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# Adjusting the management of the Antarctic krill fishery to meet the challenges of the 21st century

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**Antarctic krill (*Euphausia superba*) is the central prey species in the Southern Ocean food web, supporting the largest and fastest-growing fishery in the region, managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). Climate change is threatening krill populations and their predators, while current catch limits do not take into account climate variability or krill population dynamics. In 2024, CCAMLR was unable to renew its spatial catch limits, highlighting the urgent need for improved management of the krill fishery to prevent any harm to the Southern Ocean ecosystem. To address this, we propose a management framework that integrates variability in krill recruitment and key pathways between spawning and nursery areas—a krill stock hypothesis—to inform decisions on catch limits and conservation measures. Implementing this approach will require targeted data collection, which we propose can be achieved through a multisector collaborative network that combines traditional and new technologies, including the use of fishing vessels as data collection platforms. We use case studies to demonstrate how fisheries can contribute to data collection while promoting sustainable management. A major challenge in this effort is securing long-term funding for data collection, which is critical for managing climate-sensitive populations of high commercial interest. We therefore recommend using the industry as a source of funding, research platform and data provider, alongside national research funding opportunities. Given the fundamental role of krill in the Southern Ocean ecosystem, its decline would have cascading effects on predators and essential ecosystem services.**

Antarctic krill | CCAMLR | fisheries management

In 2024, the Antarctic krill (*Euphausia superba*) fishery landed 0.5 million tons (Mt) (1), making it the largest by tonnage caught in the Southern Ocean. Regulated by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), krill is within the ~7% of global marine stocks classified as underexploited by the Food and Agriculture Organisation (FAO) (2). The fishery's gross annual value is estimated between USD 250 and 900 million (3–5). This makes it a significant industry, comparable in scale to well-established national fisheries, such as the Norwegian cod fishery (USD 660 million in 2021) (6), the US tuna fishery (USD 118 million in 2020) (7), and the Canadian pelagic fisheries (USD 118 million in 2021) (8). Krill is primarily processed into two main products: meal, to support the aquaculture industry (9), and Omega-3 oil for the nutraceutical (diet supplement) market (4).

Krill are filter-feeding crustaceans that can grow over 6 cm in length, form massive swarms, and live for over six years. Global estimates of krill biomass range between 300 and 500 Mt wet weight—arguably the largest of any wild species (10). Due to this immense abundance, krill serve as the foundation of the Southern Ocean food web, playing a crucial role in maintaining ocean productivity, functional diversity, and carbon sequestration (11, 12).

Although krill are distributed throughout the Southern Ocean, krill fisheries are concentrated in the southwest Atlantic sector of the Southern Ocean (CCAMLR Area 48, Box 1*A*), which contains a significant amount of krill biomass (~63 Mt) (13). This region is considered a critical krill hotspot, supporting numerous krill-dependent predators, including penguins, seals, and

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**Box 1**

**Overview of the krill fishery. (A) Catch distribution and (B) catch dynamics.**

# Principles of CCAMLR's krill fishery management

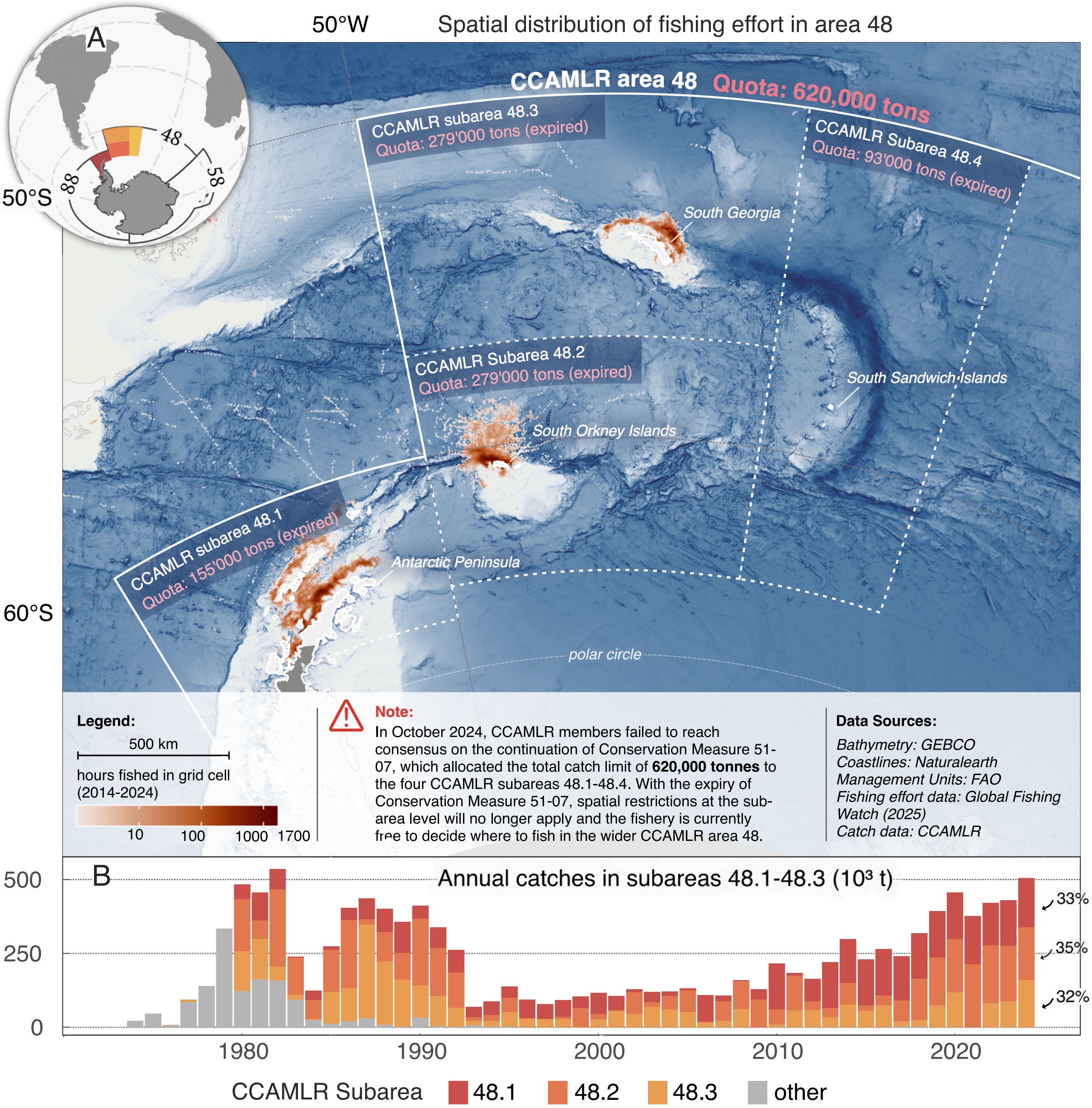
**Article II of the CCAMLR Convention** sets out the basic conservation framework for the use of living resources in the Southern Ocean.

According to Article II, conservation includes "rational use" with three underlying conservation principles (*summarized*):

**1)** Prevention of decrease in the size of any harvested population to levels below those which **ensure its stable recruitment.**

**2) Maintenance of the ecological relationships** between **harvested**, **dependent** and **related populations** of Antarctic marine living resources.

**3)** Prevention of changes or **minimization of the risk of changes in the marine ecosystem** which are not reversible over two or three decades, taking into account the state of available knowledge of the direct and indirect impact of harvesting, the introduction of alien species and of the effects of environmental changes.

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baleen whales (14–16). Conservation of the wider Southern Ocean ecosystem, therefore, depends on a comprehensive, science-based understanding of krill population dynamics and the impact of fishing on this key species.

Since 1982, CCAMLR has regulated the krill fishery to ensure that it does not cause irreversible harm to target and nontarget species or the wider marine ecosystem (17) (Box 1). To meet this conservation mandate, CCAMLR's management strategy relies on data on krill biomass, distribution, and predator population dynamics.

Since 1991, the operational upper annual catch limit for krill has been set at 0.62 Mt. for the entire southwest Atlantic fishery (part of CCAMLR Area 48). Although this annual catch represents only about 1% of the estimated krill biomass in this region, concerns about the sustainability of the fishery are growing. Since 2024, these concerns have become more pronounced due to the lack of spatial restrictions on the distribution of the catch quota (Box 1 *A* and *B*). The risks contributing to these concerns include:

- *Fluctuating Biomass*: Krill biomass can vary dramatically from year to year, introducing uncertainty about sustainable catch levels (18).
- *Spawning Stock Vulnerability*: In some years, the proportion of krill available for spawning is low, potentially affecting recruitment (19).
- *Climate Change Impact*: Environmental shifts, such as melting of sea ice and rising ocean temperatures (20), are expected to exacerbate these fluctuations, adding to the complexity of krill populations (21–23).
- *Competition with Wildlife*: Intensive fishing in key foraging areas of krill-dependent predators could threaten the survival of local wildlife (24–26).
- *Targeting of Spawning Stocks*: The fishery may disproportionately exploit localized krill spawning stocks, undermining their resilience (19).
- *Recovery of Predator Populations*: As populations of krill-dependent predators, such as baleen whales, continue to recover, the overall demand for krill will likely increase, leading to increasing competition (27).

These challenges, compounded by the rapid expansion of the krill fishery and the increasing spatial concentration of fishing activity (28, 29), are not yet fully addressed in the current CCAMLR management framework. However, they must be central considerations when setting catch quotas in this krill-dependent ecosystem.

To improve management strategies, we propose incorporating a Krill Stock Hypothesis, a conceptual model that improves understanding of krill populations and their spatial habitat use in a changing climate. We highlight the benefits of the Krill Stock Hypothesis as an effective tool for fishery management and ecosystem conservation and outline how targeted data collection can support this hypothesis. We also present a roadmap for refining krill fisheries management, emphasizing the role and responsibility of the industry as an additional source of funding, research platform, and data provider. Strengthening cross-sectoral collaboration and using both traditional and new technologies for data collection will be crucial to ensure the long-term sustainability of the krill fishery and the conservation of the Southern Ocean ecosystem.

## Current Krill Fishery Management Under CCAMLR

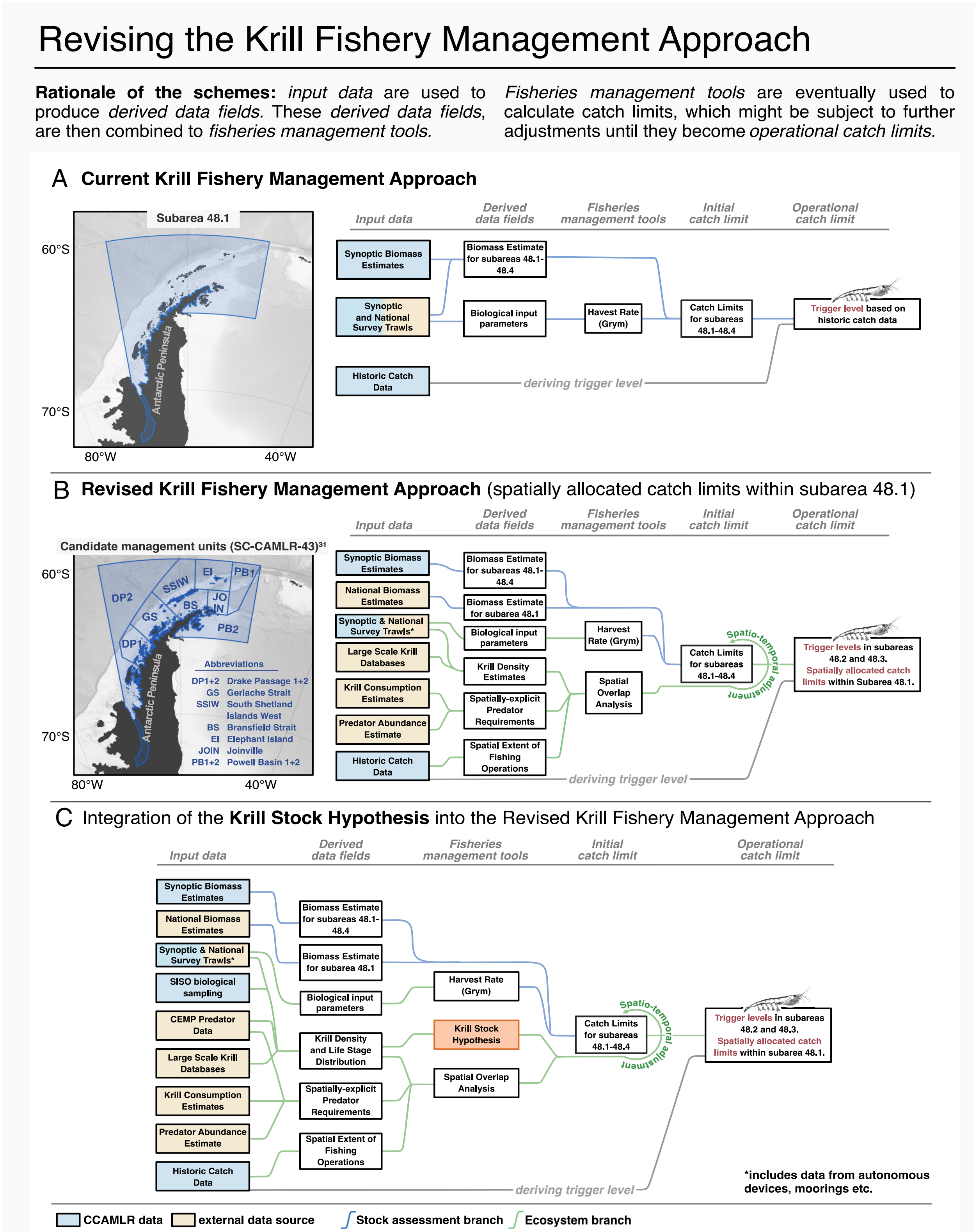
**Krill Catches Reaching New Heights.** The Antarctic krill fishery has fluctuated considerably over the past decades. In the early 1980s, total annual krill catches throughout the Southern Ocean peaked at over 0.5 million tons (Mt), of which over 0.4 Mt were harvested in Area 48, with the former USSR as the dominant fishing nation. Following the dissolution of the USSR in 1992, catches declined and remained between 0.1 and 0.2 Mt throughout the 1990s and early 2000s. Since then, however, landings have increased steadily, surpassing the historic peak of the 1980s in 2024, when they reached 0.5 Mt, the highest level ever recorded from Area 48 (1, 30) (Box 1 *B*).

The operational annual catch limit of 0.62 Mt for Area 48 is derived from the sum of the maximum historical catches of krill recorded prior to 1991 (Box 1 *B*) and is not directly linked to the size of the krill stock (30). This limit was initially introduced as a temporary replacement for the much larger "Precautionary Catch Limit," currently 5.61 Mt, which is based on a stock size estimate from a single krill biomass survey conducted in Area 48 in 2000. This survey covered ~57% of the total fishing area. The 0.62 Mt limit was intended to remain in place until CCAMLR Members could agree on a method to geographically allocate the "Precautionary Catch Limit" to minimize local ecosystem disturbance. In 2009, the operational catch limit of 0.62 Mt was further subdivided into four subareas (Box 1 *A*), based on the biomass distribution patterns observed in the 2000 survey, in order to avoid excessive fishing pressure in any one area. Although initially intended as a temporary measure, this catch allocation has been extended six times. In 2024, during complex discussions on the revision of the fishery management strategy, the measure expired due to a lack of agreement among CCAMLR Members on its renewal (31). Consequently, from the 2025 fishing season onward, there are no longer any spatial restrictions on where the 0.62 Mt catch limit can be taken within the entire fishing region (Subareas 48.1 to 48.4), with the result that the maximum allowable catch of 0.62 million tonnes was reached in July 2025 (99,97%) (20).

Fishing effort has increased over time, particularly in Subarea 48.1, near the western Antarctic Peninsula. The allowable catch limit in this Subarea until 2024 (0.155 Mt), (Box 1 *A*) has been reached in 10 of the last 13 years, and the time taken to reach this threshold has been steadily decreased. As a consequence, fishing pressure increased in other areas, such as the South Orkney Islands (Subarea 48.2, Box 1 *A*). This increasing pressure, coupled with the loss of subarea catch limits, is an urgent challenge, particularly for Subarea 48.1. In the absence of spatial controls, there is an increased risk of further concentration of fishing effort in this ecologically sensitive area, as evidenced by the increase in krill catches in Subarea 48.1 from 0.155 Mt to 0.355 Mt in July 2025 (20).

**Box 2**

**A schematic of CCAMLR's krill fishery management approach. (A) Current approach. (B) Revised krill fishery management approach. (C) Revised krill fishery management approach including a Krill Stock Hypothesis.**



Despite over 30 y of regional krill biomass surveys conducted by various CCAMLR Member States, the current catch limit in Area 48 is still based solely on historical catch levels and a single international CCAMLR krill biomass survey from 2000, a quarter of a century ago (13, 30) (Box 2*A*).

Recognizing these shortcomings, in 2019, CCAMLR committed to developing a Revised Krill Fishery Management Approach (KFMA) that includes mechanisms to spatially distribute catch limits at finer scales (Box 2*B*). This initiative formally began in 2020, using Subarea 48.1 as a pilot region due to its high krill abundance, substantial overlap between fisheries and predators, and data availability (31).

The revised approach (Box 2*B*) aims to improve upon the previous system (Box 2*A*) by implementing seasonal (summer/winter) and finer spatial-scale (~100 to 300 km) catch limits, using regular biomass estimates at both subarea and potentially smaller scales, and conducting spatial overlap analyses to evaluate interactions between fisheries and krill predators (32).

However, despite these improvements, the KFMA still lacks consideration of critical elements of krill stock dynamics, such as the seasonal distribution of krill life stages, connectivity between different krill habitats, and direct surveys quantifying local and regional recruitment dynamics.

To address these gaps, in 2022, the CCAMLR Scientific Committee supported the development of a Krill Stock Hypothesis as a framework for improving management decisions (33).

**The Krill Stock Hypothesis: A New Framework to Inform Sustainable Fisheries Management.** The Krill Stock Hypothesis will provide a conceptual understanding of the biology of krill populations and their habitat use in the fishing region, facilitating the use of information on krill ecology in fisheries management. This framework integrates key ecological factors on krill, including biomass assessments, spawning and recruitment, vertical and horizontal movements, and spatial connectivity (immigration and emigration between regions). It is intended to build on successful stock hypotheses for other Antarctic fisheries, such as Antarctic toothfish (34) and Patagonian toothfish (35). It seeks to define appropriate spatial population units for management while taking into account fluxes between these units (36). Most importantly, for the first time, a Krill Stock Hypothesis will formalize the detailed, spatially explicit data on krill populations needed to support CCAMLR fisheries management.

However, despite the potential of the Krill Stock Hypothesis, a clear framework for its application in decision-making is still lacking. By establishing a coherent foundation for understanding krill ecology and its uncertainties, the Krill Stock Hypothesis can

- Ensure that management measures align with the best available ecological knowledge.
- Establish a comprehensive framework for assessing catch limits in the face of uncertainties, including those related to climate change.
- Support the development of adaptive management strategies that evolve through the continuous collection of data on key ecological factors regarding krill and their primary predators.

To be an effective data-driven management approach, the Krill Stock Hypothesis must be continuously reviewed as new environmental data and research findings become available. This requires

- Ongoing data collection programs to improve understanding of krill stock structure and dynamics.
- Development of monitoring methods at spatial scales appropriate for effective management.
- Integration of emerging technologies to enhance data resolution and predictive capabilities.

By embracing this dynamic and precautionary approach, the Krill Stock Hypothesis will facilitate an understanding of what is still missing or needs to be better defined, enabling CCAMLR to ensure sustainable krill fishery management that balances commercial interests with the long-term health of the Southern Ocean ecosystem.

## Data Sources for a Dynamic Krill Stock Hypothesis

A robust understanding of krill population dynamics relies on integrating multiple data sources. These include commercial and research vessels, autonomous vehicles, moorings, biologging, and the compilation of existing datasets (19). While each platform has limitations, their combined use improves the analysis of spatiotemporal patterns in krill biomass and life stages (37). When paired with modeling studies that link physical and biological processes, these data sources can significantly improve predictions about krill populations, ultimately enabling more accurate management decisions.

Among these strategies, krill fishing vessels remain underutilized as platforms for data collection. However, studies have shown that data and samples collected from commercial fishing vessels can provide critical insights into krill biology (38–40) and the maturity stage structure of krill targeted by the fishery (41). For instance, a recent pilot study conducted over three fishing seasons (2020–2022) aboard a new generation krill fishing vessel with a continuous pumping fishing system demonstrated how daily, coordinated data collection on krill can effectively support the Krill Stock Hypothesis. This fishing system enables sampling and assessment of stage distribution dynamics at very fine scales. Analyses of the life stage composition (juvenile, approximately 30 mm; female; male) of krill caught during the study revealed significant regional and seasonal differences (Fig. 1). A high-resolution assessment of the length of krill caught by the fishery over topographic gradients showed that as the vessel moved into deeper waters, the size of the caught krill increased significantly, along with the proportion of female krill. Conversely, juvenile krill were most abundant in the catch when the vessel was fishing along the bank slopes (Fig. 2).

High-resolution krill length measurements from fishing vessels would greatly enhance our understanding of whether stage-specific interactions and movements are consistent features of their spatial patterns. The spatial and temporal distributions of maturity stages collected by fishing vessels could provide critical baseline data for modeling studies that test and advance knowledge within the Krill Stock Hypothesis, particularly regarding how krill may move based on age.

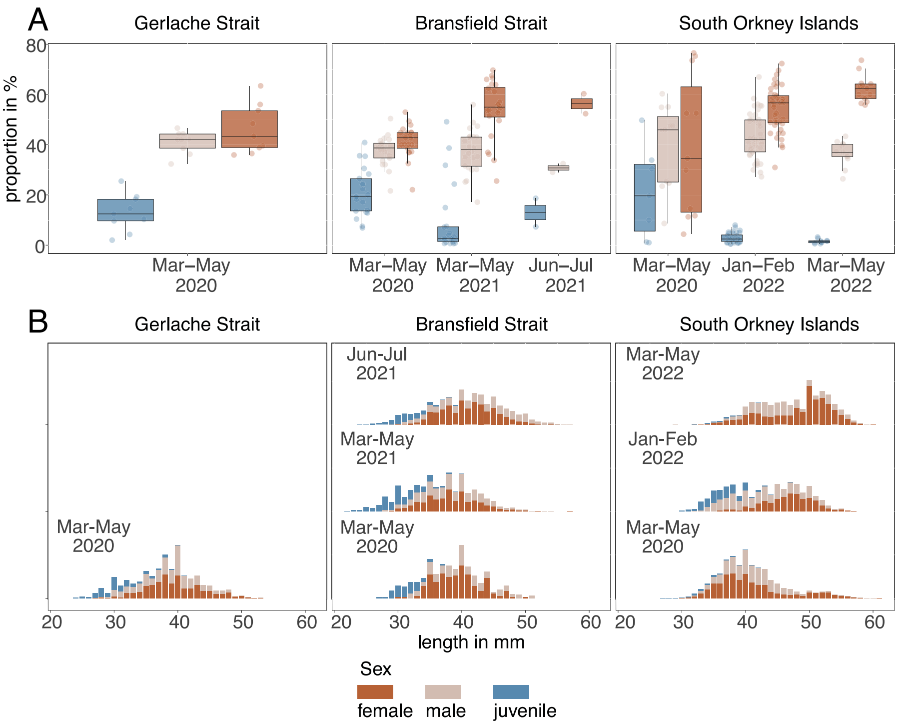



**Fig. 1.** Seasonal krill demography. (*A*) Sex composition of the sampled krill populations in different areas and seasons. (*B*) Sex-specific length frequency distributions of the sampled krill populations in other areas and seasons.

The information on maturity stage distribution, combined with advection models of the Antarctic Peninsula and krill behavior, will allow us to examine the connections between krill and their habitats (42).

During fishing operations, vessels consistently use echosounders to detect and track krill swarms. These acoustic data provide valuable insights into predator–prey interactions (40), relative biomass distribution (13), and swarm characteristics (40). An analysis of eight months of acoustic data from a fishing vessel revealed significant variations in krill vertical migration behavior, influenced by factors such as day length and environmental conditions, including food availability (40). In addition, a recent study demonstrated how acoustic data from krill fishing vessels can be used to map encounters between these vessels and air-breathing krill predators, such as fur seals, penguins, and baleen whales, as well as track the dynamics of these encounters over time and in relation to changes in fleet behavior. Thus, acoustic data from the fishery can also offer rapid low-level insights into potential impacts on krill-dependent predators with high spatial and temporal coverage (43).

Although krill fishing vessels provide valuable data, this information alone is insufficient for a comprehensive stock assessment and for fully testing the Krill Stock Hypothesis. For instance, juvenile krill (under two years old and smaller than 30 mm) are not effectively captured due to the size of the net-mesh used by the fishery (38). However, these data are crucial for modeling krill population dynamics (19) and determining sustainable harvest rates (44). To address this gap, regular scientific surveys are necessary to capture larval and early juvenile stages, which are key to understanding reproductive dynamics and recruitment. Additionally, scientific surveys can be conducted in neighboring areas where the fishery is not operating, such as the Bellingshausen and Weddell Seas, which have been proposed as potential source regions for replenishing krill stocks (36, 45). Validating the importance of these regions is a priority for understanding krill flux and the overall status of the population, underscoring the need for continued research expeditions in the Southern Ocean with national government support.

Ship-based data collection can be complemented by autonomous underwater vehicles (AUVs) such as gliders and

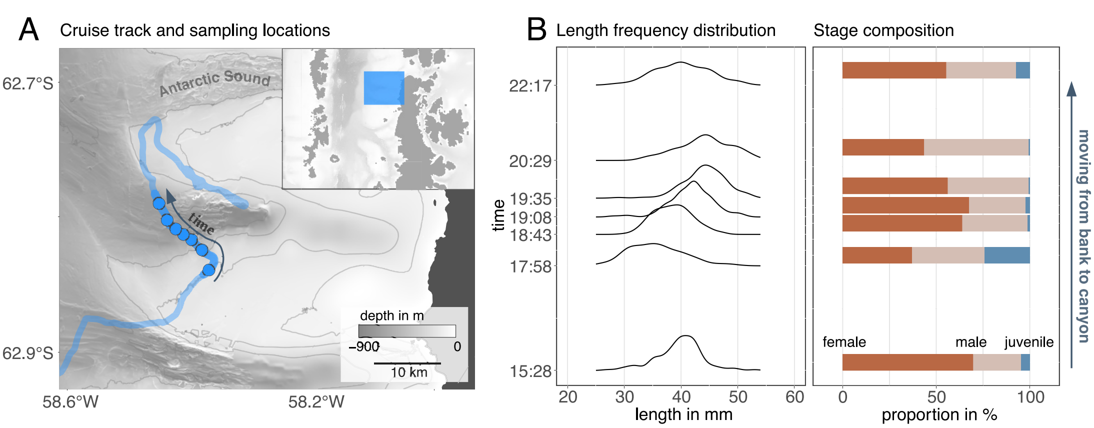



**Fig. 2.** Small-scale demographic dynamics of krill revealed by high-resolution length-frequency sampling on 28 May 2021 from a continuous pumping fishing trawler in Bransfield Strait. (*A*) Vessel track 24 h before and after the length frequency sampling (27 May–29 May 2021) and sampling locations. (*B*) Density curves (*Left*) of krill length distributions measured at each of the seven length-frequency samples and stage composition (*Right*).

moored instruments or biologging. AUVs equipped with echosounders can assess krill biomass and distribution at fine spatial and temporal scales, while echosounders on moorings can estimate krill flux into and out of marine regions. Biologging data provide information on regions of importance for the krill-centered food web and potential targeted krill stages. While these advancements provide valuable new data collection avenues, they serve as complementary tools rather than replacements for ship-based sampling (37).

Beyond these collection strategies, data from scientific expeditions are increasingly available through FAIR ("Findable, Accessible, Interoperable, and Reusable") data systems (46) and even the krill fishery has begun to make data publicly available, for example, through the HUBOcean data platform, which provides access to acoustic data (47). One particularly valuable database for the Krill Stock Hypothesis is KRILLBASE, which compiles extensive data on krill abundance, length-frequency composition (48), and distribution from national archives dating back to 1926, along with relevant environmental information. Efforts are currently underway to expand this database to include krill larval stages. Databases like KRILLBASE will support the Krill Stock Hypothesis by providing long-term regional population trends and life stage distributions (21, 49), informing simulation models, identifying regional sampling gaps, and offering a well-established, accessible infrastructure for researchers.

The integration of these diverse data collection platforms has the potential to enhance our understanding of krill population dynamics, thereby strengthening the Krill Stock Hypothesis. It will also enhance the predictive capabilities of models and facilitate more efficacious management decisions for krill fisheries in the Southern Ocean.

## A Pragmatic Roadmap for the Implementation of a Dynamic Krill Stock Hypothesis

To ensure that the Krill Stock Hypothesis becomes an efficient and integral part of the KFMA (Box 2*C*), CCAMLR Member nations and the scientific community must agree on a structured implementation strategy. This roadmap outlines four key elements necessary for successful data collection and utilization with actionable steps for each element and strategies to address existing challenges.

**Long-Term, High-Quality Data Collection.** CCAMLR plays a central role in coordinating data collection and monitoring to ensure the sustainable management of Antarctic marine ecosystems. The CCAMLR Ecosystem Monitoring Program (CEMP) (50) and the Scientific Observer Program (SISO) (51) contribute to these efforts but have limitations in supporting effective krill fisheries management. SISO, established in 1992, aims to collect catch composition data from krill fisheries (Box 3*A*).

Since 2020, it has been mandatory for all krill fishing vessels to carry at least one scientific observer who collects biological data on krill (length, sex, and maturity stage). However, these data are not used in the current management strategy, which relies solely on fishery-independent data sources to estimate key parameters like krill recruitment, the number of young krill entering the population. The current data collection effort is also limited in its ability to support the Krill Stock Hypothesis, due to its low sampling frequency (51), where high-resolution information is required. In CEMP, where predator data are collected through national research programs (50), several major krill consumers such as fish, baleen whales, and crabeater seals (52) (Box 3*B*) are not consistently studied. However, with the krill fishery expanding and whale populations recovering (27), it is increasingly important to monitor the abundance and distribution of these significant krill predators to understand ecosystem dynamics. CCAMLR is currently reviewing CEMP and seeking closer cooperation with the International Whaling Commission (IWC), offering an opportunity to address these shortcomings. In the meantime, the spatial overlap analysis developed to evaluate interactions between fisheries and krill predators in the revised Krill Fishery Management Approach (KFMA) (32) (Box 2*B*) can integrate predator species not currently covered by CEMP, helping to bridge some of these data deficiencies.

*Action Steps:*

- ***Action 1:*** *Revise SISO and CEMP to align data collection with a dynamic Krill Stock Hypothesis.*

Long-term monitoring is vital in the southwest Atlantic sector (CCAMLR Area 48), where fishing and climate pressures are most intense (22). However, traditional time series, such as the US Antarctic Marine Living Resources (AMLR) Program, have been cut or reduced in frequency due to funding shifts toward new technologies (37). While autonomous tools offer support, they cannot replace the value of consistent, long-term ship-based monitoring, needed to detect ecosystem shifts and their impacts on krill populations.

*Action Step:*

- ***Action 2:*** *Prioritize regular, coordinated surveys between national programs and the fishing industry, especially in undersampled seasons like autumn and winter, to improve understanding of krill stage structure distribution.*
- ***Action 3:*** *Combine autonomous and ship-based monitoring with mooring networks in key fishing areas to gather year-round data on krill flux, ocean currents, and seawater temperatures.*
- ***Action 4:*** *Establish a multivessel research initiative focused on krill flux in upstream regions, in collaboration with CCAMLR member nations and national and international funding sources, as a long-term strategy.*

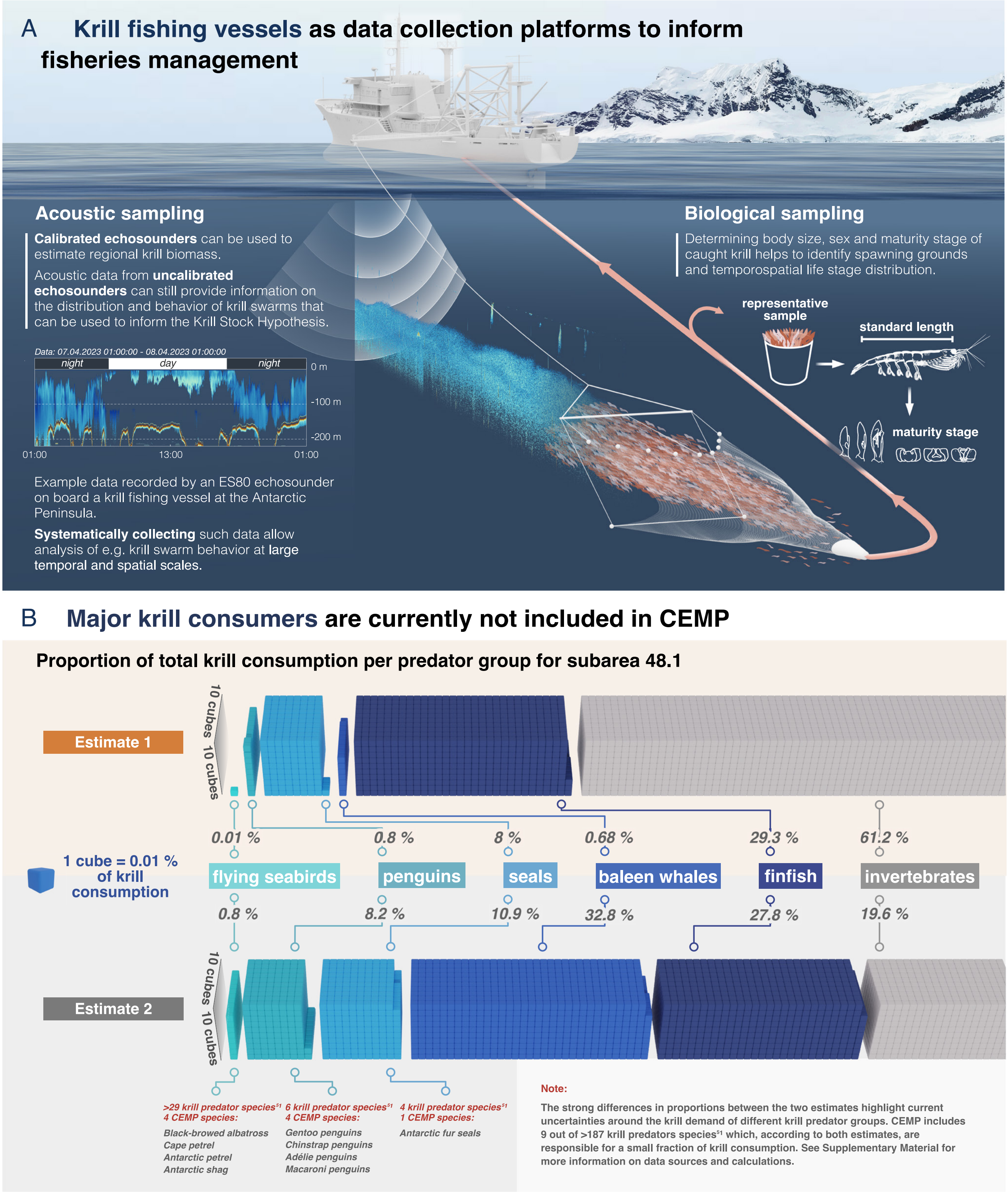
**Closer Science-Fishery Cooperation.** Strong collaboration between science and industry has been shown to improve data quality and management outcomes (53–55). At CCAMLR, programs like SISO would benefit from annual, standardized training to ensure consistent, reliable data collection and motivate observers by emphasizing their role in sustainable fisheries.

*Action Steps:*

- ***Action 5:*** *Create standardized sampling protocols for consistency between fishing and research vessels.*
- ***Action 6:*** *Implement a standardized annual training program for krill data collection on fishing vessels.*

## Box 3

**(A) Krill fishing vessels as data collection platforms and (B) krill predators included in CEMP.**

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- ***Action 7:*** *Ensure the use of scientific nets such as a rectangular midwater trawl 1+8 (RMT 1+8) (56), capable of capturing all life stages (larval, juvenile, and adult krill) during krill biomass surveys conducted by the fishery.*

**A Finance Plan for Data Collection.** Currently, CCAMLR research relies heavily on national Antarctic programs, whose funding is diminishing due to increasing competition for financial resources (57).

Other financial mechanisms, such as Members' voluntary contributions to CCAMLR contributions from the private sector and from philanthropic/charitable organizations, are essential for the provision of scientific information in support of maintaining the marine ecosystem and the ecosystem services that depend on krill. Without new and sustainable financial mechanisms, critical data collection for krill fisheries management is at risk.

Given the industry's benefits from marine living resources extracted from the Convention Area, industry participation is crucial for funding the research and monitoring required to address the challenges CCAMLR faces. Elsewhere, partnerships among industry, government, and academia, such as the Pollock Conservation Cooperative and NOAA's Research Set-Aside programs, successfully support fisheries science through cofunding and research monitoring, providing valuable information for fisheries management and allowing for informed decision-making and sustainable resource utilization (58).

Similar models exist in CCAMLR's Patagonian toothfish (*Dissostichus eleginoides*) fishery, where tagging studies and coordinated surveys, including outside the main fishing grounds, are supported by industry (35). This fishery operates under one- or two-year catch limits, which force rapid scientific progress, as both researchers and the fishing industry are incentivized to collect new data to support future access. The knowledge that catch limits will have to be renewed in two years' time encourages the fishing industry to contribute to science if they wish to continue fishing.

Funding for essential ship-based research could come from contributions made by member nations, fishing notification fees, and in-kind support from the fishery through regular biomass surveys, as well as from Non-Governmental Organisations (NGOs). The Antarctic Wildlife Research Fund (AWR) exemplifies this direction. AWR's founding partners include the fishing company AkerBioMarine, the Antarctic Southern Ocean Coalition (ASOC), and the World Wildlife Fund (WWF)-Norway. Initial funding has been provided by the industry through Aker BioMarine, Blackmores, and Swisse, three companies that harvest or sell krill products. This coalition provides funding to promote research that contributes to improving krill fishery management.

In this overall context, it is important to acknowledge that financial support to collect critical data for a dynamic krill stock hypothesis will not only serve as a crucial tool for improving krill fishery management but also for informing the establishment of conservation measures, by identifying sensitive regions, such as critical krill spawning grounds and hotspots for primary krill consumers.

*Action steps:*

- ***Action 8:*** *Organize collaborative workshops to develop a sustainable, multisource funding model with scientific and political representatives of CCAMLR member states, the fishery and NGOs.*
- ***Action 9:*** *Link funding to Conservation Measures that require relevant data collection.*

**Coordinated Data Collection, Monitoring, and Storage.** To support effective decision-making, krill data must be standardized, accessible, and integrated across platforms. Adopting FAIR data principles will ensure broad availability to scientists and policymakers.

*Action steps:*

- ***Action 10:*** *Develop a centralized data-sharing framework within CCAMLR.*
- ***Action 11:*** *Expand and update existing databases for comprehensive stock assessment.*

## Concluding Thoughts

Political decision-making profoundly influences long-term research and conservation efforts. Stable funding, evidence-based policies, and international cooperation are essential for sustaining robust scientific inquiry and protecting marine ecosystems. Since its establishment in the early 1980s, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has played a pivotal role in safeguarding Antarctic marine life by promoting responsible resource management and fostering collaborative research.

To enhance the sustainability of krill fisheries, policymakers can integrate the Krill Stock Hypothesis—a framework that accounts for environmental variability and ecosystem dynamics—into management strategies. By setting catch limits based on scientific evidence and prioritizing long-term ecological resilience over short-term economic interests, they can ensure the stability of the Southern Ocean ecosystem and the species that depend on it.

**Data, Materials, and Software Availability.** Relevant data, R-scripts and Supplementary Tables data have been deposited in Zenodo (https://doi.org/10.5281/zenodo.15261031) (59). All study data are included in the article and/or *SI Appendix*.

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1. Fishery Report 2024: Euphausia superba in Area 48, CCAMLR Secretariat. https://fishdocs.ccamlr.org/FishRep_48_KRI_2024.pdf (2024).
2. The state of world fisheries and aquaculture. World review fisheries and aquaculture. Food and Agriculture Organization of the United Nations (2022). https://openknowledge.fao.org/server/api/core/bitstreams/a2090042-8cda-4f35-9881-16f6302ce757/content.
3. R. D. Cavanagh *et al.*, Utilising IPCC assessments to support the ecosystem approach to fisheries management within a warming Southern Ocean. *Mar. Policy* **131**, 10458 (2021), 10.1016/j.marpol.2021.104589.
4. R. Cappell, G. MacFadyen, A. Constable, Research funding and economic aspects of the Antarctic krill fishery. *Mar. Policy* **143**, 105200 (2022), 10.1016/j.marpol.2022.105200.
5. N. Stoekl *et al.*, The value of Antarctica and Southern Ocean ecosystem services. *Nat. Rev. Earth Environ.* **5**, 153–155 (2024), 10.1038/s43017-024-00523-3.
6. Economic and Biological Figures from Norwegian Fisheries (2022), https://www.fiskeridir.no/English/Fisheries/Statistics/Economic-and-biological-key-figures/_/attachment/download/d505a34d-9688-4a70-9d8b-30385e4b4b33:4df0d484173bd0927fc14a3ef8cc3c5f62dfa220/nokkeltall-2022.pdf.
7. National Marine Fisheries Service, *Fisheries Economics of the United States, 2020*. (U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-236B, 2023), p. 231.
8. Canada Pelagic Fisheries (2021). https://www.dfo-mpo.gc.ca/stats/commercial/land-debarq/sea-maritimes/s2021pv-eng.htm.
9. R. Naylor *et al.*, Effect of aquaculture on world fish supplies. *Nature* **405**, 1017–1024 (2000), 10.1038/35016500.
10. Y. M. Bar-On, R. Phillips, R. Milo, The biomass distribution on Earth. *PNAS* **115**, 6506–6511 (2018), 10.1073/pnas.1711842115.
11. E. L. Cavan *et al.*, The importance of Antarctic krill in biogeochemical cycles. *Nat. Commun.* **10**, 4742 (2019), 10.1038/s41467-019-12668-7.
12. S. L. Chown *et al.*, Antarctica and the strategic plan for biodiversity. *PLoS Biol.* **15**, e2001656 (2017), 10.1371/journal.pbio.2001656.
13. B. A. Krafft *et al.*, Standing stock of Antarctic krill (Euphausia superba Dana, 1850) (Euphausiacea) in the Southwest Atlantic sector of the Southern Ocean, 2018–2019. *J. Crust. Biol.* **41**, 1–17 (2021), 10.1093/jcbiol/ruab046.
14. J. Forcada *et al.*, Ninety years of change, from commercial extinction to recovery, range expansion and decline for Antarctic fur seals at South Georgia. *Glob. Change Biol.* **29**, 6867–6887 (2023), 10.1111/gcb.16947.
15. J. Forcada *et al.*, Responses of Antarctic pack-ice seals to environmental change and increasing krill fishing. *Biological Conservation* **149**, 40–50 (2012), 10.1016/j.biocon.2012.02.002.
16. C. De Broyer *et al.*, Eds., *Biogeographic Atlas of the Southern Ocean. Scientific Committee on Antarctic Research* (Cambridge, XII, 2014), p. 498.
17. C. M. Brooks *et al.*, Protect global values of Southern Ocean ecosystem. *Science* **378**, 477–479 (2022), 10.1126/science.add9480.
18. D. K. Steinberg *et al.*, Long-term (1993–2013) changes in macrozooplankton off the Western Antarctic Peninsula. *Deep-Sea Res. I Oceanogr. Res. Pap.* **10**, 54–70 (2015). 10.1016/j.dsr.2015.02.009.
19. B. Meyer *et al.*, Successful ecosystem-based management of Antarctic krill should address uncertainties in krill recruitment, behaviour and ecological adaptation. *Commun. Earth Environ.* **1**, 28 (2020). 10.1038/s43247-020-00026-1.
20. J. Goodmann, A record catch of krill near Antarctica could trigger an unprecedented end to fishing season. *Associated Press*, Climate, 29 July 2025. https://apnews.com/article/antarctica-krill-whales-global-warming-fishing-boom-bd7708913cd1482ae190365b04d98ede. Accessed 26 August 2025.
21. A. Atkinson *et al.*, Krill (Euphausia superba) distribution contracts southward during rapid regional warming. *Nature Clim. Change* **9**, 142–147 (2019), 10.1038/s41558-018-0370-z.
22. T. Ichii *et al.*, Impact of the climate regime shift around 2000 on recruitment of Antarctic krill at the Antarctic Peninsula and South Georgia. *Prog. Oceanogr.* **213**, 103020 (2023), 10.1016/j.pocean.2023.103020.
23. Z. T. Sylvester, C. M. Brooks, Protecting Antarctica through Co-production of actionable science: Lessons from the CCAMLR marine protected area process. *Mar. Policy* **111**, 103720 (2020), 10.1016/j.marpol.2019.103720.
24. G. M. Watters, J. T. Hinke, C. S. Reiss, Long-term observations from Antarctica demonstrate that mismatched scales of fisheries management and predator-prey interaction lead to erroneous conclusions about precaution. *Sci. Rep.* **10**, 2314 (2020), 10.1038/s41598-020-59223-9.
25. L. Krüger *et al.*, Antarctic krill fishery effects over penguin populations under adverse climate conditions: Implications for the management of fishing practices. *Ambio* **50**, 560–571 (2021), 10.1007/s13280-020-01386-w.
26. P. N. Trathan *et al.*, The ecosystem approach to management of the Antarctic krill fishery – the 'devils are in the detail at small spatial and temporal scales. *J. Marine Syst.* **225**, 103598 (2022), 10.1016/j.jmarsys.2021.103598.
27. M. S. Savoca *et al.*, Whale recovery and the emerging human-wildlife conflict over Antarctic krill. *Nature Commun.* **15**, 7708 (2024), 10.1038/s41467-024-51954-x.
28. F. Santa Cruz, B. Ernst, J. A. Arata, C. Parada, Spatial and temporal dynamics of the Antarctic krill fishery in fishing hotspots in the Bransfield Strait and South Shetland Islands. *Fish. Res.* **208**, 157–166 (2018), 10.1016/j.fishres.2018.07.020.
29. F. Santa Cruz, L. Krüger, C. A. Cárdenas, Spatial and temporal catch concentrations for Antarctic krill: Implications for fishing performance and precautionary management in the Southern Ocean. *Ocean Coastal Manage.* **223**, 106146 (2020), 10.1016/j.ocecoaman.2022.106146.
30. S. L. Hill *et al.*, Is current management of the Antarctic krill fishery in the Atlantic sector of the Southern Ocean precautionary? *CCAMLR Sci.* **23**, 31–51 (2016), https://www.ccamlr.org/en/system/files/science_journal_papers/Hill%20et%20al.pdf.
31. Report of the 43 meeting of CCAMLR (CCAMLR-43), paragraph 4.35 (2024), https://meetings.ccamlr.org/system/files/meeting-reports/CCAMLR-43%20preliminary%20report_0.pdf.
32. V. Warwick-Evans *et al.*, Using a risk assessment framework to spatially and temporally spread the fishery catch limit for Antarctic krill in the west Antarctic Peninsula: A template for krill fisheries elsewhere. *Front. Mar. Sci., Sec. Global Change and the Future Ocean* **9**, 1015851 (2022), 10.3389/fmars.2022.1015851.
33. Report of the 41 meeting of the scientific committee (SC-CAMLR-41), https://meetings.ccamlr.org/system/files/meeting-reports/e-sc-41-rep.pdf.
34. S. Mormede, A. Dunn, S. Hanchet, S. Parker, Spatially explicit population dynamics models for Antarctic toothfish in the Ross Sea region. *CCAMLR Sci.* **21**, 19–37 (2014), https://www.ccamlr.org/en/publications/science_journal/ccamlr-science-volume-21/19-37.
35. P. Ziegler, D. C. Welsford, "The Patagonian toothfish (Dissostichus eleginoides) fishery at Heard Island and McDonald Islands (HIMI) - population structure and history of the fishery stock assessment" in, *The Kerguelen Plateau: marine ecosystem and fisheries. Proceedings of the Second Symposium 2017*. D. Welsford, J. Dell, G. Duhamel (Eds) (Australian Antarctic Division, Kingston, Tasmania, Australia, 2019), pp. 187–217, https://www.antarctica.gov.au/site/assets/files/61383/the_patagonian_toothfish_dissostichus_eleginoides_fishery_at_heard_island_and_mcdonald_islands_himi_-_population_structu.pdf.
36. B. Meyer *et al.*, Development of a Krill stock hypothesis (KSH) for CCAMLR area 48, REPORT of the online workshop of the SCAR Krill Expert Group (SKEG), 20-24th March (2023). https://zenodo.org/record/8130840.
37. S. L. Hill *et al.*, Observing change in pelagic animals as sampling methods shifts: The case of Antarctic krill. *Front. Mar. Sci. Sec. Marine Conser. Sustain.* **11**, 1307402 (2024). 10.3389/fmars.2024.1307402.
38. L. A. Krag *et al.*, Size selection of antarctic krill (*Euphausia superba*) in Trawls. *PLoS ONE* **9**, e102168 (2014), 10.1371/journal.pone.0102168.
39. N. Hellessey *et al.*, Antarctic krill lipid and fatty acid content variability is associated to satellite derived Chlorophyll a and sea surface temperatures. *Sci. Rep.* **10**, 6060 (2020), 10.1038/s41598-020-62800-7.
40. D. Bahlburg *et al.*, Plasticity and seasonality of the vertical migration behaviour of Antarctic krill using acoustic data from fishing vessels. *R. Soc. Open Sci.* **10**, 230520 (2023), 10.1098/rsos.230520.
41. G. A. Tarling *et al.*, Growth and shrinkage in Antarctic krill Euphausia superba is sex-dependent. *Mar. Ecol. Prog. Ser.* **547**, 61–78 (2016), 10.3354/meps11634.
42. K. L. Gallagher, M. S. Dinniman, H. J. Lynch, Quantifying Antarctic krill connectivity across the West Antarctic Peninsula and its role in large-scale Pygoscelis penguin population dynamics. *Sci. Rep.* **13**, 12072 (2023), 10.1038/s41598-023-39105-6.
43. D. Bahlburg, S. Menze, B. A. Krafft, A. D. Lowther, B. Meyer, Mapping encounters between air-breathing predators and krill fishing vessels using acoustic data from the fishery, *Proc. Nat. Acad. Sci.* **122**, e2417203122 (2025), 10.1073/pnas.2417203122.
44. D. Maschette *et al.*, Grym: A new open-source implementation of the generalised yield model for flexible stock assessments. *CCAMLR Science* **24**, 69–94 (2023), https://hdl.handle.net/102.100.100/603104.
45. B. Meyer *et al.*, The winter pack-ice zone provides a sheltered but food-poor habitat for larval Antarctic krill. *Nat. Ecol. Evol.* **1**, 1853–1861 (2017), 10.1038/s41559-017-0368-3.
46. M. D. Wilkinson *et al.*, The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* **3**, 160018 (2016), 10.1038/sdata.2016.18.
47. HUB Ocean, Retrieved March 13 (2025), https://app.hubocean.earth/catalog/collection/1e3401d4-9630-40cd-a9cf-d875cb310449-akbm-collection.
48. A. Atkinson *et al.*, KRILLBASE-length frequency database, a compilation of scientific net sampling data on length, sex and maturity stage of Euphausia superba around the Southern Ocean, 1926 to 2016 (Version 1.0). *UK Polar Data Centre, Natural Environment Research Council, UK Research & Innovation* (2020). 10.5285/dfbcbbf9-8673-4fef-913f-64ea7942d97a.
49. F. A. Perry *et al.*, Habitat partitioning in Antarctic krill: Spawning hotspots and nursery areas. *PLoS ONE* **14**, e0219325 (2019), 10.1371/journal.pone.0219325.
50. D. J. Agnew, The CCAMLR Ecosystem Monitoring Programme, *Antarctic Sci.* **9**, 235–242, 10.1017/S095410209700031X.
51. Scientific Observer's Manual, Krill Fisheries (2023), https://www.ccamlr.org/en/science/ccamlr-scheme-international-scientific-observation.
52. Scientific Committee on Antarctic Research, SCAR Southern Ocean Diet and Energetics Database (2023-04-04). (2023). [Data set]. Zenodo 10.5281/zenodo.7796465.
53. T. R. Johnson, W. L. T. van Densen, Benefits and organization of cooperative research for fisheries management. *ICES J. Mar. Sci.* **64**, 834–840 (2007), 10.1093/icesjms/fsm014.
54. T. Heimann, H. Verkamp, J. McNamee, N. D. Bethoney, Mobilizing the fishing industry to address data gaps created by shifting species distribution. *Front. Mar. Sci. Sec. Marine Fisheries, Aquaculture and Living Resour.* **10**, 1043676 (2023), 10.3389/fmars.2023.1043676.
55. T. W. Hartley, R. A. Robertson, Stakeholder collaboration in fisheries research: Integrating knowledge among fishing leaders and science partners in northern New England. *Soc. Natural Resour.* **22**, 42–55 (2008), 10.1080/08941920802001010.
56. A. de C. Baker, M. R. Clarke, M. J. Harris, The N.I.O. combination net (RMT 1+8) and further developments of rectangular midwater trawls. *J. Mar. Biol. Ass.* **53**, 167–184 (1973).
57. P. N. Trathan, What is needed to implement a sustainable expansion of the Antarctic krill fishery in the Southern Ocean? *Marine Policy* **155**, 105770 (2023), 10.1016/j.marpol.2023.105770.
58. M. R. Baker *et al.*, Mechanisms and models for industry engagement in collaborative research in commercial fisheries. *Front. Mar. Sci. Sec. Marine Fisheries, Aquaculture Living Resour.* **10**, 1077944 (2023), 10.3389/fmars.2023.1077944.
59. D. Bahlburg, B. Meyer, Code and data for "Code for data figures in 'Adjusting management of the Antarctic krill fishery to the challenges of the 21st Century'". Zenodo. https://doi.org/10.5281/zenodo.15261031. Deposited 22 April 2025.