability to describe bycatch rates and composition in different fishing areas and throughout the season. Bycatch in the Antarctic krill fishery (range = 0.1–2.2%) was lower than for other trawl fisheries globally (range = 10–55%), of which pelagic otter trawl fisheries are lowest (10%; Gilman et al., 2020). Bycatch sampling of fishing activity (observer coverage) in the Antarctic krill fishery was also high with a 20% coverage. If the observer samples are an unbiased sample of the fishery, literature review and simulation studies suggest that coverage levels of at least 20 per cent for common species, and 50 percent for rare species, would give reasonably good estimates of total bycatch (Babcock et al., 2003). The Southern Ocean has a short-chained food web, with many species of which few dominate its biomass (Clarke, 1985). Antarctic krill are targeted by trawlers when aggregated in swarms large enough to maintain optimal factory productivity that seemingly contain few other species (this study), which likely explains the low bycatch in the Antarctic krill fishery compared to trawl fisheries in other ecosystems, particularly the large difference between our study and estimated discard for other crustacean trawl fisheries (Gilman et al., 2020).

Catch levels in Subarea 48.1 were stable at the quota level since its inception (155,000 tonnes), but increased in Subarea 48.2, particularly in 2018–2020, as this region became the primary Subarea for harvesting Antarctic krill, and fluctuated annually in Subarea 48.3 where the population relies on influx from other regions (Tarling et al., 2007; Whitehouse et al., 2008). While overall catch increased over the preceding decade, the greatest increases occurred during the last 3 years, along with associated higher levels of bycatch. The elevated bycatch we describe in 2010 may reflect unintentional misreporting while implementing the newer methods described above. Last, observer coverage in 2010 may have been too low to reliably estimate mean annual bycatch.

In the context of providing management relevant information concerning the potential ecosystem impact of bycatch, a higher degree of taxonomic information may be important. Reporting bycatch to the species level may enable more precise spatiotemporal monitoring, particularly for rare or ecologically important species (ICES, 2022). However, increasing resolution in the description of bycatch would likely require more taxonomic training of observers doing onboard monitoring, with a commensurate increase in workload. In the management of some other trawl fisheries, large efforts are devoted to streamline and reduce manual bycatch monitoring methods by employing new technologies like continuous camera monitoring and near-real-time bycatch description using machine and deep learning computational approaches (e.g. Sokolova et al., 2021), which likely will be the future solution also in the Antarctic krill fishery.

Reported discards from the Antarctic krill fishery decreased from almost 2000 tonnes in 2010 to nearly zero from 2018 onwards. These earlier, relatively high, levels of discards were presumably damaged or imperfect and therefore unfit for production. Given that the Conservation Measure CCAMLR put in place limited the discarding of catch to north of 60°S, the trend of decreasing discards to zero presumably reflects the refinement and development of fishing technology over time culminating in the incorporation of all discards into the meal production process in recent years. Similarly since 2018 once bycatch is recorded to determine ecosystem impacts, it has then been used in meal. Consequently, bycatch in the Antarctic

Year	Tonnes Total catch	Observed catch	Bycatch	Estimated total bycatch	Bycatch ratio
2010	213,667	1977	44	4710	0.022
2011	181,012	6482	12	341	0.002
2012	161,244	18,724	52	451	0.003
2013	216,056	10,064	20	422	0.002
2014	294,149	17,504	10	167	0.001
2015	225,647	13,782	8	134	0.001
2016	260,158	23,622	13	139	0.001
2017	238,626	7470	5	147	0.001
2018	313,021	9866	21	660	0.002
2019	390,195	14,461	41	1118	0.003
2020	450,813	24,019	55	1036	0.002

TABLE 2 Total catch, observed catch, observed bycatch, estimated total bycatch and bycatch ratio for the Antarctic krill-fishery in subareas 48.1, 48.2 and 48.3 of the Southwest Atlantic sector of the Southern Ocean and across the Scotia Sea during the 2010–2020 fishing seasons

krill fishery is not a discarded waste product of marine resources as in other fisheries but a utilised aspect of the catch. The krill fishery is expanding, with two different fishing techniques both of which fluctuate greatly in rates of discard but with no clear difference between them. Future studies should assess whether one method consistently has a lower bycatch than the other method.

Data on incidental mortality of seabirds and marine mammals are also collected by vessel crews and observers (https://fishdocs.ccamlr.org/FishRep_48_KRI_2020.pdf). However, these data are reported to CCAMLR as Incidental Mortalities Associated with Fishing (IMAF) in a more detailed format and are not part of the bycatch or discard data used in our study. Discussions are ongoing within scientific groups of CCAMLR regarding the context of IMAF data and how best to arrange appropriate reporting systems of such data from the krill fishery (SC-CAMLR-XXII, 2003, Annex 5, paragraph 6.231). Placing the level of IMAF within CCAMLR fisheries into a global context will form the basis for future studies.

Total catch of Antarctic krill increased during 2010–2020 and is expected to continue to increase in the future due to increased marked demand by the fish-farm feed industry and omega-3 nutraceuticals for human consumption, which constitute major products for krill. The fishery is also expected to expand beyond its current geographical extent into historical fishing grounds used in the 1970s and 1980s. Newer fishing vessels have longer range and more storage capacity and extended use of supply vessels facilitate logistical challenges that can make fishing in these areas profitable. Quotas are already set and available in the South-West Indian sector of the Southern Ocean, but the potential diversity and distribution of bycatch species is also likely to differ (Nicol et al., 2010). The fishery today is well monitored through high observer coverage, which makes the approach robust in detecting any rapid changes in bycatch levels or composition in existing as well as in new fisheries. Maintaining a high observer coverage of fisheries bycatch is important as the temporal stability in bycatch patterns also will be impacted by a warmer climate (IPCC, 2018). Accurate data is essential to understand whether management strategies and implementing fishing method modifications are effective at mitigating impact. The review of the bycatch species we present here included groupings on a high taxonomical level, but observer data are available at a finer taxonomic resolution. For some species or groups, their representativeness to describe impacts from changes in the physical and biological environment can also be studied.

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CONFLICT OF INTEREST

The authors hereby declare that the current work do not involve any competing interests or any Financial Disclosure.

DATA AVAILABILITY STATEMENT

Permission has been obtained for the use of Fine-scale catch and effort data for the trawl fisheries (C1 data), following the 'Rules for Access and Use of CCAMLR Data' (www.ccamlr.org).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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