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Whale recovery and the emerging human-wildlife conflict over Antarctic krill

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The Southern Ocean ecosystem has undergone extensive changes in the past two centuries driven by industrial sealing and whaling, climate change and commercial fishing. However, following the end of commercial whaling, some populations of whales in this region are recovering. Baleen whales are reliant on Antarctic krill, which is also the largest Southern Ocean fishery. Since 1993, krill catch has increased fourfold, buoyed by nutritional supplement and aquaculture industries. In this Perspective, we approximate baleen whale consumption of Antarctic krill before and after whaling to examine if the ecosystem can support both humans and whales as krill predators. Our back-of-the-envelope calculations suggest that current krill biomass cannot support both an expanding krill fishery and the recovery of whale populations to pre-whaling sizes, highlighting an emerging human-wildlife conflict. We then provide recommendations for enhancing sustainability in this region by reducing encounters with whales and bolstering the krill population.

Humanity exerts pressure on the oceans at a global scale. The pernicious but diffuse threats from climate change are causing major transformations of the Southern Ocean ecosystem. By comparison, overharvesting of marine resources is a direct stressor that can be mitigated through regionally targeted management and regulation. The Southern Ocean is still recovering from two centuries of unsustainable exploitation, beginning with sealing in the 19th-century and then industrial whaling in the 20th-century. Following industrial whaling, the commercial fishery for Antarctic krill (*Euphausia superba*, hereafter "krill") began in 1973, mainly for fish meal (largely for farmed salmon) and omega-3 supplements. Reported krill catch of the fishery has wavered since then, but has never exceeded 0.6 Mt yr^{-1} [1]. The Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), the multilateral organization in charge of managing all Southern Ocean fisheries (Box 1), came into force in 1982 over trepidation regarding the ecosystem impacts of a developing krill fishery, including concerns that fishing could impede the recovery of whales and seals[2]. Over the last four decades, krill catch has become increasingly concentrated in the southwest Atlantic, overlapping in space and time with Antarctic predators, including whales[3–5].

Krill are a vital mid-trophic link in the Southern Ocean food web. They are a highly versatile, long-lived (5–7 years on average) pelagic crustacean that primarily feed on diatoms and other small crustaceans, including cannibalizing other krill[6]. In addition to being a central node of the Southern Ocean food web, krill also play important roles in biogeochemical cycles by (1) transporting carbon downward via their fast-sinking fecal pellets, molts, and carcasses[7–9], and (2) moving limiting iron upward into the photic zone via benthic feeding and vertical migration[10]. Krill often exists as a superorganism, in large, dense swarms. It is these krill swarms that are vital to Antarctic predators, particularly baleen whales[11,12].

In this Perspective, we address the emerging human-wildlife conflict between whales and the krill fishery with an assessment of baleen whale prey demands using rough calculations of available data.

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BOX 1

Management, power and inequity in the Southern Ocean

Since the late 19th-century, access to the Southern Ocean and Antarctica has been determined by a positive feedback loop of wealth, exploitation, and power. The Antarctic Treaty (adopted in 1959, in effect since 1961), the first of a suite of agreements collectively known as the Antarctic Treaty System, was created by 12 States, spearheaded by the USA. The Treaty is subject to consensus-based decision-making by a group of Consultative Parties. The Treaty entrenches inequity through codifying costly prerequisites to participate in decision making for the region as it requires countries to demonstrate interest by "conducting substantial research activity" in Antarctica[113]. Currently, 17 States have qualified under this requirement, joining the 12 original member States as voting members. Of these 29 States with decision-making power, only 9 are Global South States.

The CCAMLR is the arm of the Antarctic Treaty System that applies to marine life and has a similar membership requirement: a State must be "engaged in research or harvesting activities in relation to the marine living resources to which the convention applies" (CCAMLR Convention Article VII.2 b)[13]. Although only a limited number of States are currently active in the Southern Ocean krill fishery, namely Chile, China, Norway, South Korea, and Ukraine (with Russia recently notifying their intention to restart fishing), the impacts of a collapsed Southern Ocean ecosystem effects all countries. In this context, the financially demanding requirement of conducting research activity or fishing operations for States to have a voice in decision-making represents an undue burden and continues to entrench a history of Antarctic imperialism and exclusion. While this was a topic of concern raised by Global South nations in the 1980s, the requirement still exists[114]. Given the global value of the Southern Ocean, a global community which includes Global South nations needs to have a voice in its management.

CCAMLR's Convention requires proactive protection of krill-dependent species from potential threats including, but not limited to, fishing activity[13]. While baleen whales are never explicitly mentioned in the Convention, they are krill-dependent species. In the following sections, we first detail the relevant ecological and industrial history of the Southern Ocean, explaining how baleen whales and commercial fisheries have come into conflict over krill. We then use published data to provide rudimentary estimates of the prey demands of baleen whales, using feeding data from ref. 14 and species-specific population sizes before[11] and after[12,15–17] whaling. Pre-exploitation baleen whale prey consumption estimates serve as a proxy for estimating the krill demands of fully recovered populations (see Supplementary Note 1 for more details). There are numerous data gaps that preclude a formal analysis of baleen whale prey consumption at spatiotemporal scales relevant to the krill fishery. These gaps include limited information on the number of heavy feeding days of each whale species, no data on feeding rates of Southern Ocean fin (*Balaenoptera physalus*) and blue whales (*B. musculus*), and an unknown number of individuals of each species the ecosystem could support (i.e., carrying capacity) to inform recovery targets. Therefore, our first-order approximation should be interpreted cautiously. We hope the present paper urges the research and management communities to address these, and many other, knowledge gaps before allowing any expansion of the krill fishery. As baleen whales continue to rebound in the 21st-century, understanding their prey requirements is vital to determine whether current or increasing krill harvests can coexist with the rising prey demand of the whales. We conclude by outlining steps that can be taken, either voluntarily or through CCAMLR regulation, to help avoid this human-wildlife conflict and ensure a sustainable future for the whales, krill, and people who depend on the Southern Ocean.

Whales and whaling in the Southern Ocean

Rorqual whales (baleen whales in the family Balaenopteridae)—including blue, fin, humpback (*Megaptera novaeangliae*), and Antarctic minke (*B. bonaerensis*) whales—maximize krill ingestion via bulk filtration with a process known as lunge-feeding[18]. During periods of intense feeding, a rorqual can lunge 200–1200 times and consume several tons of krill per day[14]. Antarctic blue whales (*B. m. intermedia*), the largest blue whale subspecies, feed exclusively on krill and all other baleen whales south of the Antarctic Convergence are reliant on krill as their main prey item[19]. Baleen whales generally migrate to lower latitudes in the Southern Hemisphere where they stay during austral winter and spring to breed and time their return to the Southern Ocean to coincide with maximum krill availability[20,21]. Outside their Southern Ocean feeding grounds, rorquals may not feed for months at a time[19]. This life history, unique among endotherms that do not hibernate, is possible due to low mass-specific metabolic rates at extreme body size[22] and endogenous stores of energy-rich blubber that made whales valuable to hunt.

At the turn of the 20th century, scientists described a Southern Ocean where "Whales' backs and blasts were seen from horizon to horizon… The sea was swarming with *Euphausia*…"[23]. Both sights are rare today, which could be a synergistic effect because large aggregations of foraging whales led to surface swarming behavior of krill[24]. In 1904, Antarctic whaling began in earnest, initially led by Norwegian and Argentinian whaling interests (Fig. 1). Motivations for whaling were largely driven by the market for whale oil. However, in the Antarctic, whaling also served the purpose of staking and supporting sovereignty claims[25] (Box 1). Humpback whales, the most coastal of the large species, were hunted first. The larger and more profitable blue and fin whales were also intensely harvested close to nearshore feeding grounds[26], while the offshore feeding grounds of these species were initially safe from harvesting due to their remoteness. When 'floating factory' whaling ships were introduced in 1925[26], the pelagic realm was no longer a safe haven. Fifty years later—roughly the lifespan of a rorqual whale—less than 20% of humpback and sei (*B. borealis*) whales, 5% of fin whales, and 0.5% of blue whales remained[11,27]. Of the 1.5 million baleen whales killed in the 20th-century[27], >90% were harvested by only four countries – Norway, United Kingdom, Japan, and the Soviet Union (Fig. 1).

The whaling industry suggested regulating catches as early as 1932[28]; however, no catch limits were agreed upon until 1944[26,29]. These initial quotas were species agnostic and instead created the Blue Whale Unit (BWU) based on oil yield from one average blue whale, where one BWU was equivalent to one blue whale, two fin whales, or two and a half humpback whales. In 1946, the International Convention for the Regulation of Whaling stipulated the formation of the International Whaling Commission (IWC). That same year, the IWC established the first international catch quotas of 16,000 BWUs[28,29], which were unsustainably high and did not protect the severely depleted humpback and blue whale populations. In the 1960s, bans on hunting humpback (1963) and blue (1964) whales were enacted[29], although the Soviet Union continued whaling these species illegally until the 1980s[30,31]. Finally in 1982, IWC passed a total moratorium on commercial whaling which took effect in 1986. By then however, Southern

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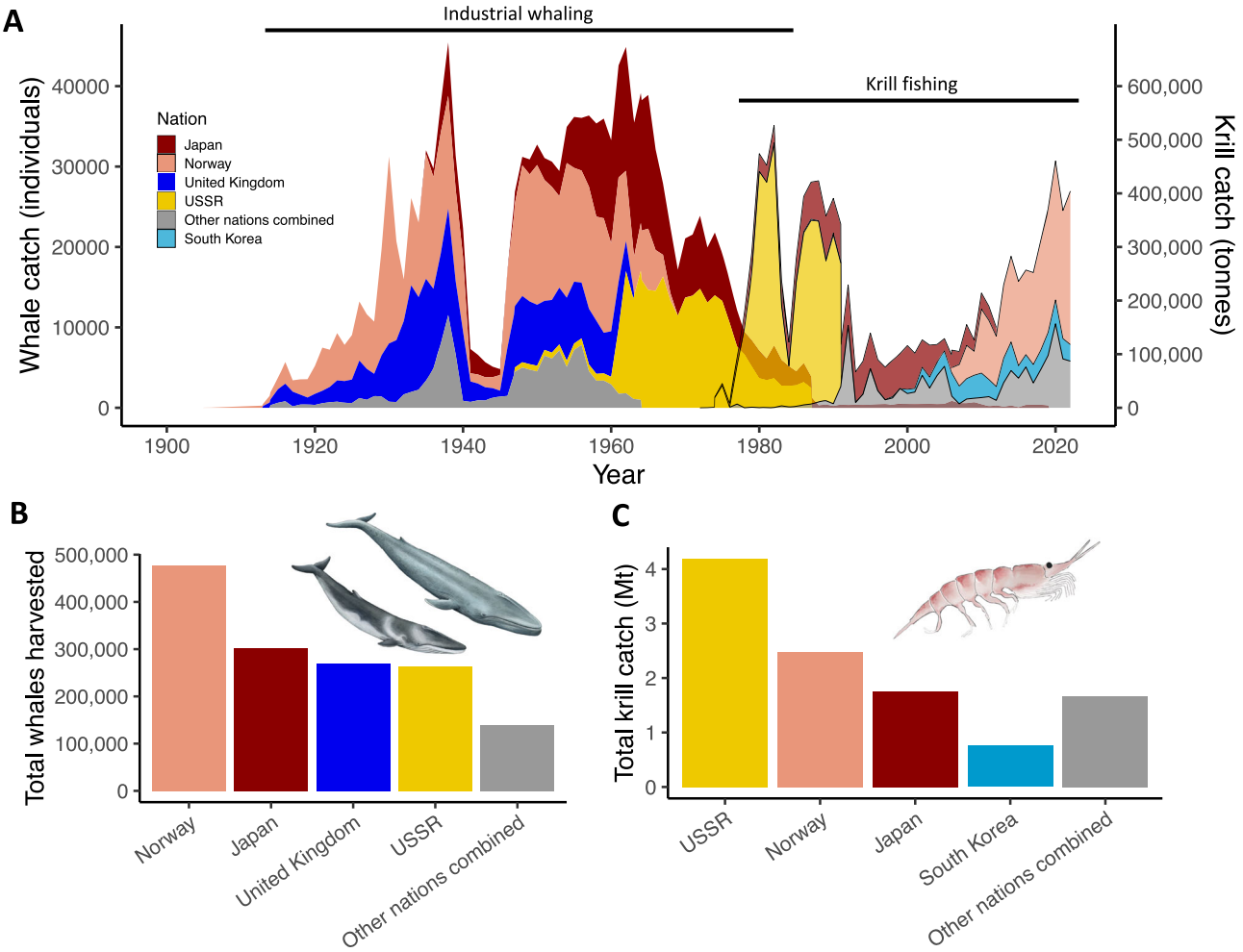

Fig. 1 | Industrial whaling and krill fishing by nation. A Timeline of Southern Ocean whaling and krill fishing, with krill fishing occurring in recent decades shown with a transparent filter and outlined in black. **B** 90.4% of the 1.5 million baleen whales killed in the Southern Ocean were harvested by only four countries (11 nations total have harvested whales in the Southern Ocean). **C** 91.2% of all krill ever harvested in the Southern Ocean has been caught by only four nations (22 nations total have reported krill catch). Whaling data from ref. 111, krill data from ref. 1. Fin and blue whale illustrations by Alex Boersma, krill illustration from the authors.

Hemisphere baleen whale populations—with the exception of Antarctic minke whale—were depleted by >90% as compared to the pre-whaling baseline[23,28].

In 1994, the IWC designated the Southern Ocean a whale sanctuary, further prohibiting whaling by signatories of the moratorium in this region. Japan continued 'scientific whaling' for decades following the commercial whaling ban, harvesting several hundred whales per year, mostly Antarctic minke whales. However, after intense public pressure, and a ruling against Japan in the International Court of Justice[32], Japan left the IWC and ceased Southern Ocean whaling following the 2018–2019 season[33]. Thus, the entirety of Antarctic whaling lasted little more than a century. The cumulative biomass of the whales killed was estimated to be equivalent to one-third of all people[34], and twice that of all wild mammals, on Earth at the turn of the 21st-century[35].

Can Southern Ocean krill support humans and whales?

Following the IWC moratorium, krill populations in the Southern Ocean were expected to boom as a result of the reduced predation pressure from the significantly depleted whale populations (i.e., the 'krill surplus hypothesis'[36]). Estimates of the circumpolar krill stock before whaling vary widely, from 44 Mt to 1350 Mt (reviewed by ref. 37). The higher end of these estimates would support both a full recovery of whale populations and a robust krill fishery, and is what was likely needed to support the estimated prey demand of pre-whaling rorqual populations[14,19,38]. Yet today, the total biomass of the same krill population is estimated at <400 Mt, but large uncertainties persist[37,39,40]. Nevertheless, krill is still by far the largest fishery in the Southern Ocean in terms of tonnage caught[1].

After a 15-year lull in fishing effort (1993–2007) following the collapse of the Soviet Union, annual krill catches have increased rapidly since 2007 (Fig. 1A). The burgeoning fish meal and omega-3 supplement industries are largely responsible for this renewed interest in krill, rather than human consumption[41]. Currently, the total allowable krill catch across the Southern Ocean is 8.6 Mt yr^{-1}, but reported krill catch is <10% of this upper limit[1]. Functionally, the 620,000 t yr^{-1} 'trigger limit'—a precautionary level to prevent an overconcentration of fishing effort—in the Southwest Atlantic sector (CCAMLR Subareas 48.1–48.4) is the maximum catch at present to protect krill-dependent species (Supplementary Note 2). However, krill catch is becoming increasingly concentrated in space and time[42,43], leading to direct overlap with foraging whales[3,44,45].

The estimated krill biomass in 2018–2019 from CCAMLR Subareas 48.1–48.4, which is where the vast majority of Southern Ocean resource extraction such as sealing, whaling, and krill-fishing has occurred, is 62.6 million tonnes (with a 13% coefficient of variation, CV)[46]. In the past two decades, all krill harvested have been taken from

the waters surrounding the Antarctic Peninsula, South Shetland Islands, South Orkney Islands, and South Georgia Island (CCAMLR Subareas 48.1–48.3). Harvest limits are defined using a set of rules to account for krill replenishment and predator demand (Supplementary Note 2)[47]. Current krill catch in this region is ~0.5 Mt yr^{-1} but increasing. This is particularly true in Subarea 48.2 where catch has risen rapidly, from 37 Kt yr^{-1} from 2012 to 2016 to 193 Kt yr^{-1} from 2020 to 2022[1].

Krill demand has been estimated for seabirds, pinnipeds, and whales in portions of CCAMLR Subareas 48.1–48.4. In Subarea 48.1, 1,858,201 (CV: 0.156) crabeater (*Lobodon carcinophaga*), 151,702 (CV: 0.364) Weddell (*Leptonychotes weddellii*), and 5279 (CV: 0.408) leopard seals (*Hydrurga leptonyx*) are estimated to consume 1.28 Mt krill yr^{-1} (CV: 3.4)[48]. These important krill consumers' prey demand is not explicitly considered by CCAMLR, though France has initiated a monitoring program for crabeater seals with the intention to contribute to CCAMLR's management[49]. Of seabirds, penguins are the major krill consumers; their estimated krill consumption is 5 Mt yr^{-1} in the Scotia Sea[50] and 0.6 Mt yr^{-1} in the northwest Antarctic Peninsula alone[51]. Whale prey consumption has also been estimated for the northwest Antarctic Peninsula, where fin and humpback whales combined are estimated to consume ~2 Mt krill yr^{-1} [51]. In this Perspective, we estimate that current populations of these two species consume 18 Mt krill yr^{-1} (range: 10–31 Mt krill yr^{-1}) in Subareas 48.1–48.4 (Fig. 2, Table 1). Humpback whale populations in this region (Breeding Stocks A and G) have shown a > 90% recovery to carrying capacity from a low of 450 individuals in the mid 20th-century[12,15,52]. This is in stark contrast to fin and blue whales, though recent evidence shows signs of increasing populations[15,16,53,54]. Before whaling, when blue, fin, and humpback whales were at carrying capacity in this region, we estimate their combined abundance was ~180,000, which we estimate may have consumed 51 Mt krill yr^{-1} (range: 28–90 Mt krill yr^{-1}; Fig. 2, Table 1). This consumption rate may have been sustainable by ecosystem engineering effects of the whales themselves, boosting primary productivity from the recycling of limiting nutrients in their fecal material[24,55,56]. However, at present, our estimates suggest that there is likely not enough krill in Subareas 48.1–48.4 (~63 Mt[46]) to support recovered whale populations, which would require total krill biomass much larger than they consume annually, even in the total absence of krill fishing.

While there is currently only krill fishing in the Southwest Atlantic sector, other regions of the Southern Ocean have been considered for exploitation as well. CCAMLR Division 58.4.2 (Fig. 2) has an annual krill catch quota of 2.6 Mt yr^{-1}; however, the current catch limit is capped at 452,000 t yr^{-1}, akin to the 'trigger limit' in Subareas 48.1–48.4[1]. The eastern half of this Division has an estimated krill standing stock of 4.8 Mt[57]; extrapolating to the entire Division, it is unlikely that this region has more than 10 Mt krill in total at present. Recent work using population modeling derived from whaling data reported a carrying capacity of 61,363 (95% CI: 46,343–85,163) blue whales in this region[17]; combined with estimates of prey consumption[14], a population this size in Division 58.4.2 might consume 26 Mt krill yr^{-1} (range: 15–44 Mt krill yr^{-1}; Table 1). As with Subareas 48.1–48.4, the current krill stock in Division 58.4.2 would be unable to support historic whale numbers even in the total absence of krill fishing.

In addition to krill catch being geographically compressed, transshipments of catch allow these vessels to fish with little interruption when conditions allow. This spells trouble for whales because the fishing boats can act as bulk-feeding super-predators, thus occupying the same niche as the whales. Of greatest concern is the 16,100 km^2 region known as South Orkney West (SOW) located in Subarea 48.2, northwest of Coronation Island, an important whale feeding ground[16,58]. SOW represents <2% of all of Subarea 48.2, but >96% of all krill fishing in the entire Subarea occurs there[43]. Since 2000, nearly 30% of all krill harvested from the entire Southern Ocean has been from SOW[43]. In 2022, active krill fishing was observed in SOW among a foraging fin whale supergroup[3]. These factors place SOW at the epicenter of the emerging conflict between whales and commercial interests over krill.

A vision for the future of whales, krill, and people

Whalers referred to krill as 'whale food' and knew that finding krill swarms often meant finding whales to harvest[59]. It is possible that

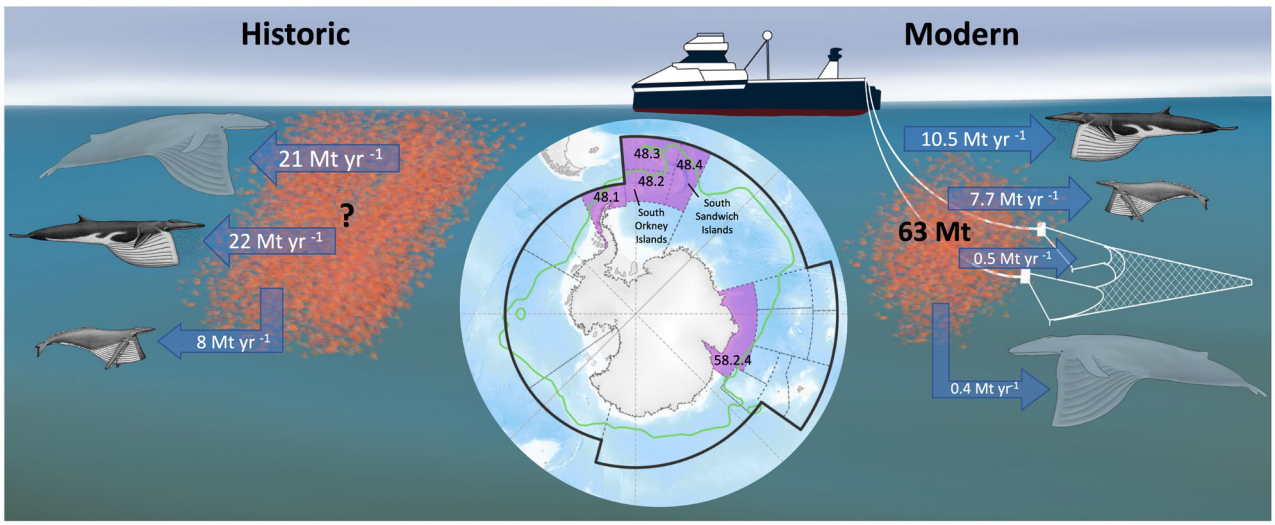

Fig. 2 | Using the past and present to guide the future of the Southern Ocean. On the left, is CCAMLR Subareas 48.1–48.4 (purple shaded region at top of inset map) before whaling where more krill would have been needed to support the prey demands of approximately 180,000 blue (at top left), fin, and humpback (bottom left) whales, in addition to other krill predators. On the right is a representation of the same region, but in the early 21st-century where a reduced krill population[46,112] supports a partially recovered fin whale population (at top right), a near-fully recovered humpback whale population, an expanding krill fishery, and a still-depleted blue whale population (bottom right). We generated krill consumption estimates by combining published information on whale feeding behavior with past and present estimates of population size (see Table 1 and Supplementary Note 1 for details). The annual catch of the Antarctic krill fishery is more than the estimated annual prey demand of the current blue whale population in this region. The regions we discuss in the paper are highlighted in purple; the polar front is shown in green. Fin and humpback whale illustrations by Alex Boersma, the rest are by the authors.

Table 1 | Estimated rorqual krill consumption for regions of interest

Species	CCAMLR region	Era	Estimated individual krill consumption (t d^{-1})	Estimated days feeding	Estimated population size	Estimated population krill consumption (Mt yr^{-1})
Humpback whale (*M. novaeangliae*)	Subareas 48.1–48.4	Historic	3.15 (1.81–4.93)	100 (90–120)	25,973	8.03 (4.23–14.73)
		Modern	3.15 (1.81–4.93)	100 (90–120)	24,900	7.69 (4.06–12.28)
Fin whale (*B. physalus*)		Historic	2.06 (1.25–3.12)	100 (90–120)	104,745	21.58 (11.78–39.22)
		Modern	2.06 (1.25–3.12)	100 (90–120)	50,837	10.47 (5.72–19.03)
Antarctic blue whale (*B. m. intermedia*)		Historic	4.19 (2.68–6.04)	100 (90–120)	50,345	21.09 (12.14–36.49)
		Modern	4.19 (2.68–6.04)	100 (90–120)	925	0.39 (0.22–6.70)
Antarctic blue whale (*B. m. intermedia*)	Division 58.4.2	Historic	4.19 (2.68–6.04)	100 (90–120)	61,363	25.71 (14.80–44.48)
		Modern	4.19 (2.68–6.04)	100 (90–120)	476	0.2 (0.11–3.45)

Estimates of humpback, fin, and blue whale krill consumption in CCAMLR regions with prior (Division 58.4.2) and current (Subareas 48.1–48.4) krill fishing. Individual daily krill consumption from ref. 56. Estimated range of days feeding from refs. 19,109. Modern population sizes from the published literature for *M. novaeangliae*[12], *B. physalus*[16], and *B. m. intermedia*[15,110]. Historic population sizes derived from ref. 11. For more details on the calculations, see Supplementary Note 1.

similar logic, but in reverse, may be used by the krill fishery today[3]. Without specific regulations in place, krill fishing vessels can 'forage' by locating and harvesting the largest, densest patches. These same dense krill swarms are crucial for rorqual whales; dispersed krill are not energetically viable[60–63]. Competition is not the only threat to whales from the fishery, there are also the threats of ship strike from fishing vessels in close proximity to whales[3] and entanglement in fishing gear[64]. In early 2021, the krill fishery reported the deaths of three humpback whales as bycatch (two from Subarea 48.1 and one from Subarea 48.2), the first known examples of direct mortality from the fishery[64]. These bycatch events led to the implementation of barriers at the mouth of the net to mitigate whale bycatch[65], and yet another humpback whale became entangled and died in 2022 (the following season)[66]. Unless new management measures are passed by CCAMLR or voluntarily agreed upon by the fishing industry (Supplementary Note 2), these interactions between whales and the krill fishery will likely increase as whales recover from whaling and fishing effort becomes increasingly concentrated in specific regions[1]. In addition, climate change is expected to exacerbate this conflict as krill contracts poleward[67–69]. To provide refuge from these stressors, restricting or precluding fishing in regions lacking data (e.g., information on krill abundance, recruitment, movement and/or predator abundance and krill requirements), with limited commercial interest (e.g., the South Sandwich Islands), or of known whale foraging aggregations (e.g., SOW, Elephant Island, the Gerlache and Bransfield Straits) would be prudent[68,69]. Further, variability in krill density among years should be considered by CCAMLR to reduce the likelihood of competition between the fishery and whales.

The Association of Responsible Krill Harvesting Companies (ARK; which includes the majority of krill fishing companies) agreed to several voluntary exclusion zones within 40 km of large colonies of central place foraging penguins and pinnipeds in Subarea 48.1 to mitigate harm to these krill-dependent predators[70]. Moreover, the government of South Georgia and the South Sandwich Islands has closed krill fishing from November through March to prevent conflict between krill-predators and the fishery[71]. The effectiveness of these measures on krill predators should be closely monitored and reported. This protection of Subarea 48.3 and the adherence of the voluntary exclusion zones in Subarea 48.1 provides hope that, even in the face of CCAMLR's inability to reach consensus on conservation strategies (Supplementary Note 2), progress can still be made. Below we highlight conservation measures that would potentially help mitigate harmful interactions between whales and the fishery and help uphold CCAMLR's legal responsibility of precautionary ecosystem-based management.

Include whale prey demand and population recovery in krill catch limits

Currently, the prey consumption of all krill-dependent species such as penguins, pinnipeds, and whales are roughly factored into the decision rules that help determine the precautionary catch limits for krill as the amount of krill considered to escape fishing pressures (see Supplementary Note 2 for explanation of how precautionary catch limits are determined under current management). This "escapement level" is general and does not consider the needs of any specific species, including whales. Moreover, the trajectory of baleen whale populations must be considered. With a few notable exceptions[72,73], populations of other major krill consumers (seabirds and pinnipeds) have been relatively stable or declined since the advent of CCAMLR[74–77]. In contrast, baleen whale populations have grown significantly. Humpback whale populations have almost fully recovered across much of the Southern Ocean, but the same is not true of blue whales[15,17]. Meanwhile, fin whale populations have just begun to grow rapidly[16,53]. Both blue and fin whales have potentially substantial population recoveries ahead.

Including whale prey requirements, as well as other krill-dependent species, in management is crucial but has not been done explicitly yet. As whale populations rebound, it is essential that CCAMLR includes recovered (humpback whales) and recovering (blue and fin) whales as monitoring species (Box 2). CCAMLR and the IWC should work together to quantify and include whale prey requirements in any updated krill harvesting regulations. This comes at a time when CCAMLR is currently moving towards revised and refined management for Antarctic krill (Supplementary Note 2). A key aspect to the revised approach is to spatially allocate the precautionary catch limit between smaller management units within sub-areas by including a spatial analysis to reduce any potential impact based on overlap of krill and predators. Additional efforts to conduct a management evaluation assessment of the decision rules regarding escapement, such has been begun within the toothfish fishery[68], would greatly improve adequate inclusion of predator requirements for the revised krill management. Concurrent to these efforts, CCAMLR's Scientific Committee has

BOX 2

Targets for sustainable use and recovery of the Southern Ocean ecosystem

- **Strengthen spatial management**
  - Establish or expand no-take areas; implement move-on rule in the presence of foraging whales. Move-on rule is defined as: a regulation or guideline that triggers the targeted closure of an area in a fishery for a temporary period, without closing the entire fishery[115].
- **Improve monitoring**
  - Increase data on krill egg and larvae hotspots, recruitment locations, year-class strength, and adult length distributions; conduct regular monitoring and reporting of whale population trends; quantify direct overlap between whales and the krill fishery; project changes to regions of overlap with climate change.
- **Mandate CCAMLR-IWC ties**
  - Continue Working Group on Incidental Mortality Associated with Fishing; add whales as CCAMLR's Ecosystem Monitoring Program (CEMP) indicator species; include whale prey requirements in fishery's precautionary catch limits; encourage policy coordination.
- **Enhance accountability**
  - Use the UN High Seas Treaty[104] as an instrument to assess whether CCAMLR is meeting its mandate of conservation, "rational use", and precautionary, ecosystem-based management.
- **Incorporate global viewpoints**
  - Include Global South States that receive little benefit from tourism and fisheries, but are indirectly impacted by a degraded Southern Ocean, in decision-making.

CCAMLR, Commission for the Conservation of Antarctic Marine Living Resources; IWC, International Whaling Commission

recommended increased future monitoring on dependent predator species, including cetaceans[78]. CCAMLR's Ecosystem Monitoring Program (CEMP), which was designed to detect the impacts of fishing on krill-dependent species, is also being updated as it has not been effectively used in krill management thus far[79]. CEMP currently includes penguins, tube-nosed (Procellariiform) seabirds, and some pinnipeds, though notably not crabeater seals––due to challenges recording ice-associated seals. However, these seals, which have the largest krill demand of any pinniped, must also be monitored (see above comment about new contributions to crabeater seal monitoring). In addition, CEMP's list of monitoring species should be expanded to include baleen whales (Box 2).

Avoid fishing in the presence of whales

CCAMLR re-convened its Scientific Committee's Working Group on Incidental Mortality Associated with Fishing (WG-IMAF) for the first time in 11 years in response to the lethal bycatch of three humpback whales in the 2020–2021 season, along with increasing concerns over incidental mortality of seabirds and seals[44]. To reduce cetacean interactions, a variety of management tools and approaches were discussed by WG-IMAF, including: acoustic deterrent devices, sonars to detect cetaceans, marine mammal exclusion devices, and other mitigation measures to decrease risks of entanglement and bycatch[44]. Further, the company which incidentally caught the juvenile whales made voluntary modifications and reinforcements to their marine mammal exclusion devices on their nets[44,66]. While this is a start, and reflects actions being taken by regional fisheries management organizations (RFMOs)[80], they fall short of suggesting the fishery prevents setting gear in the presence of whales[68]. Yet, there is precedent for implementing measures that forbid fishing or setting nets on and in the presence of cetaceans in other fisheries management bodies. For example, some tuna RFMOs require avoiding encircling dolphins[80]. Others require parties to eliminate incidental catch of cetaceans during fishing operations (e.g., the General Fisheries Commission for the Mediterranean)[80]. Given how large and visible whales are, particularly pods of whales, implementing a measure to avoid fishing in the presence of large whales is a critical rule to implement immediately. In addition to visual observations, infrared cameras could be used to avoid whales when visibility is poor[81]. With technology rapidly improving, a combination of high-resolution satellite imagery and vessel tracking via automatic identification systems[82] can remotely monitor compliance to such regulations. CCAMLR's work on setting conservation measures to avoid incidental catch of seabirds is commendable, and shows that management can act quickly to allow the coexistence of seabirds and fishing[83,84]. Here, we reiterate the recommendation of immediate implementation of a move-on rule if whales are detected within a set distance (e.g., 100 m) of fishing operations[68].

Dynamic approaches have been applied successfully elsewhere to reduce whale-ship interactions[85,86]. Forecasts of whale presence could be created using environmental data and whale-habitat relationships; those areas could be avoided for fishing at times when a high degree of whale presence is predicted. If data to inform these models are unavailable, more rudimentary dynamic approaches can be applied. For example, whaling records and modern observations indicate that whales feed heavily and gain weight rapidly within the first two months of returning to Antarctic waters (late November through mid-January)[87,88], while other work indicates late season feeding prior to the onset of northward migration[53,89]. More precise information about what regions and times are most important to foraging baleen whales is needed. During particularly sensitive times, krill fishing can be avoided or monitored more closely. Future research can also determine what percentage of baleen whale foraging habitat is included in the voluntary exclusion zones implemented by ARK during these hyperphagic periods. Additional exclusion zones should also be implemented around Elephant, Clarence, and the South Orkney Islands, which would benefit land-based predators[70] as well as fin whales which are known to aggregate and feed around these islands. Ideally these closures would be mandated via CCAMLR, but voluntary exclusion zones could bridge the gap and be implemented immediately. Even seemingly marginal reductions in foraging opportunities

can have outsized impacts on individual and population health of capital breeding species, such as baleen whales[90,91]. As both krill swarms and whale aggregations are dynamic in space and time, flexible management approaches such as those outlined here are more likely to be successful than conventional static management[92].

Eliminate harvesting of sensitive krill life stages

Seasonal distribution of krill shows high abundance in oceanic regions and along the shelf break during summer. In autumn, adult as well as subadult/juvenile krill are concentrated on the shelf along the Antarctic Peninsula[93,94]. Autumn and winter krill fishing in this region is increasing[93]. In this context, it is important that krill fishing should avoid sensitive life stages, such as female krill and subadults during autumn and winter, which are the spawners in the upcoming season. The current data collection on krill fishing vessels in autumn and winter measure and sex krill samples every five days (personal observations, B.M.). We believe this approach may no longer be sufficient and can be improved by a daily krill sampling frequency. In addition, upon arrival to a krill swarm, a requirement could be made for the patch to be sampled via an exploratory haul to assess if fishing should proceed based on evidence-based thresholds to protect sensitive krill life stages.

At present, the shelf break around the South Sandwich Islands (in Subarea 48.4) is the only known spawning region in Area 48 that is not impacted by fishing[95]. Rapid climate change in the Southwest Atlantic has already led to declining krill in their most northern spawning grounds off South Georgia Island[67,96,97]. More data is needed to design tangible mitigation for this issue. Monitoring approaches would need to be developed for this purpose. This monitoring can be done by observers with the 100% observer coverage across the krill fishing fleet[1] in combination with hydroacoustics to identify these critical life stages due to their differences in migration and behaviors[98]. CCAMLR could use that data to implement measures to reduce fishing on these stages in the specific seasons. Encompassed within this element is the need to generate a krill stock hypothesis[99], which is currently under development (Supplementary Note 2). This should also include appropriate data collection for improving krill fishery management.

Conclusions and outlook

Our back-of-the-envelope calculations suggest that blue and fin whale populations are likely to be limited by krill availability before they can reach pre-whaling sizes. This is likely to drive increasing conflict between whales and the krill fishery. It should be noted that our whale consumption estimates are rough calculations; they will need deeper evaluation to draw final conclusions. Nonetheless, we hope that they will spur future research and conversation to include baleen whale prey demand and population trajectories in management of the krill stock. CCAMLR has an opportunity and responsibility to refine management so that Antarctic wildlife, including but not limited to whales, is not threatened by human interests including the krill fishery; however, the consensus required for change has allowed political obstinacy and economic interests to trump science to the detriment of people and planet[41,100].

However, there is hope. We outline several management strategies to alleviate these conflicts including those that CCAMLR is currently developing (Box 2). A key outstanding question is: who would develop and enforce updated management approaches, especially those concerning whales? CCAMLR's Convention stipulates that CCAMLR, and its Scientific Committee, should cooperate with the IWC as appropriate (CCAMLR Convention Article XXIII 3). Nevertheless, collaborative management for whales has proved challenging, though this may be changing. In September 2018, a resolution was adopted at the IWC general assembly to take action on whale conservation; however, Japan stated that they wanted to revisit the moratorium and consider sustainable possibilities to resume commercial whaling[101]. This impasse led to Japan leaving the IWC in 2019. Now, the focus on conservation not only in CCAMLR but also in the IWC might facilitate cooperation between the two organizations. Moreover, CCAMLR's Scientific Committee has reinstituted its WG-IMAF, which has taken strides to engage with the IWC's Scientific Committee to receive guidance on addressing whale entanglements.

Further, the fishing industry has shared data to enable monitoring of the krill stock[46,102,103]. This collaboration will continue to be vital. At present, working directly with ARK to create more voluntary measures based on sound science could implement changes quickly without the need for consensus. However, despite industry support, CCAMLR is unable to adopt these voluntary measures as conservation measures unless they are submitted by members directly and approved by consensus. Notably, there is now a new High Seas Treaty under the United Nations which provides a legal pathway for more comprehensive governance of the high seas, including marine protected areas (MPAs)[104]. The High Seas Treaty will be required to engage with the respective competent bodies in international waters, so in the Southern Ocean, this would mean CCAMLR and the wider Antarctic Treaty System. However, given CCAMLR's inability to reach consensus on conservation initiatives in recent years, some have questioned whether it will be considered a competent body under the new High Seas Treaty[105]. Further, the High Seas Treaty calls for strengthening and enhancing cooperation among relevant legal frameworks, this would include between CCAMLR and the IWC (Box 2). CCAMLR can demonstrate itself as a leader in international spatial management through further strengthening coordination with the IWC, and through implementing krill management measures CCAMLR has been developing for decades alongside specific whale avoidance measures.

While CCAMLR is responsible for managing Antarctic krill, it is important to acknowledge that the Southern Ocean is an international space that provides global benefits[41]. The Southern Ocean and its biota provide a globally important carbon sink, accounting for 75% of heat uptake and 43% anthropogenic carbon uptake by the ocean globally[106]. Robust krill populations, supported by whale iron recycling[14], drive carbon export in the Southern Ocean[7,107,108]. Thus, arguably, the global community should have a say in the process and targets of ecosystem recovery (Box 1, Box 2). The tradeoffs of fishing krill to generate luxury products versus the global benefit of keeping krill in the ocean needs to be assessed. Finally, CCAMLR is currently evaluating proposed MPAs in the western Antarctic Peninsula and Weddell Sea regions (encompassing key portions of Area 48), as well as in the East Antarctic (encompassing key portions of Area 58)[49]. The proposed MPA along the Antarctic Peninsula explicitly considers whales in its design. Safeguarding umbrella species such as baleen whales could afford ecosystem-wide protection[68]. Conservation strategies that consider the benefits of whales and krill to ocean ecosystems can help preserve the Southern Ocean and its global benefits in the 21st-century and beyond[41].

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Author contributions

M.S.S. and C.M.B. conceptualized the study; M.S.S., B.M., J.A.G., and C.M.B. framed the paper, and M.S.S. drafted the main text. M.K. drafted Box 1 and several illustrations in Fig. 2; Z.S. drafted Supplementary Note 2; M.F.C. assisted with data analysis and visualization. All authors assisted with editing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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