WWF

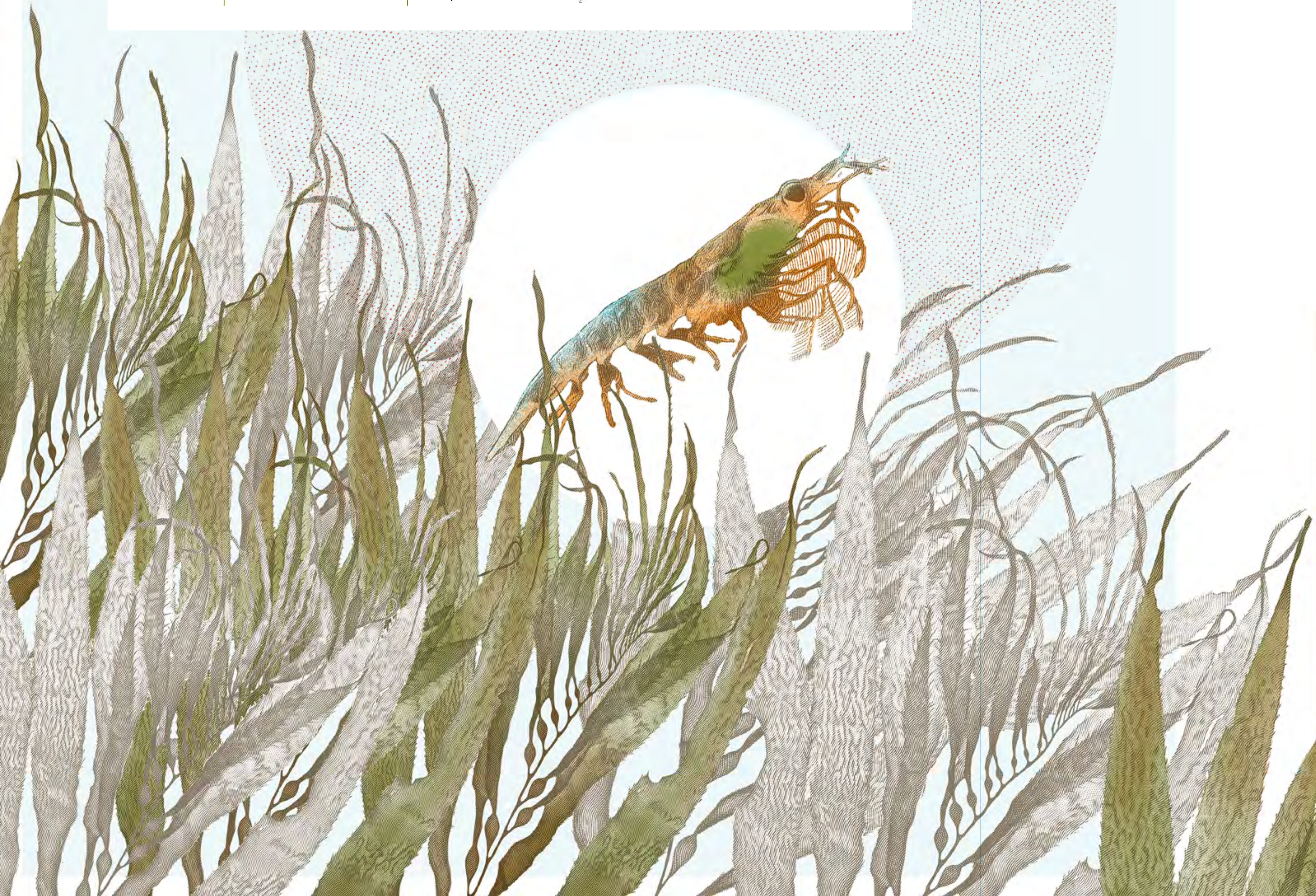
AUSTRALIA

ANTARCTIC KRILL

POWERHOUSE OF THE SOUTHERN OCEAN

TABLE 1 - KEY TERMINOLOGY AND ACRONYMS

E	Faecal pellet egestion rate	Rate at which faecal pellets are released from krill.
FP	Faecal pellet	Krill faeces.
FPT	First passage time	The time it would take for a FP at a given depth and location to be returned to the surface by ocean circulation.
K	Krill density	The number of krill per meter squared as reported in KRILLBASE.
KRILLBASE	A historical database of krill catches	Compilation database providing key data and metadata on Antarctic krill from over 200 national datasets.[95]
OCIM	Ocean Circulation Inverse Model	Output from this ocean circulation model was used to find the depth that krill FPs had to sink to be stored for 100 years.[96]
POC	Particulate organic carbon	The type of carbon measured in krill FPs.
$SSCO_2$	Social cost of CO_2	The marginal cost of emitting one extra tonne of carbon dioxide (CO_2) into the atmosphere (US$/tonne of CO_2).



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WWF

WWF is one of the world's largest and most experienced independent conservation organizations, with over 5 million supporters and a global network active in more than 100 countries. WWF's mission is to stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature, by: conserving the world's biological diversity, ensuring that the use of renewable natural resources is sustainable, and promoting the reduction of pollution and wasteful consumption.

WWF ANTARCTIC PROGRAMME

The WWF Antarctic Programme works to safeguard the diversity of life in a thriving wild Antarctica for future generations. Collaborating with individuals, NGOs, governments, industry and scientific bodies, we monitor and report on the state of species, ecosystems and human impacts, to co-design and communicate urgent solutions that achieve impact.

INFOGRAPHIC 1

ANTARCTIC KRILL POWER THE SOUTHERN OCEAN

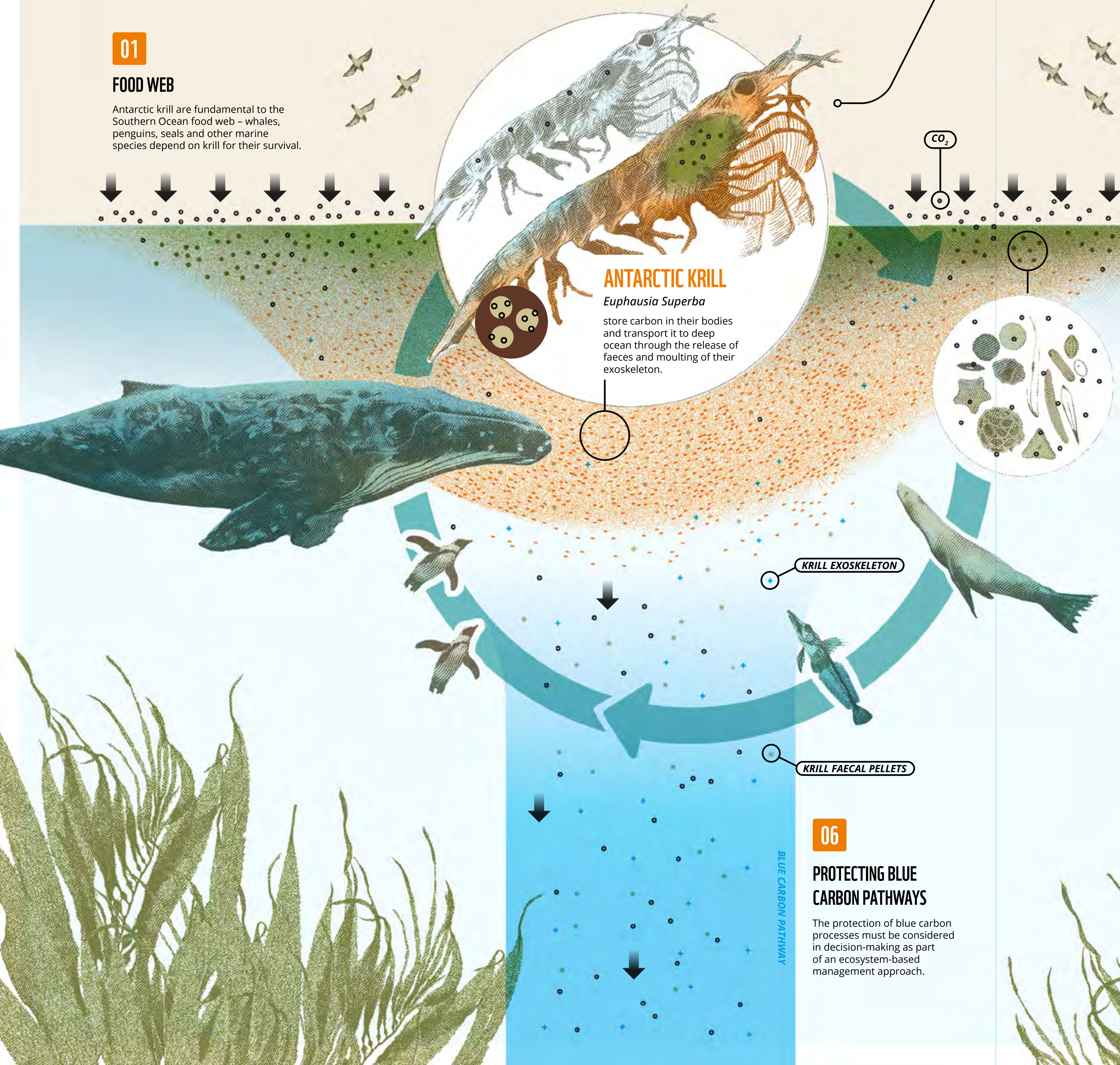
ANTARCTIC KRILL PROVIDE BENEFITS TO ANTARCTIC WILDLIFE AND THE PLANET

01 FOOD WEB

Antarctic krill are fundamental to the Southern Ocean food web – whales, penguins, seals and other marine species depend on krill for their survival.

02 CARBON STORAGE

Through their faeces and moults, Antarctic krill play an important role in regulating and storing atmospheric carbon (maintaining blue carbon pathways) – a natural ecosystem function that helps to maintain stable atmospheric carbon dioxide levels.



ANTARCTIC KRILL

Euphausia Superba

store carbon in their bodies and transport it to deep ocean through the release of faeces and moulting of their exoskeleton.

PHYTOPLANKTON

near the ocean's surface take up CO_2 during photosynthesis and store carbon. Krill then eat phytoplankton and take up this carbon in their own bodies.

03 ANTARCTIC KRILL AS NATURAL CAPITAL IN THE ANTARCTIC PENINSULA AND SCOTIA SEA

US$ 15.2 BILLION ANNUALLY

People and the planet receive benefits from carbon storage services provided by Antarctic krill, through their faeces and exoskeletons, as a function of their presence in the Antarctic Peninsula ecosystem. It is time to re-evaluate the management of Antarctic krill as an extractive resource for economic gain.

04 COMMERCIAL KRILL FISHING

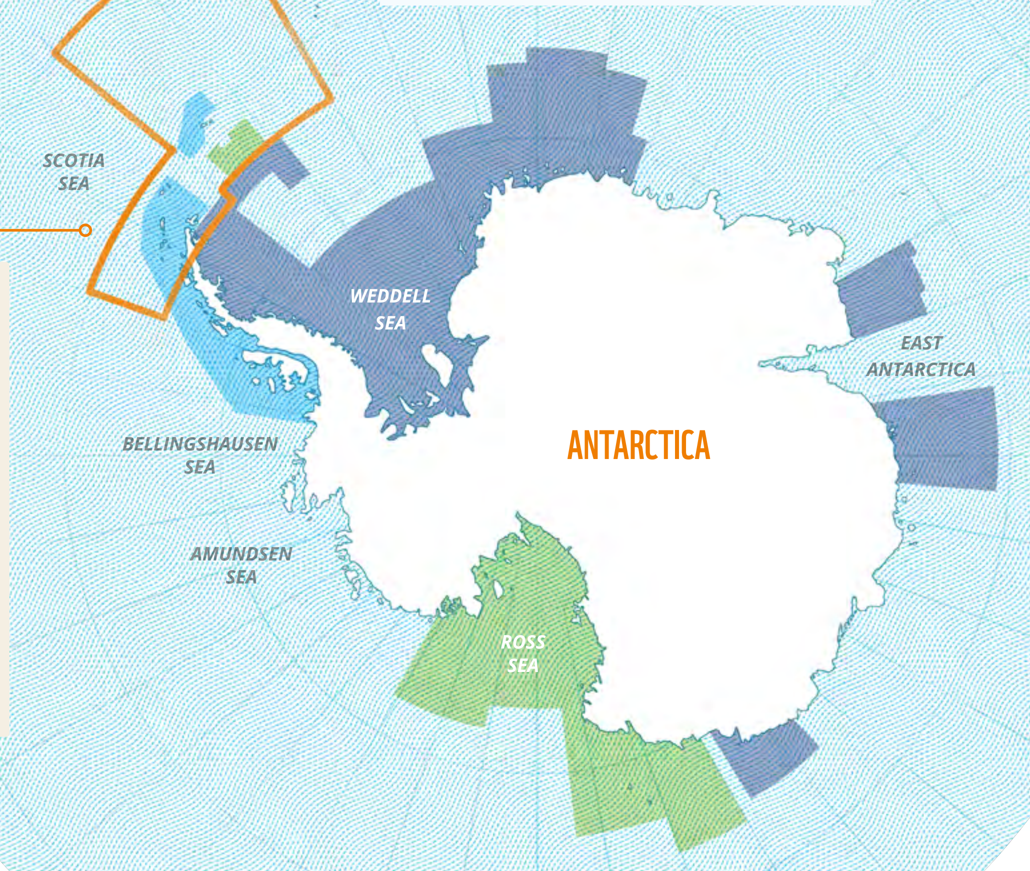
Krill fishing in the Southern Ocean has increased significantly and threatens the resiliency of populations of Antarctic krill and marine animals that depend on krill, and may also have impacts on ecosystem services, including krill's role in the carbon cycle.

05 MARINE PROTECTED AREAS (MPAs)

Improved, internationally binding protection measures for krill populations, via Marine Protected Areas and strengthened management regulations, are urgently needed to safeguard important ecosystem functions from the impacts of commercial fishing and climate change.

AREAS DISCUSSED IN THIS REPORT:

- CCAMLR Subareas 48.1-48.3
- Proposed Antarctic Peninsula MPA
- Established MPAs
- Other Proposed MPAs



THREATS

CLIMATE CHANGE

Antarctic krill are sensitive to increased ocean temperatures, the loss of sea ice and ocean acidification driven by rising CO_2 concentrations in seawater.

KRILL FISHING

Management of commercial krill fishing is outdated. The fishery has increased and become more concentrated around the Antarctic Peninsula, with negative impacts on krill predator populations.

06 PROTECTING BLUE CARBON PATHWAYS

The protection of blue carbon processes must be considered in decision-making as part of an ecosystem-based management approach.

EXECUTIVE SUMMARY

Antarctic krill power the Southern Ocean ecosystem and provide important ecosystem services that benefit both nature and people. They are a key species of the Southern Ocean food web and a critical food source for Antarctic wildlife – whales, penguins, seals and other marine species depend on krill to survive.

Antarctic krill are impacted by climate change through increased warming and acidification and the loss of sea ice – critical habitat for krill. The Antarctic Peninsula region to waters north of South Georgia (the Scotia Sea) has the highest concentration of Antarctic krill in the Southern Ocean. This is also one of the most rapidly warming regions on the planet.

A large-scale commercial krill fishery managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) occurs in this region. This fishery has become increasingly concentrated around the Antarctic Peninsula and Scotia Sea, overlapping with important feeding areas for iconic wildlife. This spatial concentration of fishery operations puts additional pressure on krill and krill predators that, along with growing bycatch of non-target species and a lack of transparency across the industry, suggest that the current management framework is outdated. CCAMLR has the opportunity to prioritise the conservation of Antarctic krill and krill predators through the strengthening of management measures, designation of marine protected areas (MPAs), and integration of environmental variability and ecosystem functions into decision-making as part of an improved ecosystem-based approach to management.

Emerging research is revealing that, in addition to being the foundation of the Antarctic ecosystem, krill play a fundamental role in the global carbon cycle – that is, the natural cycle responsible for regulating atmospheric carbon dioxide (CO_2) levels. Antarctic krill store carbon in their bodies through the consumption of phytoplankton, and transport part of the carbon they consume deep into the water column through the release of carbon-rich faecal pellets and the moulting of their exoskeleton. The process of capturing carbon dioxide near the ocean surface by phytoplankton and transporting a proportion of this carbon for safe storage in the deep ocean through biological and physical processes is referred to as the blue carbon pathway.

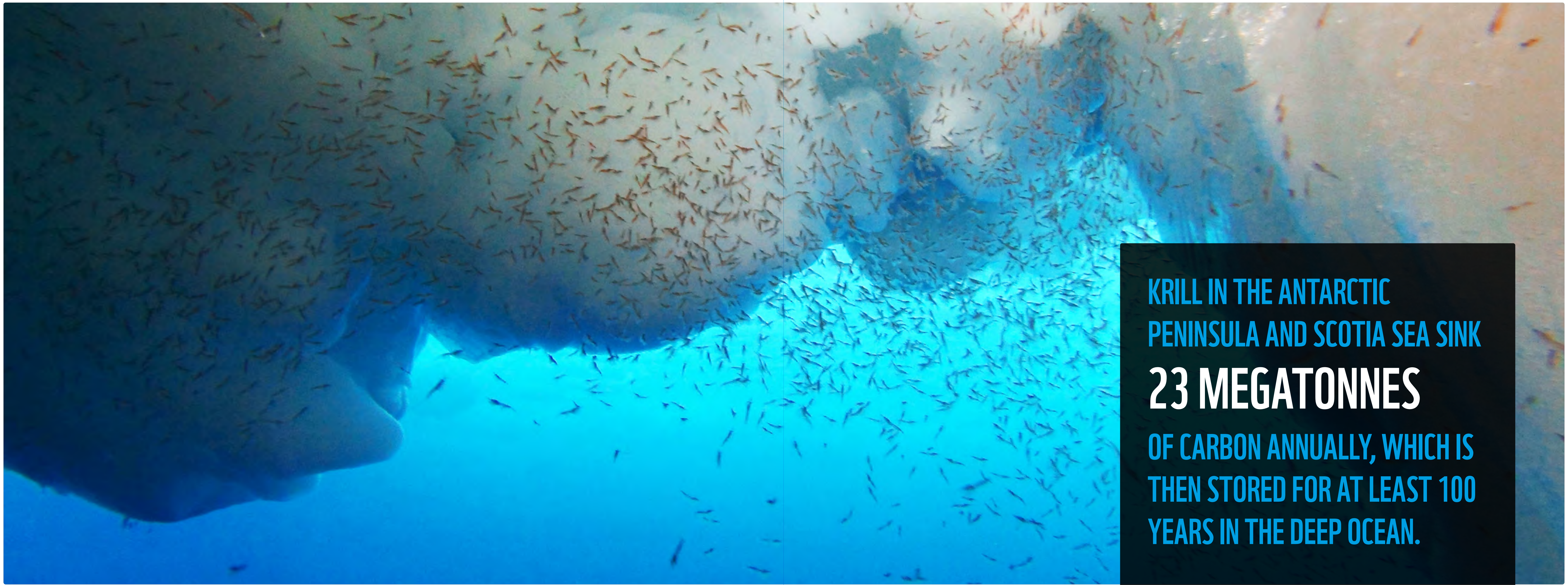
This report examines the potential carbon storage capacity of Antarctic krill around the Antarctic Peninsula and Scotia Sea (i.e., the Atlantic sector of the Southern Ocean) through the release of faecal pellets and moulting during the spring and summer months (October – March). It further provides a preliminary evaluation of the economic value of Antarctic krill carbon sequestration in this region, as a component of their natural capital, using recent estimates of the social cost of carbon (SCC). The SCC is the economic cost of emitting one extra tonne of carbon dioxide into the atmosphere (US$/tonne of CO_2) and is a central tool in the determination of policies to regulate greenhouse gas emissions.

This analysis reveals that carbon sequestration by Antarctic krill in the Antarctic Peninsula and Scotia Sea could be valued at US$8.6 billion per year based on their faecal pellets alone, and that krill may contribute an additional US$6.6 billion through the shedding of exoskeletons. This is estimated to equal the sinking of 23 megatonnes of carbon annually, which can then be stored for at least 100 years in the deep ocean. This value and carbon storage capacity of Antarctic krill carbon sequestration could increase further if the contribution of larval krill, carbon flux by carcasses, and active transport of carbon dioxide by migrating krill were quantified.

The annual worth of the Antarctic krill fishery is nearly two orders of magnitude (or 60 times) lower (~US$0.25 billion) than the estimated worth of Antarctic krill carbon sequestration (US$15.2 billion per year). Our results show that Antarctic krill are worth more to nature and people left in the ocean than removed.

While the aim of this report is to highlight the potential role Antarctic krill play in Southern Ocean carbon sequestration via faecal pellets and exoskeletons during summer, when pellet egestion is highest, further work is required to understand the full perspective of carbon storage in this region. Even with this large number of krill faecal pellets sinking to the deep ocean each spring/summer season, this region of the Southern Ocean is not necessarily a continuous net sink of CO_2, as respiration (release of CO_2) in the upper ocean may outweigh the storage and sequestration of carbon at certain times of the year. A full ecosystem budget from phytoplankton to krill accounting for all life history traits would be required to investigate this.

Each tonne of carbon that krill sequester can help to maintain stable atmospheric CO_2 levels, and thus provides an economically valuable service to society. As the climate crisis threatens global economies and fragile ecosystems, every opportunity to protect fundamental ecosystem services must be taken. Such valuable natural processes may, indeed, influence the future of our planet.



KRILL IN THE ANTARCTIC PENINSULA AND SCOTIA SEA SINK **23 MEGATONNES** OF CARBON ANNUALLY, WHICH IS THEN STORED FOR AT LEAST 100 YEARS IN THE DEEP OCEAN.

RECOMMENDATIONS

As climate impacts are accelerating, there is great urgency to protect krill and the ecosystem services they provide. WWF recommends the following actions are required by the members of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR):

01 PROTECT CRITICAL HABITATS FOR KRILL AND KRILL PREDATORS

- *Deliver the commitment made by CCAMLR to implement a representative network of Marine Protected Areas surrounding the Antarctic continent. This commitment will significantly contribute to global goals to protect 30% of our ocean by 2030.*

02 CONSIDER BLUE CARBON PROCESSES AS PART OF AN ECOSYSTEM-BASED MANAGEMENT APPROACH

- *Include the protection of important blue carbon processes in future discussion on the management of Antarctic krill;*
- *Support research to assess the contribution of krill to blue carbon processes, including all life history traits, and the identification of potential impacts that krill fishing may have on this and other ecosystem functions.*

03 STRENGTHEN MANAGEMENT MEASURES FOR THE CONSERVATION OF ANTARCTIC KRILL AND KRILL PREDATORS

- *Strengthen measures to limit the spatial concentration of krill fishing operations;*
- *Strengthen measures to limit krill fishing during the spring/summer when carbon sequestration is greatest;*
- *Implement move-on rules for krill fishing vessels to reduce bycatch in (i) areas with actively foraging wildlife, and (ii) in response to excessive by-catch of non-target species;*
- *Strengthen the transparency of krill fishing operations including requiring daily catch reporting; introducing standardised methodology to accurately estimate krill catch and eliminate the risk of under-reporting; and providing transparency on commercial end products from point of harvest along the supply-chain.*

IN ANTARCTICA, THE INTRICACIES OF THE FOOD WEB ARE FRAGILE AND FINELY BALANCED – THE SOUTHERN OCEAN ECOSYSTEM DEPENDS ON KRILL.

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ANTARCTIC KRILL: POWERHOUSE OF THE SOUTHERN OCEAN

ANTARCTIC KRILL

Euphausia Superba

are small crustaceans that live in the cold waters of the Southern Ocean around Antarctica. Individual krill measure up to 6 centimetres in length – about the size of a paperclip. They travel in large, dense swarms made up of hundreds of millions of krill that can be seen from space.[1]

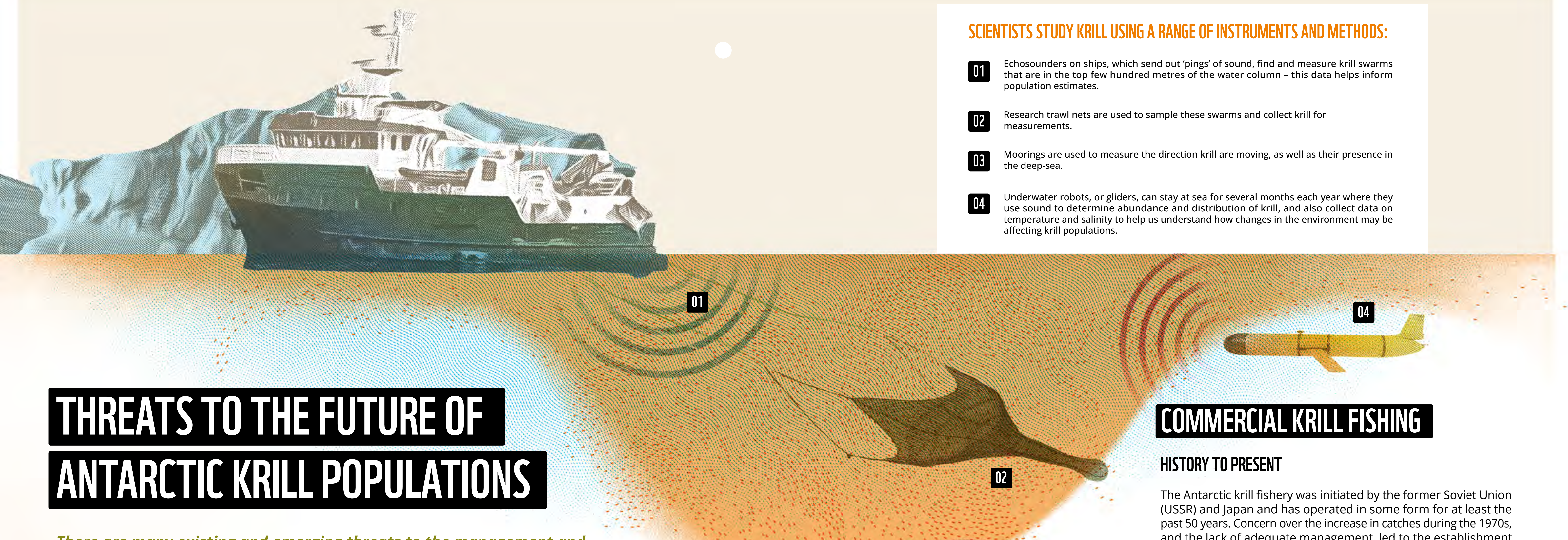
Antarctic krill are central to the Southern Ocean food web. Krill feed on phytoplankton and comprise a critical food source for much larger species at the top of the food chain, such as whales, seals, fish, penguins and other seabirds.[2,3] The term "krill" was even derived from the Norwegian word for "whale food".[4] In Antarctica, the intricacies of the food web are fragile and finely balanced – the Southern Ocean ecosystem depends on krill.

Antarctic krill can live for up to six years. During their complicated life cycle, krill inhabit diverse environments in benthic, surface and pelagic zones of the water column, across shelf areas, shelf-slopes and deep-ocean basin regions south of the Polar Front.[4–6] Their annual and lifecycle phases are closely reliant on sea ice, particularly larval 'baby' krill, which use under sea-ice habitats to survive their first winter, feeding on ice algae and sheltering from predators.[5,7–9]

Natural variations in krill abundance year to year are driven by changes in the number of young krill that reach adulthood – known as 'recruitment'. In the spring, as the sea ice retreats, phytoplankton blooms emerge.[10,11] Larval krill that survive their first winter join the adult population in a feeding frenzy that promotes growth and maturation in preparation for the summer reproduction period.[11] The sequence and timing of the expansion and contraction of sea ice are key determinants for successful krill recruitment and subsequent abundance.[9,11]

Krill are found in swarms at the ocean surface that can number just a few hundred or millions of individuals, stretching for tens of kilometres.[12] Krill swarms are very dynamic and provide feeding opportunities for a variety of species. While a penguin might only catch a few krill at a time, whales take large mouthfuls that contain thousands of krill. The varying size of swarms therefore avoids one predator from becoming the dominant consumer.

The Southern Ocean is a highly seasonal environment due to extreme changes in day length and sea-ice cover.[13] While food for krill may be plentiful in the long, ice-free days of summer, it is a very different story in winter. Krill have adapted by using the abundant summer food to store fat as oil to see them through the colder months.[14]



SCIENTISTS STUDY KRILL USING A RANGE OF INSTRUMENTS AND METHODS:

01 Echosounders on ships, which send out 'pings' of sound, find and measure krill swarms that are in the top few hundred metres of the water column – this data helps inform population estimates.

02 Research trawl nets are used to sample these swarms and collect krill for measurements.

03 Moorings are used to measure the direction krill are moving, as well as their presence in the deep-sea.

04 Underwater robots, or gliders, can stay at sea for several months each year where they use sound to determine abundance and distribution of krill, and also collect data on temperature and salinity to help us understand how changes in the environment may be affecting krill populations.

THREATS TO THE FUTURE OF ANTARCTIC KRILL POPULATIONS

There are many existing and emerging threats to the management and conservation of krill. Antarctic krill are sensitive to climate change, including increased temperatures, the loss of sea ice and ocean acidification driven by rising carbon dioxide (CO_2) concentrations in sea water. Krill are also the target of a large-scale commercial fishery in the Southern Ocean, which is growing rapidly.[15]

CLIMATE CHANGE

Changes in krill abundance are often reflected in the breeding success of its predators – from fish and penguins, to seals and even whales. The rate at which krill biomass is produced, known as its productivity, and changes to krill distribution and abundance, have consequences for the entire ecosystem.[16,17] Variations in krill abundance are further aggravated by changes in environmental conditions, which can hamper predator foraging success and overall performance,[18] highlighting the fragility of the Antarctic ecosystem. Understanding the frequency and severity of years of low krill abundance, and how they correspond with changes in environmental conditions, is critical to forecasting not only the future of krill populations but also the future of species that depend upon it for food.[19–21]

Climate variability and change has the potential to drive major fluctuations in krill biomass. The latest assessment by the Intergovernmental Panel on Climate Change (IPCC) found poleward shifts in the distribution of krill in the Atlantic sector of the Southern Ocean had already occurred,[22] and that their optimum habitat is expected to decline, along with a shortening of the suitable season for krill growth and reproduction in the Scotia Sea.[23,24] This could have widespread ecological impacts and threaten the sustainability of healthy krill populations. As oceans heat, and the sea ice that protects krill nurseries melts, krill risk losing important habitat as they are exposed to the upper limits of their thermotolerance.[25] The south Atlantic sector of the Southern Ocean – the location of the main krill population and focus of the Antarctic krill fishery – warmed rapidly during the past century.[26–28] Declines in krill density within this sector,[22,29] particularly in the northern part of the Southwest Atlantic,[30] have already been reported.

Projected climate change scenarios that consider temperature, sea-ice cover and climatic models indicate a likely negative impact on adult krill biomass.[17,30–32] It is reasonable to expect that more frequent warmer conditions in the Antarctic will correspond with more frequent years of poor performance for Antarctic wildlife.[18]

COMMERCIAL KRILL FISHING

HISTORY TO PRESENT

The Antarctic krill fishery was initiated by the former Soviet Union (USSR) and Japan and has operated in some form for at least the past 50 years. Concern over the increase in catches during the 1970s, and the lack of adequate management, led to the establishment of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). CCAMLR is an international inter-governmental organization responsible for the management and conservation of the Southern Ocean. 'Conservation' for CCAMLR includes rational use, which allows harvesting and associated activities so long as such harvesting is 'carried out in a sustainable manner that takes account of the effects of fishing on other components of the ecosystem'.[33] CCAMLR operates under consensus decision-making that requires its 26 members to agree on all decisions 'on matters of substance'.[34]

During the 1980s, the krill fishery operated all around the Antarctic. For the past 20 years it has been concentrated, almost exclusively, in the Southwest Atlantic region, where krill abundance is highest, particularly in areas near the South Orkney Islands and in the Bransfield Strait near the Antarctic Peninsula (Figure 1). Changes in the distribution of the krill fishery have paralleled changes in the nations that fish for krill, with the total catch of around 350,000–450,000 tonnes per annum (for 2018-2021) shared between Norway (50-60%), China (20%), Korea (10%), Chile and the Ukraine.[35]

Krill fishing has increased significantly, with current catches around four times greater than that of the early 2000s – a change driven largely by the demand for high-value krill oil.[15] This has meant that fishers increasingly target krill in late summer and early winter (March to June), when krill have the highest oil content.[14] Aker Biomarine, a Norwegian company responsible for the majority of harvesting operations in the Southern Ocean, has been one of the drivers of the expansion of the krill fishing industry, along with several Chinese krill fishing companies that are being supported by government investments, including Jiangsu Sunline Deep Sea Fishery Co Ltd which recently launched one of the world's largest purpose built vessels for krill fishing.[36,101]

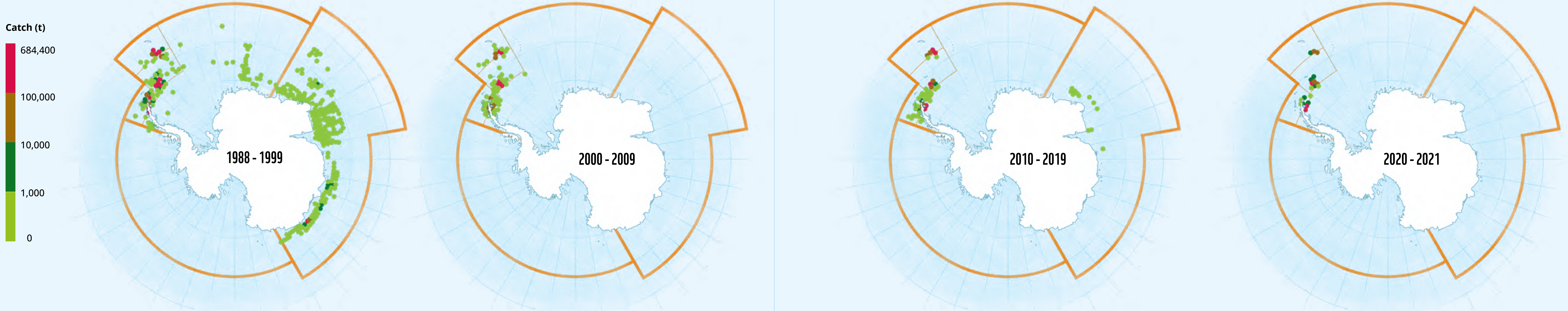


FIGURE 1 *Spatial distribution of krill catches by decade in the krill fishery from 1988-2021, as reported to CCAMLR.*[35]

WHAT IS KRILL USED FOR COMMERCIALLY?

Antarctic krill are mainly harvested to make aquaculture feed, livestock and pet feed, and nutraceutical supplements for human consumption. In the 1980s, there were attempts to develop krill meat for human consumption; however, factors relating to the difficulty of processing krill, concerns over its high-fluoride content, and a lack of consumer acceptance and/or demand slowed the development of krill as a food product.[36,37]

The large-scale operation of the fishery sees the majority of fishing vessels processing krill on board to produce dried and ground krill meal, which can then be further processed on land to extract the oil. The two krill-based end products that currently dominate the market are: krill meal (typically low-oil content meal that is used as feed additives in the aquaculture industry)[38] and krill oil (extracted mostly to produce Omega-3 dietary supplements).[36] Most of the krill catch ends up as meal to be used in aquaculture feed, specifically in the rearing of farmed salmon.[39] Krill contains a natural pigment called astaxanthin, which is used in aquaculture salmon feed to turn the salmon's flesh pink or red.[36] On average, it takes about 6.5 tonnes of krill to produce 1 tonne of krill meal, although this ratio depends on the size of the krill and the time of year.[15]

Although krill meal represents the largest mass of krill product, krill oil is the most commercially valuable end product by weight. In the past 20 years, the krill fishing industry has put significant effort into marketing krill oil for purported health benefits, labelling Antarctic krill oil as a premium product 'from the pristine waters of Antarctica'.[40] **The market for krill oil as a pharmaceutical food supplement is predicted to grow by 10% per annum from 2021-2031 – an increase that would require current catches to almost double over the same period.**[41] The market is also being driven by the growing utilization of krill oil in infant formula and in the manufacturing of skin-care products, as well as an additive in high-end pet food.[42] A growing market for krill products effectively means whales, penguins and other species that depend on krill for their survival face increasing competition for their natural food source from humans, pets and farmed animals distanced thousands of miles from the Southern Ocean.

Perhaps in response to this market expansion, the past few years have seen Norway and China introduce purpose-built krill fishing boats that have required long-term capital investment, and to commence construction of additional fishing vessels to expand their fleet.[38,43] Aker Biomarine is intending to increase its production of krill products. Its strategy is to increase the number of fishing days, increase the price of its aquafeed and pet feed products following higher harvesting rates, expand into new krill oil markets (targeting growth in Asia), and to develop new products for human use, such as protein powder.[39]

Krill meal is much harder to trace than krill oil.[36] Weak reporting requirements through the supply chain reduce overall transparency of the fishery and make it difficult to ascertain exactly how much krill is being harvested to produce each commercial product. While fishing nations identify the intended product as part of their notifications to CCAMLR prior to fishing, CCAMLR does not require fishing nations to report the number of different end products that are ultimately derived from the fishery each year.

GROWING CONCERNS REGARDING THE MANAGEMENT OF THE COMMERCIAL KRILL FISHERY

The krill fishery is managed by CCAMLR under two Conservation Measures (CMs). CM 51-01 sets out the Total Allowable Catch (TAC) combined across the CCAMLR management areas in the Atlantic sector of the Southern Ocean (Subareas 48.1, 48.2, 48.3 and 48.4)[44] and CM 51-07 sets out the overall management measures and percentage of the TAC that can be taken from each management area.[45] The current CM 51-07 catch limit was established using research from the 2000s. This approach was initially considered not to affect predators regionally, but it was noted by CCAMLR in 2016 that local effects on predators may occur if the full catch limit is taken.[46] CM 51-07 was supposed to be revised in 2016, however this was delayed until 2021 to ensure adequate time to develop a feedback management approach and to deliver on an agreed krill management workplan.[46] In 2021, this was again delayed, and CM 51-07 was rolled over for another year.

Krill catches have increased in recent years but the increase has not been evenly distributed. While catches in the Antarctic Peninsula have remained the same, catches in the South Orkney Islands have increased by an average of 15% per year over the past four years.[35] The commercial krill fishing fleet is modernising through the use of purpose-built vessels equipped with advanced technology to locate and trawl krill swarms, making fishing more 'efficient'. Fishers tend to return to where they have successfully fished previously, which creates a spatially concentrated fishery, often in small areas equally important to natural krill predators, such as near Adelie penguin colonies or the feeding grounds of juvenile humpback whales.[18,47] A key issue of concern is not the amount of krill that is harvested, but rather where the fishing is conducted. Spatial heterogeneity of Antarctic krill populations may not be adequately considered and accounted for in management.

ON AVERAGE IT TAKES ABOUT 6.5 TONNES OF KRILL TO PRODUCE 1 TONNE OF KRILL MEAL.

This leads to concentrated fishing effort overlapping with important feeding areas for wildlife, such as penguins and seals, who must then compete with fishing vessels for their main food source: krill. Long-term monitoring in the Antarctic Peninsula has shown that in years of low krill abundance, the fishery has an additional impact on predators that would already be expected to struggle.[18]

The Olympic nature of the krill fishery (where there is a catch limit and the fishery is only closed when that limit is reached, with no quota allocations to individual vessels or countries) means there is competition to maximise catches before the fishery closes. This management approach can compromise environmental and safety standards, but is unlikely to change because any system of resource allocation is not considered to be in the tradition of the Antarctic Treaty System, of which CCAMLR is an important part.[48]

Accurate reporting of catches is a cornerstone of any fishery management process, and krill fishing vessels use a range of methods to estimate their catch. Some are more precise, like using flow scales that weigh all krill that pass over a scale; some convert the depth of krill and water in holding tanks to the weight of krill; while others rely on converting the amount of product produced back to a weight of fresh krill. The precision of actual catch reports therefore varies widely.

Vessels are required to report their catches to CCAMLR every five days, allowing it to monitor the overall catch and to forecast when the catch limit will be reached. Once reached, all vessels in the fishery are advised that the fishery is closed, and they must leave the area.[48] Over the past three years, the total catch in the Antarctic Peninsula region has exceeded the catch limit of 155,000 tonnes, with a bigger overrun each consecutive year, suggesting there is increasing pressure on the management approach being used.[35] **There is currently no process for reconciling the reported krill catches with the actual amount of product that is landed. A strengthened fisheries management framework is required to ensure that the reporting process is not undermined.**

Additionally, perhaps one of the most concerning issues with the current management framework for Antarctic krill is that krill are managed with catch limits that are deemed precautionary, however these limits are set using a stock assessment that does not account for environmental variability or climate change impacts.[18,49] Both the impacts of climate change and the concentration of fishing effort on local wildlife populations have been reported, while development of an ecosystem-based and highly precautionary management framework is delayed each year.

BYCATCH: AN EMERGING ISSUE

Antarctic krill fishery operations around the Antarctic Peninsula and in the Scotia Sea have become increasingly concentrated in areas of high predator abundance – leading to an increased overlap with wildlife foraging on krill, and consequently a greater risk of incidental by-catch.[50,51] Since 2021, several incidents of juvenile humpback whales being caught and killed in trawling nets have been reported, inciting new concerns about interactions between foraging migratory whales and krill fishing vessels.[52,53] Baleen whales depend on krill for their survival, including the Antarctic blue whale (*Balaenoptera musculus intermedia*) that is listed as Endangered by the IUCN Red List of Threatened Species, and it is vital that they are afforded protection from existing and emerging threats.[52,54]

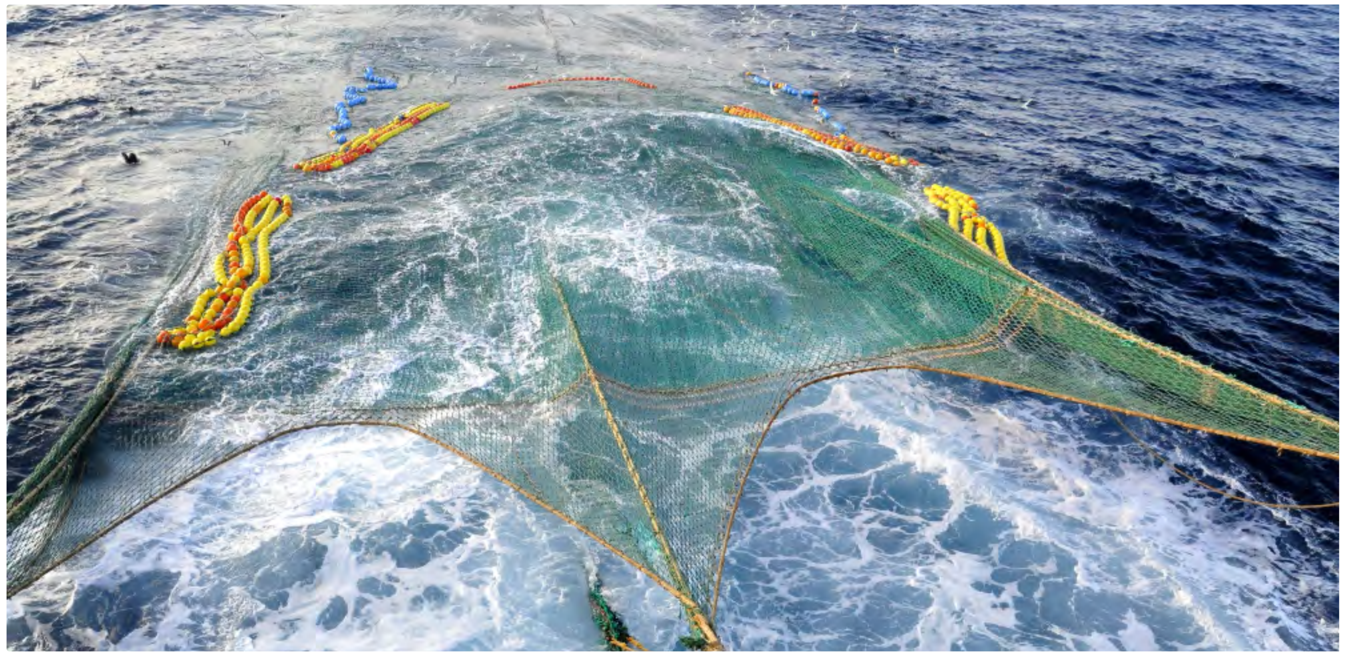
Recent attention has also focussed on the number of birds that become injured or drown when they collide with cables that connect trawl nets to fishing vessels, including net monitoring cables used to transmit operational data from the net during fishing.[55]

Top and middle picture © Dr Conor Ryan

FIGURE 2

The Aker Biomarine krill fishing vessel Antarctic Endurance, a Norwegian flagged ship, was photographed actively trawling towards and through a large group of fin whales 25 km north of Coronation Island on 13 January 2022. The aggregation included an estimated 500–1,200 fin whales, as well as blue and humpback whales.

A STRENGTHENED FISHERIES MANAGEMENT FRAMEWORK IS REQUIRED TO ENSURE THAT THE REPORTING PROCESS IS NOT UNDERMINED.



© CCAMLR Secretariat

The use of net monitoring cables has been prohibited by CCAMLR since 1994 as they were associated with a high rate of seabird mortality; however, Norway and China have been permitted to trial an updated net monitoring cable design on their vessels over the past few years.[56] This 'trial' period has been accompanied by an increase in observations of birds around vessels, indicating that there are potentially much greater numbers of birds striking these warp cables than previously recognised, and thus potentially more incidences of bycatch than are being reported.[53]

In addition to the large numbers of mammals and birds that eat krill, there are a host of fish, including icefish[57] and lanternfish,[58] that depend on krill as their primary food source. Being in the water feeding on krill puts these fish at high risk of also becoming bycatch in the krill fishery.

CCAMLR requires the reporting of fish bycatch in catch data by fishing nations. However, the rate of reporting in catch data is considerably lower than in the scientific observer data. This is due to the fact that most of the fish are less than 10 cm long and are only likely to be found in the detailed sampling done by scientific observers.[35] This suggests that the magnitude of fish bycatch is probably underestimated. Currently, all krill fishing vessels are required to have a mammal excluder device fitted to their nets to prevent fur seals from being caught.[44] While these devices have proven effective for seals, additional measures are needed to prevent bycatch. CCAMLR must urgently address when and how to introduce measures to reduce impacts on non-target species, be they whales, birds or fish. Appropriate measures are vital to ensuring an ecosystem-based approach to management.

ANTARCTIC KRILL'S CONTRIBUTION TO BLUE CARBON PROCESSES

The predominant cause of global climate change is the release of fossil fuel carbon dioxide into the atmosphere by human (or anthropogenic) activities.[59]

The ocean plays a crucial role in mitigating the effects of this through physical and biological processes. Where marine ecosystems and biology effectively store, or sequester, carbon it is termed 'blue carbon'.[60-62] The highest levels of average annual anthropogenic CO_2 emissions in human history were recorded in the last decade (2010 – 2019). Of these emissions, most (46%) remained in the atmosphere, while 31% was taken up by terrestrial ecosystems and 23% was removed by the oceans.[63]

The Southern Ocean accounts for the uptake of up to 40% of the total anthropogenic atmospheric carbon dioxide captured by our oceans, predominantly through physics. This makes it one of the largest carbon sinks globally.[60,64]

When phytoplankton feed in the surface zone, they consume carbon dioxide and 'capture' carbon from the water as they incorporate it into their bodies through photosynthesis.[30] Whilst the live phytoplankton are in the upper ocean this

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carbon is not yet sequestered. Efficient sequestration occurs when carbon is removed from exchange with the atmosphere for at least 100 years.[102] When organisms such as Antarctic krill consume phytoplankton, some (~ 42-94 %) of that carbon is absorbed and becomes body tissue, is excreted or is respired as CO_2.[30] The unabsorbed carbon (so between 6 – 58 %) is ejested as faeces.[30,65] The proportion of carbon ingested by krill that ends up as body tissue, faecal pellets or respired CO_2 depends on the season, food availability and quality of food for the krill,[103] with highest pellet egestion rates in summer when food availability is high.[66] In summer, pellet carbon egestion by krill can equate up to 14 % of total primary production (mean average = 3.5 %) in the Southern Ocean.[66] The large, fast-sinking and tightly packed krill faecal pellets can sink rapidly to the deep Southern Ocean and ocean floor, where the carbon can remain for hundreds of years.[30,66] In addition, krill grow by moulting their exoskeleton, and the old exoskeleton, which also stores carbon, sinks to the ocean floor. Krill (*Euphausiacea*) are unique among crustaceans in that they moult regularly throughout their adult life, providing a potentially significant and consistent contribution to carbon sequestration.[67]

Krill's important role in carbon sequestration can reduce the amount of carbon in the upper ocean, indirectly allowing the ocean to absorb more carbon dioxide from the atmosphere.

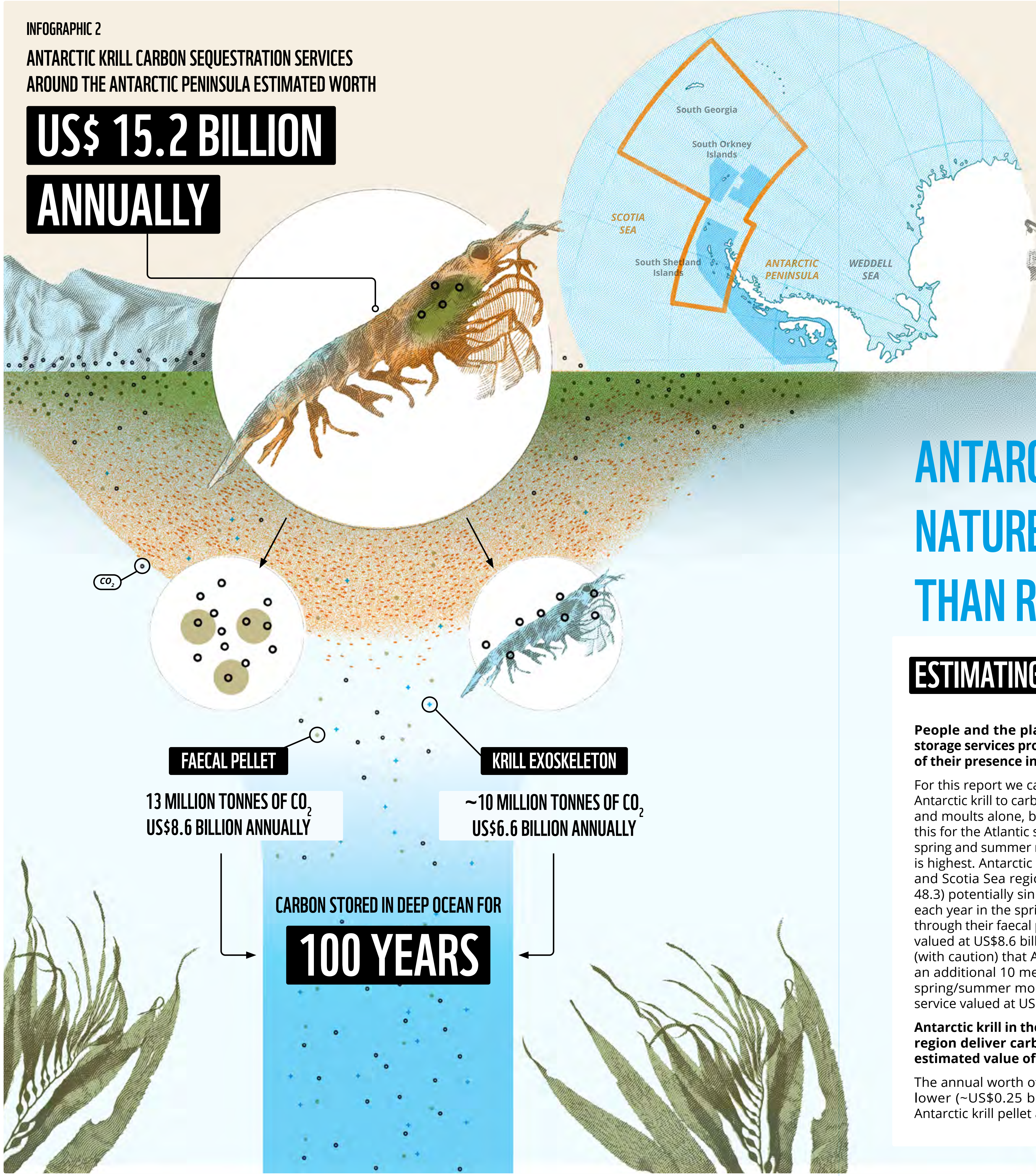
The process of capturing carbon dioxide from water near the ocean surface by phytoplankton and transporting it for safe storage in the deep ocean through biological processes is referred to as the blue carbon pathway.[68]

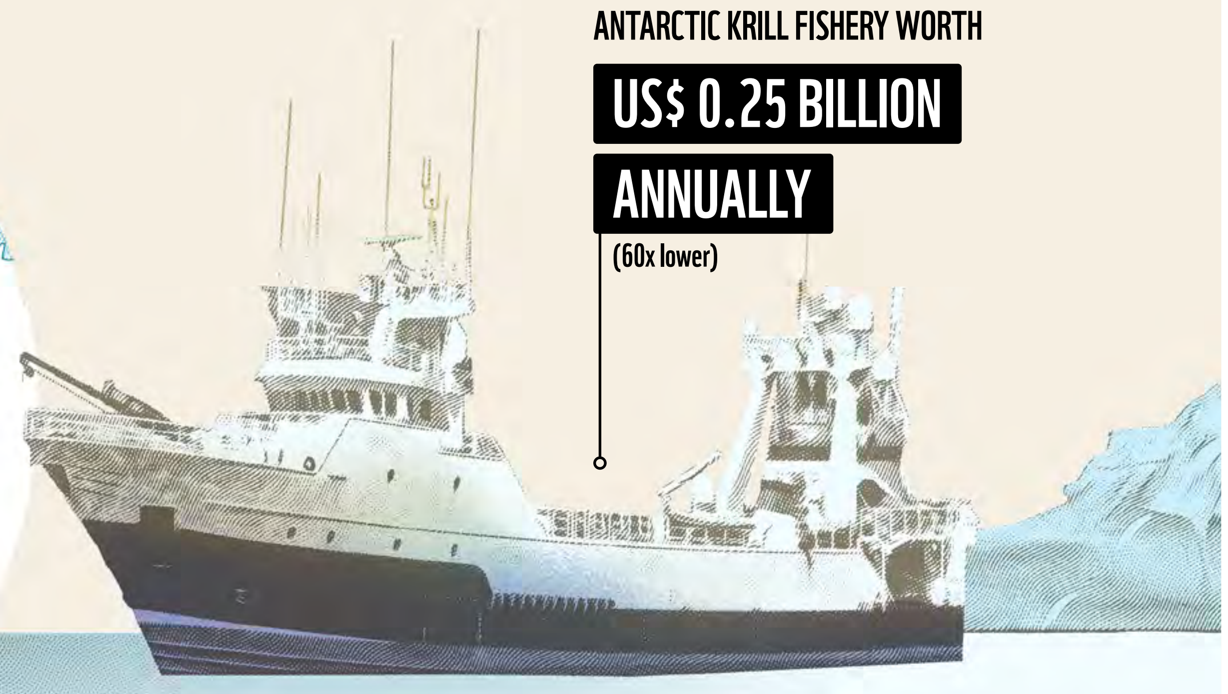
Krill have a central role in this blue carbon pathway because of their tremendous abundance in the surface layers of the Southern Ocean. Egested krill carbon is a natural 'ecosystem service' that is increasingly recognised from both a biological and a policy perspective.[68]

BLUE CARBON PATHWAY

The process of capturing carbon dioxide (CO_2) from water near the ocean surface by phytoplankton and transporting it for safe storage in the deep ocean through biological processes is referred to as the blue carbon pathway.[68]

THE SOUTHERN OCEAN ACCOUNTS FOR THE UPTAKE OF UP TO 40% OF THE TOTAL ANTHROPOGENIC ATMOSPHERIC CARBON DIOXIDE CAPTURED BY OUR OCEANS.





ANTARCTIC KRILL ARE WORTH MORE TO NATURE AND PEOPLE LEFT IN THE OCEAN THAN REMOVED.

ESTIMATING THE VALUE OF ANTARCTIC KRILL IN THE ECOSYSTEM

People and the planet receive benefits from carbon storage services provided by Antarctic krill as a function of their presence in the Antarctic Peninsula ecosystem.

For this report we calculated the potential contribution of Antarctic krill to carbon sequestration via the faecal pellets and moults alone, based on krill abundance data. We did this for the Atlantic sector for the Southern Ocean and for spring and summer months only, when krill pellet egestion is highest. Antarctic krill located in the Antarctic Peninsula and Scotia Sea region (CCAMLR Subareas 48.1, 48.2 and 48.3) potentially sink a total of 13 megatonnes of carbon each year in the spring/summer months (October–March) through their faecal pellets alone. This ecosystem service is valued at US$8.6 billion per annum. We can also estimate (with caution) that Antarctic krill exoskeletons contribute an additional 10 megatonnes of carbon each year in the spring/summer months over the region of our study – a service valued at US$6.6 billion per annum.

Antarctic krill in the Antarctic Peninsula and Scotia Sea region deliver carbon sequestration services with an estimated value of US$15.2 billion annually.

The annual worth of the Antarctic krill fishery is 60 times lower (~US$0.25 billion) than the estimated worth of Antarctic krill pellet and moulting carbon sequestration.[68]

The contribution by Antarctic krill to carbon sequestration would likely increase if we also consider the carbon flux by carcasses,[69] the contribution of larval krill[30] and active transport by migrating krill.

Our results emphasise the benefit of reducing CO_2 emissions to prevent further sea-ice melt. This would help to ensure that krill nurseries survive and krill populations do not decline, therefore maintaining this important ecosystem service to humans.[22] Krill's importance to Antarctic food webs also means many other Antarctic marine animals (birds, seals, penguins and whales)[70] will benefit from its protection and, in turn, may produce further positive benefits to Earth's systems through the movement of nutrients (e.g. migrating whales and their faeces).[2,71] As pellet egestion and the contribution of krill pellets to deep (300 m) carbon flux is highest in summer,[66,69] protecting krill from the fishery in summer could be important. However, it is important to maintain a krill population the following year, and so over-wintering krill which will be a year older and therefore larger than the previous summer, could contribute larger faecal pellets to carbon sequestration the following year.

Further information on this analysis, including methodology, results, and consideration of the uncertainties associated with the model and limitations in data availability, are further expanded in the **Analysis** section.

CONSIDERATION OF BLUE CARBON RESEARCH IN MANAGEMENT

MEETING GLOBAL TARGETS: PRESERVING NATURAL CAPITAL ASSETS IN THE SOUTHERN OCEAN

The current climate change crisis is threatening economies as it accelerates the loss of marine biodiversity and habitats.[72] There is growing awareness of the costs in social and economic terms, and increasing urgency for change that puts societies on a more sustainable path.

The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 parties in 2015 and came into force in 2016, with the goal of limiting global warming to 2° Celsius and achieving a climate neutral world by the second half of the century.[73] All parties to CCAMLR are signatories to the Paris Agreement.

Since 2016, more countries, regions, cities and companies have established carbon neutrality targets, committing to achieving net-zero emissions by a determined year.[73] Meeting these targets will require urgent efforts on multiple fronts to reduce CO_2 emissions, promote carbon sequestration and develop negative-emission technologies.[74] While the main objective is to reduce emissions through zero or low-carbon solutions, the Paris Agreement also sees nations commit to "***promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases … including biomass … oceans … coastal and marine ecosystems***" under the parent convention, the United Nations Framework Convention on Climate Change.[75]

As nations race to become carbon neutral, we must take every opportunity to protect important carbon sequestration ecosystems. The protection of Antarctic blue carbon assets, including krill populations, by CCAMLR nations fits squarely within the scope of this international legal obligation.[76]

HIDDEN COST OF KRILL FISHING

Commercial krill trawling vessels travel vast distances and use large amounts of fossil fuel to reach remote fishing grounds in the Antarctic. When they reach their destinations, these vessels remove large amounts of biomass from the oceans – biomass that serves valuable functions, notably in the carbon cycle. Fishing operators target large swarms of krill, and in doing so they spatially overlap with important habitats for krill and this blue carbon pathway. These results indicate that the overlap, and fishery-driven declines in adult krill biomass, could seriously compromise the functioning of blue carbon pathways and the ability of the Southern Ocean to act as a carbon sink.[30]

In addition to the evidence that krill fishing has and continues to impact on local wildlife populations, such as krill, penguins and whales, there is an additional cost that has so far not been considered – the cost to humanity. We show that **Antarctic krill may provide an essential service to nature and people**. This analysis provides further evidence that Antarctic krill may help to remove carbon from the atmosphere each year and, in doing so, contribute to the current and future health of our planet. Commercial krill fishing is and will continue to impact on the global carbon cycle by removing krill from the Southern Ocean and reducing krill abundance around the Antarctic Peninsula and Scotia Sea, negatively impacting the blue carbon pathway. Further research is needed to better quantify this impact.

AS NATIONS RACE TO BECOME CARBON NEUTRAL, WE MUST TAKE EVERY OPPORTUNITY TO PROTECT IMPORTANT CARBON SEQUESTRATION ECOSYSTEMS. THE PROTECTION OF ANTARCTIC BLUE CARBON ASSETS, INCLUDING KRILL POPULATIONS, BY CCAMLR NATIONS FITS SQUARELY WITHIN THE SCOPE OF THIS INTERNATIONAL LEGAL OBLIGATION.[76]

URGENT NEED TO PROTECT CRITICAL BLUE CARBON HABITATS

The preservation of marine ecosystem functions requires far greater attention from decision-making bodies as a means of safeguarding the future health and well-being of the planet.[77,78]

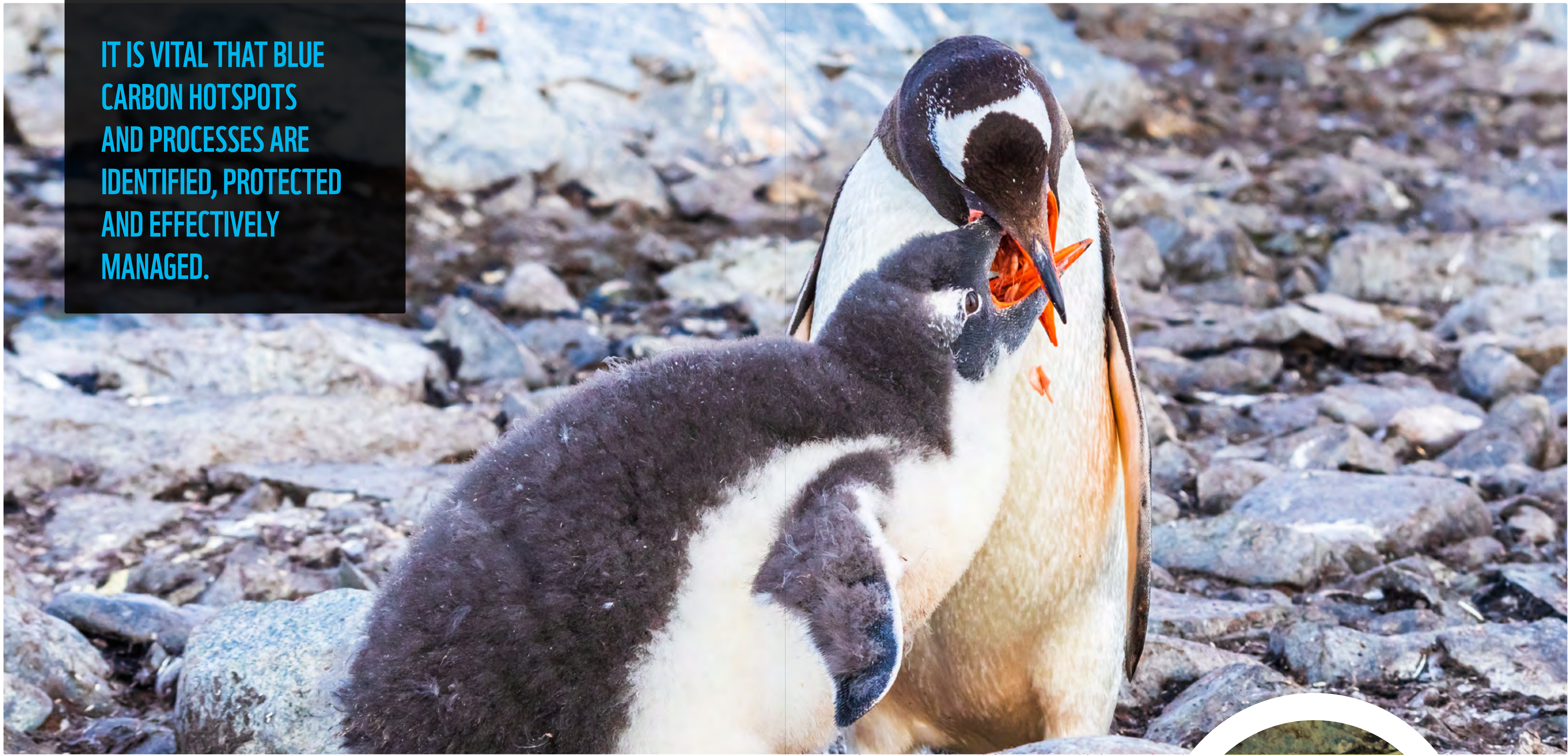
Management of the south Atlantic sector of the Southern Ocean is currently centred around a sustainable commercial fishery and the importance of krill to supporting predator populations (e.g., seals, penguins and whales). There has been no consideration of the effect that harvesting large quantities of krill could be having on global ocean carbon cycles, and hence atmospheric CO_2 levels.[30] Important blue carbon processes like those delivered by Antarctic krill require genuine consideration by CCAMLR and should be integrated into ecosystem-based management frameworks, including spatial protection measures.

There is a compelling need for a change in societal attitudes to recognize nature as essential to our economic well-being.[78] In 2019, 66% of the signatories to the Paris Agreement committed to include nature-based solutions in their climate change programs.[79] Nature-based solutions use ecosystems and the services they provide to address societal challenges like climate change, while simultaneously providing benefits to wildlife and humanity.[104] A Marine Protected Area (MPA) is an area where human activities are limited, managed or prohibited to conserve and protect the marine environment, including biodiversity, ecosystem processes, species and habitats. MPAs are a nature-based solution that supports global climate change adaptation and mitigation efforts.[80] They have the ability to protect or restore ecosystems and, in doing so, to counter or mitigate the negative effects of global change, including through the reduction in atmospheric concentrations of CO_2.[79,81]

The International Union for the Conservation of Nature (IUCN) and others recommend that 30% of the ocean should be protected by 2030 to safeguard nature and people.[80] In 2002, CCAMLR committed to implementing a representative network of MPAs in the Southern Ocean by 2012.[82] The South Orkney Islands Southern Shelf MPA was adopted in 2009, setting a precedent for the use of spatial closures as part of a precautionary management approach.

THERE IS A COMPELLING NEED FOR A CHANGE IN SOCIETAL ATTITUDES TO RECOGNIZE NATURE AS ESSENTIAL TO OUR ECONOMIC WELL-BEING.[78]

IT IS VITAL THAT BLUE CARBON HOTSPOTS AND PROCESSES ARE IDENTIFIED, PROTECTED AND EFFECTIVELY MANAGED.



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Further, a framework for establishing a network of MPAs in the CCAMLR Convention Area, **Conservation Measure 91-04**, was adopted in 2011. This decision exemplifies CCAMLR's mandate for applying ecosystem-based management to help protect biodiversity and restore depleted populations, as stipulated in the CCAMLR Convention (see IX.2(g), CCAMLR Convention).[83]

To date, only two MPAs have been established by CCAMLR – in the South Orkneys (located in the region of study – subarea 48.2) and the Ross Sea (outside the region of study). CCAMLR must honour the commitment made 20 years ago by all CCAMLR Members by considering the designation of three new large-scale MPAs – in the East Antarctic, Weddell Sea and Antarctic Peninsula.

An MPA in the Antarctic Peninsula is an insurance policy for the future of Antarctic wildlife and would mitigate against the growing impacts of commercial krill fishing and climate change. It would ensure healthy populations of krill, the powerhouses of the Southern Ocean, and protect blue carbon pathways, with benefits to both nature and people.[78]

It is vital that blue carbon hotspots and processes are identified, protected and effectively managed.

ANALYSIS

THE ECONOMIC VALUE OF KRILL CARBON SEQUESTRATION IN THE ANTARCTIC PENINSULA AND SCOTIA SEA

EVALUATING KRILL CARBON SEQUESTRATION AS A COMPONENT OF NATURAL CAPITAL

Natural capital expresses the idea that nature can be considered an economic asset, while ecosystem services represent the flow of benefits to society generated by these assets.[84] This includes services such as potable water provided by aquifers, coastal vegetation providing natural flood defences, and wild pollinators stimulating crop growth. Natural capital also includes carbon stored in nature that forms an essential part of the Earth's carbon cycle and helps to maintain the relatively stable climatic conditions that humanity has enjoyed for thousands of years.[78] On land, trees and soils are among the most important terrestrial carbon assets; in our oceans, small organisms like plankton and/or their grazers, including Antarctic krill, play a key role in the carbon cycle. The value to society of the ocean's biological carbon pump, or carbon sink, has been evaluated for various locations, such as the North Atlantic[85] and the Mediterranean.[86]

Each tonne of carbon that krill sequester can help to maintain atmospheric CO_2, and thus provides an economically valuable service to society. This report seeks to value the natural carbon sequestration service provided by Antarctic krill faecal pellets and moults in the Southern Ocean using the social cost of carbon (SCC).

The SCC is the estimated marginal social cost (in US$) of emitting one extra tonne of carbon dioxide into the atmosphere.[87] The SCC is intended to provide a comprehensive measure of the monetized value of the net damages from global climate change that results from an additional unit of CO_2 – this includes, but is not limited to, changes in agricultural productivity, human health effects, property damage and energy use. The SCC has become a central tool in climate change policy, particularly in the determination of policies to regulate greenhouse gas emissions.[88] The three most cited models for the SCC are William Nordhaus' DICE model (Yale University), Richard Tol's FUND model (Sussex University) and Chris Hope's PAGE model (Cambridge University). These models are necessarily complex as they involve the full range of impacts from emissions, through the carbon cycle and climate change, and include economic damage from climate change.[89] The Interagency Working Group (IWG) formed by the United States Government in 2010 estimated the interim SCC in 2020, based on these models, at US$51 per tonne of carbon dioxide (tCO_2).[90]

It has been argued that the IWG's estimate of the SCC does not adequately reflect more recent advances in climate impact studies and empirical findings.[87,91] Other estimates of the SCC range up to US$2,000 per tCO_2.[92] The difficulties in determining an accurate SCC value are due to the uncertainties in modelling assumptions required for simulations, including but not limited to, projections of future greenhouse gas emissions, climate responses and impacts of climate change.[90,92] On average, climate scientists calculate a higher SCC of around US$300 or more, while some economists calculate a SCC of around US$170.[93] Based on the literature, a range of US$51 tCO_2 (more conservative) to US$307 tCO_2 (based on Kikstra *et al* 2021)[94] is used in this report, with a median value of US$179 tCO_2.

NATURAL CAPITAL

Natural capital expresses the idea that nature can be considered an economic asset, while ecosystem services represent the flow of benefits to society generated by these assets.[84]

ECOSYSTEM SERVICE

Vital ecological function or process, such as the production of atmospheric oxygen or the maintenance of stable climatic conditions, that contributes to the natural capital of a region.

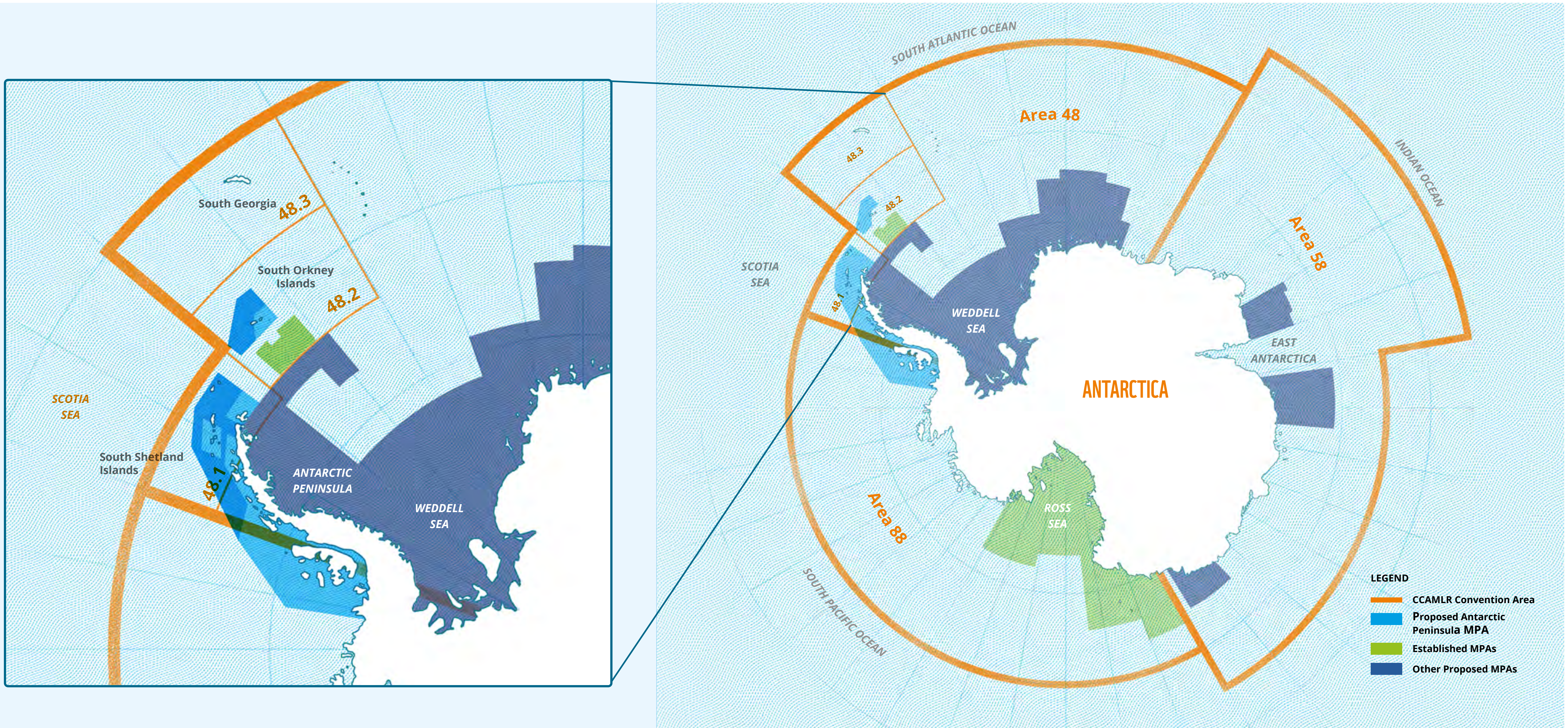
FIGURE 3

CCAMLR Convention Area, with statistical subareas 48.1, 48.2 and 48.3 (reference from www.ccamlr.org/node/86816).

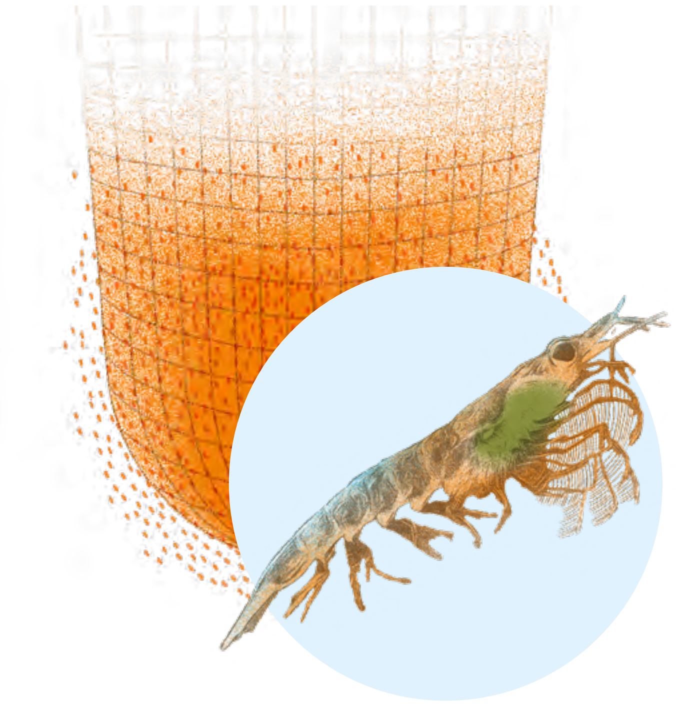
THIS REPORT FOCUSES ON THE ANTARCTIC PENINSULA AND SCOTIA SEA SECTOR OF THE SOUTHERN OCEAN WHERE KRILL ABUNDANCE IS HIGHEST.

LEGEND

- CCAMLR Convention Area
- Proposed MPA General Protection Zone (GPZ)
- Proposed MPA Krill Fishery Zone
- Established MPAs
- Other Proposed MPAs



This analysis focuses on the Antarctic Peninsula and Scotia Sea sector of the Southern Ocean where krill abundance is highest – known in management as CCAMLR Subareas 48.1, 48.2 and 48.3 (**Figure 3**). The analysis concentrates on calculating the amount of carbon (and the equivalent volume of tCO_2) that is sequestered by krill faecal pellets, given the data and parameters available to do this over a wide temporal and spatial area. Only data for spring and summer months are included when faecal pellet egestion is highest, and when carbon assimilation into krill bodies and egestion rates are most likely to outweigh respiration. On a much coarser spatial and temporal scale, the contribution of krill exoskeletons has been estimated, however caution should be exercised when interpreting the exoskeleton values because large assumptions have been made, given the lack of knowledge and data on their contribution to carbon sequestration.



METHODOLOGY

Standardised (to a night-time net haul to 200 m) krill density (# m-2) data from KRILLBASE was used to estimate the density of Antarctic krill. KRILLBASE is a compilation database providing key data and metadata on Antarctic krill from over 200 national datasets.[95] Only haul and stratified haul data, and that from where the top net sampling depth was < 20 m and the bottom net sampling depth was > 50 m, has been included, in line with similar studies.[22,97] As most pellet egestion and data collection occurs in the spring/summer months, data was further subset to include only data from October to March inclusive. This resulted in a final data set of almost 11,000 data points.

The mean krill density (k) at each longitude/latitude (1º x 1º) and month was calculated to give an average krill density for a given location and month. The standard deviation and proportion of area sampled in each CCAMLR subarea each month was calculated. The area (A) of each 1º x 1º longitude/latitude cell was computed, ranging from ~10,200 km^2 at 34 ºS to ~3,800 km^2 at 77 ºS, and converted to meters squared.

The following equations were used to calculate krill faecal pellet flux (mgC d^{-1}) at 20 m depth for each grid cell (*i*) using the FP egestion rate (E) of 3.2 mgC d-1 from (Belcher *et al*., 2019), per month (t) and then summing for each CCAMLR subarea (n):

$$\textbf{FP}\ flux_{n,t}(mgCd^{-1}) = \Sigma k_{i,t} * A_i * E$$

To calculate the total FP particulate organic carbon (POC) egested each month in each location, the FP flux (mgC $^{d-1}$) was multiplied by the number of days (N) in the month (t) to give the FP flux per month:

$$\textbf{FP}\ flux_{n,t}(mgC) = \textbf{FP}\ flux_{n,t}(mgCd^{-1}) * N_t$$

To estimate the amount of krill FP POC that would remain sequestered for > 100 years, the depth to which the FP would need to sink was computed using the Ocean Circulation Inverse Model (OCIM) output to find the depth where the First Passage Time (FPT) is equal to 100 years at each location.[96] The FPT is the time it would take for a FP at a given depth and location to be returned to the surface by normal ocean circulation, and hence an FP that sinks to the depth where FTP = 100 years (FPT_{100}) will be sequestered for that length of time. In this analysis, this depth only varies in space and not time.

The krill FP POC at the mean FPT = 100 years depth (i.e. sequestered) was calculated by applying a Martin b attenuation curve,[98] where the exponent b = 0.32, in line with Belcher *et al*. (2019) for krill FPs.[97]

$$\textbf{FP}\ flux_n sequestered(mgC) = \textbf{FP}\ flux_n(mgC) * \left(\frac{z_{FPT100}}{z_{20}}\right)^{-0.32}$$

The sequestered FP POC (mgC, Fig. 1) was converted to Mt (megatonnes, or a million tonnes) by multiplying by 10^{-15} and summed over all months analysed. To find the 'natural capital' value, the Social Cost of Carbon (US$/ tCO_2) was set to $179. This value has been used in the resulting figure and results section, although results using SCC = $51 and $307 are reported in **Table 2**. Accounting for the fact that the SCC value is for CO_2, and we have estimated a mass of sequestered POC, the result was scaled using the elemental mass of carbon (12) and CO_2 (44):

$$POC\ value\ (US\$) = 179 * \left(\frac{44}{12}\right) = \$656.30$$

Applying the POC US$ value per tonne to the amount of sequestered POC (in Mt/year) gives the average estimated value of krill FP POC in each CCAMLR subarea for the Austral spring/summer season.

RESULTS

Our analysis found that Antarctic krill in the Antarctic Peninsula and Scotia Sea could sink a total of 13 Mt of carbon per annum for at least 100 years through their faecal pellets in the spring/summer months. Using the SCC, the carbon stored by Antarctic krill faecal pellets over the spring and summer months has a value of US$8.6 billion (**Table 2**) per annum, based on a central estimate of the SCC at $179 per tonne of CO_2.

We further estimate the volume of carbon stored by Antarctic krill exoskeletons, based on the Manno *et al.*, 2020 sediment trap data near South Georgia (Subarea 48.3).[69] Based on the findings that Antarctic krill exoskeletons contributed 37.8% to total POC flux over an annual cycle[69], and krill faecal pellets 49.2%, we can estimate (with caution) that Antarctic krill exoskeletons may sink an additional ~10 Mt of carbon per annum, worth US$6.6 billion in carbon sequestration annually, over the region of study.

Although it spans many decades and a large geographical area, the krill density data (KRILLBASE) is spatially and temporally patchy, see (Atkinson *et al*., 2017).[95]. This results in the large standard deviations shown in (**Figure 4**). For instance, some net samples suggest very high krill density at that moment in time and space, when the net tow happened to sample a krill swarm. This makes it complicated to average krill density out over the surrounding area. Many of our 1º x1º lat/long cells had a krill density from just one net sample per month, even over a 35-year period. Checking the coverage of krill density data, we found the proportion of a CCAMLR subarea for which data on krill abundance had been collected each month (by surface area) ranged from 6-60%, highlighting the data gaps that exist in KRILLBASE. A lack of data for other processes (e.g. pellet egestion rate and pellet attenuation rate) made it impossible to ascertain a quantitative error estimate for them. We therefore emphasise the need for caution when interpreting these results.

TABLE 2

Estimated mean krill faecal pellet (FP) particulate organic carbon (megatonnes, MT) sequestered for at least 100 years, on average, over the Austral spring/summer months (October-March inclusive), and the corresponding economic value using the SCC. The standard deviation of the mean is given in parentheses.

AREA	FP CARBON SEQUESTERED (Mt C)	FP ECONOMIC VALUE (USD $ BILLION)		
		$SCCO_2$ = 179	$SCCO_2$ = 51	$SCCO_2$ = 307
48.1	3.6 (10.0-0.00)	2.4 (6.6-0.0)	0.7 (1.9-0.0)	4.1 (11.2-0)
48.2	4.1 (6.4-2.5)	2.7 (4.2-1.6)	0.8 (1.2-0.5)	4.7 (7.2-2.8)
48.3	5.3 (10.9-0.8)	3.5 (7.2-0.5)	1.0 (2.0-0.2)	5.9 (12.3-0.9)
ALL	13.0 (27.3-3.3)	8.6 (18-2.1)	2.5 (5.1-0.7)	14.7 (30.7-3.7)

ECONOMIC VALUE OF ANTARCTIC KRILL CARBON SEQUESTRATION

Our results suggest that Antarctic krill located in the Antarctic Peninsula and Scotia Sea (CCAMLR subareas 48.1, 48.2 and 48.3) may contribute carbon sequestration services valued at US$8.6 billion per annum over the Austral spring/summer season through their faecal pellets alone.

This estimated value could be almost doubled if other aspects of krill life histories are accounted for, including the shedding of their exoskeletons, the contribution of larval krill and active transport of carbon dioxide (CO_2) by migrating krill. It is important to highlight that this value is one component of the natural capital value of krill – an estimate of the total (net) amount of carbon sequestered by Antarctic krill annually including in winter would require further analysis integrating additional aspects of krill life history as indicated above, along with respiration (release of CO_2) rates by krill at varying depths, which is important to understand the longevity of CO_2 storage in the deep ocean.[30] This would be particularly important over winter when food availability is lower, or regions of the study area where summer food availability is lower or of poorer quality. As stated earlier in the report, krill pellet egestion is highest in summer during our analysis period. Any recycling of krill FP material, such as through respiration by microbes, below the FPT=100 years depth means that CO_2 will not be in contact with the atmosphere for at least 100 years.

UNDERSTANDING UNCERTAINTY IN OUR ANALYSIS

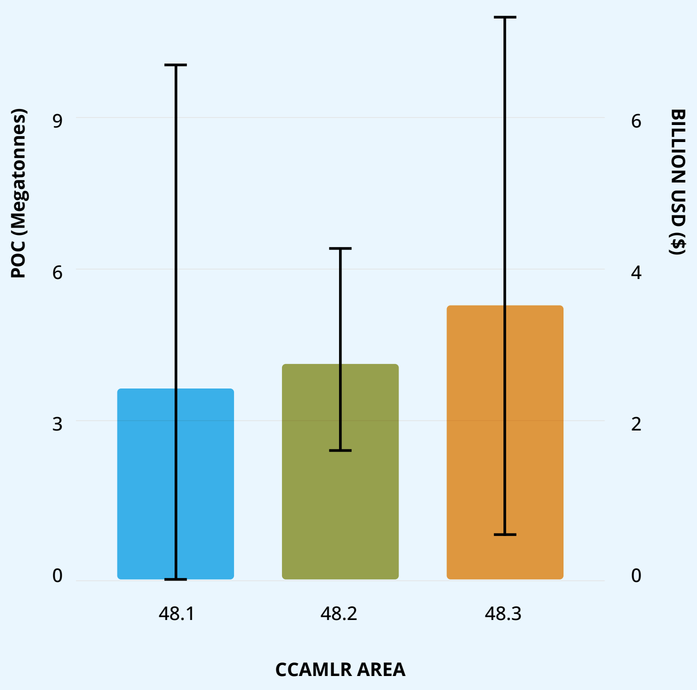
Uncertainty is inherent to science. All knowledge on which decisions and policies are based contains uncertainties of varying types and degrees.[100]

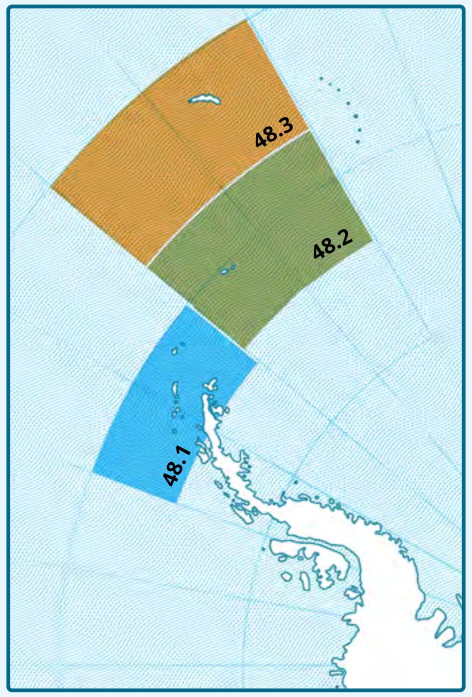
In this scientific analysis, two types of uncertainty exist. The first relates to the randomness of the world and future events that can never be predicted with accuracy – like economic forecasts and climate change models. The second concerns past or present phenomena – things currently beyond our understanding but which we could, in theory, establish knowledge around.[100] The highlighted data gaps on krill distribution, abundance and behaviour in this report fall into this category.

As research expands to fill data gaps, and evidence grows, decisions and policies evolve. This report highlights a new and developing area of research in blue carbon – one that should be fostered, developed, and considered by researchers and policy-makers alike.

FIGURE 4 - KRILL FP CARBON SEQUESTERED (OCTOBER - MARCH)

Krill faecal pellet carbon sequestered on average over spring/summer (October-March) in CCAMLR subareas 48.1-48.3, and the associated social value of the carbon sequestered. Error bars are calculated from the standard deviations of mean krill density data computed at each latitude and longitude in a month over the time series, and from the standard deviation around the mean FPT = 100-yr depths (Table 2).





Our results show that Antarctic krill are worth more to nature and people left in the ocean than removed. The annual worth of the Antarctic krill fishery is nearly two orders of magnitude (or 60 times) lower (~US$0.25 billion) than the estimated worth of Antarctic krill carbon sequestration.[68] The contribution of Antarctic krill to carbon sequestration may increase if we also consider the carbon flux by carcasses,[69] the contribution of larval krill[30] and active transport by migrating krill. At present, the KRILLBASE dataset does not include larval krill stages.

The active transport of faecal pellet carbon by vertically migrating Antarctic krill is not explicitly calculated here but might be captured by the low attenuation rate (b = 0.32) used by Belcher *et al*., 2019.[97] This is because this attenuation is based on observations of sinking krill FP fluxes, without knowledge of whether those krill FPs were released deeper in the water (below 100 m) or in the surface ocean. Cavan *et al*. (2019) hypothesised that the low attenuation rate of krill FPs (i.e., high deep FP fluxes) is due to egestion of FPs below the surface by migrating krill, and particularly by larval krill near the sea ice.[30] Regardless, the active transportation of respired CO_2 by migrating krill is not included in our calculations but would contribute to carbon sequestration if the krill migrate below the FPT100 depth.

There is also uncertainty associated with the model used to estimate first passage times, and thereby to establish the depth below which carbon is sequestered by krill on timescales of 100 years or more. The physical model of the ocean circulation used to estimate FPT derives from a coarse resolution (2° latitude/longitude) model that has been constrained by tracer observations. The coarse resolution means finer scale turbulent mixing, which could affect the mixing of faecal pellets and whether they sink or not, is not fully represented. This means FPTs have uncertainties of 50-150 years associated with them,[99] which is not represented in our standard deviation calculations in Figure 4 or Table 2. In addition, the model has a steady-state circulation, which means that the ocean currents and mixing that carries particles through the ocean do not vary in time. Consequently, we do not account for any differences between the ocean circulation experienced by the sampled krill and the long-term mean circulation in the model. However, despite these limitations, the OCIM provides the best available estimate of ocean FPT values with the broad spatial coverage required for the purposes of estimating krill carbon sequestration.

The large uncertainty in the results means it is not possible to determine which areas should be prioritised in terms of conservation. However, the large amount of carbon sequestered in spring/summer (i.e. in the order of megatonnes and valued at billions of dollars) provides strong justification for further protection and conservation measures to limit krill fishery activity during the Austral spring and summer. The economic value of krill's ecosystem service is unquestionably much higher than its worth as fishery catch.

THE ECONOMIC VALUE OF KRILL'S ECOSYSTEM SERVICE IS UNQUESTIONABLY MUCH HIGHER THAN ITS WORTH AS FISHERY CATCH.

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