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Prospects for a sustainable increase in the availability of long chain omega 3s: lessons from the Antarctic krill fishery.

Simeon L. Hill

British Antarctic Survey, Natural environment Research Council, High Cross, Madingley Road, Cambridge, UK CB3 0ET

KEY POINTS

- The global summit on nutrition, health and human behaviour (GSNHHB) identified the objective of increasing “the availability of long chain Omega-3 (especially docosahexaenoic acid) for human consumption in a sustainable, environmentally responsible way”.
- The objectives of management for sustainability include maintaining continuity of supply and limiting negative impacts. These objectives have associated challenges which are best illustrated using a case study.
- Marine fisheries are likely to remain the main source of docosahexaenoic acid (DHA) for the foreseeable future. I use the example of the Antarctic krill fishery, which is a minor but high value source of DHA, to illustrate the issues, processes, actors and risks involved in attempting to manage natural resources in a sustainable, environmentally responsible way.
- One of the key issues is uncertainty: The natural state of ecosystems, how they respond to exploitation, and how these responses will be affected by environmental change are not clearly understood. The solution is to use “precautionary” measures, which often means catching less than is theoretically possible, and additional restrictions on where the fishery can operate.
- The “sustainability” of the Antarctic krill fishery has been questioned in a way that has impacted the delivery of Antarctic krill products to consumers. In reality, the fishery is one of only 3% of fisheries worldwide that the Food and Agriculture Organisation of the United Nations considers “under-exploited” and one of the few that have a management approach committed to limiting impacts on the both the target stock and the wider ecosystem. Disagreement arises partly because there is no universal agreement about the definitions of “sustainable” and “environmentally responsible” or about the standards of evidence required to support a claim. A

potential solution is to identify the different objectives that people have for the ecosystem, and to agree acceptable trade-offs, levels of risk, and standards of evidence. This approach is compatible with the ecosystem approach to fisheries recommended by the 2002 World Summit on Sustainable Development.

- The GSNHHB's commitment to sustainability is a positive step which should be followed by engagement with suppliers to support the appropriate management and recovery of fished ecosystems.
- GSNHHB's objectives imply an increase in supply beyond the capacity of marine fisheries and therefore the development of alternative sources.
- The steps towards sustainability are similar for all sources. They include identifying the different objectives that people have for the source ecosystem, evaluating the risks of not achieving these objectives, establishing trade-offs between objectives, and ensuring appropriate monitoring. It is essential for groups with an interest in source ecosystems to work with each other, and with scientists and managers, to achieve these steps.

KEY WORDS: Antarctic krill *Euphausia superba*; soupfin shark; Antarctic fur seal; black-browed albatross; whale; penguin; flagship species; docosahexaenoic acid; Vitamin A; sustainable; environmentally responsible; marine; fisheries; rational use; exploitation; harvesting; conservation; conservation principles; sustainability; reference point; sustainability criteria; ecosystem; ecosystem services; fisheries management; ecosystem approach to fisheries; precautionary approach; precautionary catch limit; trigger level; uncertainty; risk; evidence; standards of evidence; trade-offs; governance; decision making; stakeholders; stakeholder engagement; cooperation; monitoring; continuous pumping system; patent; nutraceutical; aquaculture; funding; Marine Stewardship Council (MSC), Aker Biomarine; High Seas; Food and Agriculture Organisation of the United Nations (FAO); Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR); World Commission on Environment and Development (WCED); World Summit on Sustainable Development; Antarctic and Southern Ocean Coalition (ASOC); Whole Foods;

INTRODUCTION

The Global Summit on Nutrition, Health and Human Behaviour (GSNHHB) identified a target intake of long chain Omega-3 (LC-ω-3) of around 1g day^{-1} and therefore a need to "*increase the availability of LC-ω-3 (especially DHA) for human consumption in a sustainable, environmentally responsible way*" [1]. Papers elsewhere in this volume make the case for increased consumption of LC-ω-3. The issue of a sustainable increase in availability also merits serious consideration. Marine fish are the main source of the two key LC-ω-3s for human consumption, docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA)[2]. Any increase in demand for of LC-ω-3 is likely to increase pressure on marine living resources. Historically, increases in demand for marine living resources have often resulted in the degradation of marine ecosystems' ability to supply the relevant product. The GSNHHB's commitment to sustainability and environmental responsibility indicates an intention to avoid exacerbating this situation, but it also presents a considerable challenge in terms of both defining and achieving sustainability.

The sustainable use of living resources is a complicated issue. This is partly because there are many, sometimes contradictory, interpretations of what "sustainability" means. It is also because living resources exist within complicated ecosystems. These ecosystems are networks of organisms, interacting with each other and their physical and chemical environments over multiple scales. Consequently it is difficult both to understand how ecosystems function and to predict how they will respond to pressures such as harvesting and fluctuations in the climate. Ecosystems generally provide a range of benefits ("ecosystem services") to humanity and there are tensions between the different expectations people have of ecosystems. For example, it is not possible to maintain an area of land in a pristine natural state while using it for agriculture. Most interpretations of "the sustainable use of living resources" recognise the need to avoid long term damage to the exploited resource and, increasingly, the ecosystem in which it occurs. This suggests a need to predict how resources and ecosystems will respond to exploitation, even if that prediction is a qualitative assessment of susceptibility to long term damage.

Marine crustaceans called krill provide about 1.1% of the current supply of EPA and DHA by weight, but 6% by value in a market worth $1.45 billion[2]. The most commercially important krill species is Antarctic krill, *Euphausia superba*, which is harvested in the Southern Ocean. The Antarctic krill fishery has been managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) since the Commission's inception in 1982. CCAMLR aims to ensure the "rational use" of Antarctic marine living resources subject to three "principles of conservation" which are: (1) prevention of excessive decreases in the size of harvested stocks; (2) maintenance of the ecological relationships between harvested stocks and other species; and (3) minimisation of the risk of irreversible changes to the ecosystem[3]. These principles are a possible basis for the "sustainable use of living resources." Nonetheless the Antarctic krill fishery is the focus of a high profile controversy over the issue of sustainability which has affected the market for LC-ω-3 products. This fishery is therefore an ideal case study to explore the issues and challenges associated with increasing the availability of products derived from marine living resources in a sustainable, environmentally responsible way.

This chapter summarises the context, ecology, history, and management of the Antarctic krill fishery as well as the roles of a wider group of "stakeholders" (individuals and organisations who influence or have an interest in the outcome of management decisions) to illustrate the issues, processes, actors and risks involved in attempting to manage natural resources in a sustainable, environmentally responsible way. Its purpose is to identify the challenges and suggest potential routes towards achieving the goal of a sustainable increase in the availability of LC-ω-3. The issues are directly relevant to the Antarctic krill fishery, but they are also of general relevance to all LC-ω-3 sources that involve marine capture fisheries. The chapter also includes some comments on sustainability issues associated with the development of alternative sources of LC-ω-3.

CONCEPTS

This chapter frequently refers to sustainability, uncertainty, risk, the precautionary approach, and the ecosystem approach. The following paragraphs provide a brief introduction to these terms.

Sustainability is the focus of this chapter. The word "sustainable" is widely used but there is no universal agreement about what it actually means. The World Commission on Environment and Development (WCED) was convened by the United Nations in 1983 *inter alia* "*to propose long-term environmental strategies for achieving sustainable development by the year 2000 and beyond*."[4] The WCED defined sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*."[4] However the word "sustainable" is frequently used in ways that do not conform to this definition and even within this definition there is scope for disagreement about the details.

Uncertainty is incomplete knowledge or agreement. This is particularly relevant to marine ecosystems. Even estimating the abundance of a fish stock is riddled with uncertainty because "*counting fish is like counting trees, except they are invisible and they keep moving*"[5]. Understanding how fish stocks interact with the wider ecosystem and how they will change over time is still more uncertain. Consider how uncertain weather predictions can be over ranges greater than a few days, yet the models on which these uncertain predictions are based represent the fundamental laws of physics, which are well understood[6]. There are no universally true laws that predict the outcomes of ecological interactions[7]. Uncertainty is a fact of life. It is impossible to know the consequences of most decisions or actions with absolute certainty. Formal decision making processes that acknowledge this often use the concept of **risk** which is an assessment of the potential for a decision or action to lead to an undesirable outcome. Another relevant form of uncertainty is "linguistic uncertainty" which is a lack of clarity or agreement about the meaning of words and phrases[8] such as "sustainable".

The **precautionary approach** is a decision making framework used when the risks associated with an action are difficult to assess. It requires policies that "*reduc[e] the probability of occurrence of bad events within acceptable limits*" when the potential for these events is plausible but not necessarily demonstrated "*and the potential costs are significant*"[9]. Application of the precautionary approach in fisheries management should reduce the risk of harm to the ecosystem by setting low catch limits (and protecting areas from fishing) until there is evidence that the risks associated with more intensive fishing are acceptable.

The **ecosystem approach to fisheries** is "*management recognizing ... the interdependence between human well-being and ecosystem health and the need to maintain ecosystems productivity for present and future generations, e.g. conserving critical habitats, reducing pollution and degradation, minimizing waste, protecting endangered species*"[10]. There are several overlapping terms[11] including **ecosystem based management** which is "*an integrated approach to management that considers the entire ecosystem, including humans. [Its goal] is to maintain an ecosystem in a healthy, productive and resilient condition so it can provide the services humans want and need"*[12]. These concepts recognise that fished stocks are part of complex ecosystems and they generally promote management that recognises multiple objectives. The 2002 World Summit on Sustainable Development encouraged "*the application by 2010 of the ecosystem approach*"[13]. I am not aware of any assessment of how widely this approach has been applied.

CONTEXT: MARINE CAPTURE FISHERIES

Marine capture fisheries reportedly provide around 80 Mt y^{-1} of fish and invertebrate products which are mainly destined for human consumption either directly or indirectly as food for farmed animals[14] (although estimates suggest that illegal, unreported or unregulated fishing adds a further 30 Mt y^{-1} [15]). Although most terrestrial food production shifted from hunting to agriculture millennia ago, fishing is the only large scale food production process that involves hunting wild animals, albeit generally with technology that facilitates very effective location and capture. Fishing therefore relies on natural production without the inputs and systematic habitat manipulation associated with farming.

Mankind has over-exploited marine ecosystems around the world and reduced their ability of many to supply fishery products compared to their pristine state, or even their state a few years ago[14]. There are many reasons for this, including the now discredited view that fishery production is inexhaustible[16]; the "tragedy of the commons" in which short term maximisation of individual benefits leads to the depletion of a shared resource[17]; attempts to maximise production without adequately accounting for uncertainty or ecological complexity[18]; failures in governance[19]; and a tendency for governments to subsidise otherwise non-viable harvesting[15,18]. Global marine fisheries production has been declining since the mid-1990s[14] despite improving technology and the exploitation of new species and new fishing grounds. The Food and Agriculture Organisation of the United Nations (FAO) classifies 32% of all fish stocks as over-exploited ("being exploited at above a level which is believed to be sustainable"), depleted ("catches are well below historical levels"), or recovering ("catches are again increasing after having been depleted")[14,20]. This suggests that there is little, if any, capacity for an increase in production. However, there are pockets of so called under-exploitation ("believed to have a significant potential for expansion in total production")[20] including the Antarctic krill fishery in the Southern Ocean[21].

Fisheries mainly produce flesh for direct human consumption. However, there is a long history of using extracts as health supplements (e.g. "cod liver oil") or to enhance livestock feeds. Demand for these products has contributed to the over-exploitation of marine living resources, such as the soupfin shark, *Galeorhinus galeus*, which was harvested to near extinction on the Pacific Coast of the United States because of the demand for vitamin A for poultry feed between 1935 and 1950[22].

Capture fisheries have important benefits for human beings. They are economically important (the estimated first-sale value of marine and freshwater capture fishery products is \$93 billion y^{-1}), they provide the main livelihood of numerous communities and their products are important as a food source and in promoting health[14]. Fisheries management aims to maintain these benefits ("the continued productivity of the resources" [23]) and should also aim to prevent or reverse damage to fish stocks and fished ecosystems[11,15].

ANTARCTIC KRILL

There are many detailed reviews of Antarctic krill biology[24,25], ecology[26,27,28,29,30,31,32], and fisheries and management[33,34,35] in the volume edited by Everson[36] and elsewhere. This section summarises the relevant points.

Ecology

The Southern Ocean is the only ocean which does not border any permanently inhabited land masses. Its remoteness and frequent inhospitability have constrained the development of commercial and scientific interest. The Discovery Expeditions of 1928 to 1951 provided a great advance in scientific understanding of the Southern Ocean ecosystem. These expeditions were funded through a tax on the whaling industry and their objective was to "*obtain further information on whales and the factors which influence them*"[37]. Sadly this knowledge did little to prevent the depletion of the great whales. The international geophysical year (1957 to 1958) marked the beginning of the modern era of Antarctic research and since then there has been an expansion of research activities, mainly funded by national science programmes, which have further increased our understanding of Southern Ocean ecosystems. Research activities tend to be concentrated around 68 research stations[38] and they mainly take place in the summer months. As Antarctic research is a relatively recent development, ecological time series have a maximum current span of 3 to 4 decades. Ecological processes in the Southern Ocean operate over large spatial and temporal scales and are strongly affected by seasonal variability. The mismatch between the scales of these processes and the scales at which data are available means that scientific understanding of these processes is uncertain. Consequently much of what follows is accompanied by qualifiers.

Krill, or euphausiids, are shrimp-like crustaceans that occur throughout the world's oceans. Antarctic krill is one of several krill species found in the Southern Ocean, but is the only one that is commercially harvested. It occurs in most waters between the Antarctic Polar Frontal Zone and the continental shelf (Fig. 1), but its distribution is extremely patchy at number of scales. Antarctic krill aggregate in swarms containing upto 60,000 krill m^{-3} [27]. Swarms can occur predictably in some areas, including the shallow shelf waters around islands in the Scotia Sea and southern Drake Passage (SS-DP) region[39]. Despite the greater density of Antarctic krill close to land in the SS-DP, the vast majority of the region's Antarctic krill occur in lower densities over the much greater area of open ocean[39,40]. At the regional scale the main concentration of biomass is in the SS-DP, whereas Antarctic krill is virtually absent from some parts of the Southern Ocean including northern parts of the Pacific and Indian Ocean sectors[39]. Adult Antarctic krill occur mainly in the upper 150m of the water column[41] and are best known from open water habitats, but they also occur under sea ice[42] and at depths of upto 3,500m[41] where, respectively, they feed on ice-associated algae[42], and from the sea bed[43].

Genetic analysis suggests that the population of Antarctic krill is well mixed throughout the Southern Ocean with no distinct subpopulations[44]. This is due in part to their interaction with ocean currents such that individual Antarctic krill might be transported over considerable distances in a lifetime[45,31]. One consequence of this is that the South Georgia shelf in the SS-DP, which apparently lacks a self-sustaining Antarctic krill population, is nevertheless an important predator feeding area because ocean currents import a predictable supply of Antarctic krill[29].

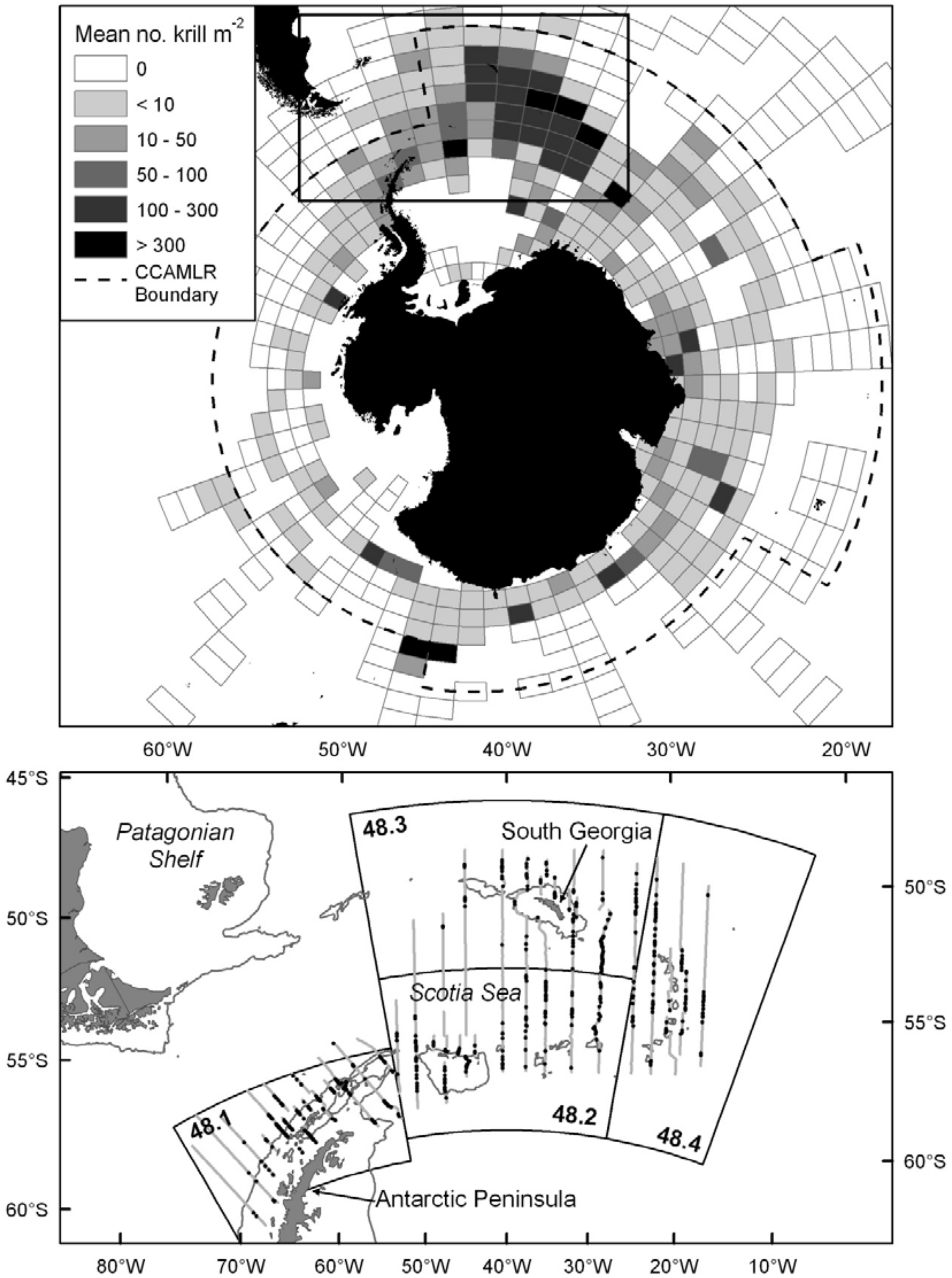

Fig 1: Top: The distribution of krill in the Southern Ocean from [39], and the boundary of the area managed by CCAMLR, which approximates to the Antarctic Polar Frontal Zone[30]. **Inset and bottom:** The main krill fishing areas labelled with FAO subarea codes, and the transect lines from the 2000 survey[84] with areas of high krill density (>100g m^{-2}) highlighted in black[40].

Antarctic krill feed mainly on phytoplankton and are, in turn, prey for a range of larger organisms including fish, seals, baleen whales, and penguins and other seabirds[28,31,32,46]. Their suitability as prey is due to a combination of factors including their abundance and relatively large size large size (upto 65mm[25]), and the fact that dense swarms occur predictably in some locations. Most Antarctic krill predators also feed on alternative prey such as other crustaceans, fish, and squid[31,46]. The composition of predator diets varies between seasons, years and habitats depending on which prey are available. Consequently while, for example, Antarctic fur seals found on South Georgia are often described as "krill-dependent predators"[47], those found on Heard Island in the Indian Ocean sector feed mainly on fish[48].

Antarctic krill probably influence the spatial pattern and overall productivity of phytoplankton in the Southern Ocean. Locally high densities of Antarctic krill suppress phytoplankton production[49]. Recent research suggests that ammonia excreted by Antarctic krill might also promote production by ungrazed phytoplankton[50] while the dissolved organic carbon they release might also facilitate bacterial production[51].

Antarctic krill is clearly an important species in the Southern Ocean ecosystem. This importance is due in part to its abundance, the visible signs of which include and the distinctive pink stain of Antarctic krill-rich penguin faeces (Fig 2). This importance is also due to the diversity of habitats that Antarctic krill occupy, such that they connect otherwise remote parts of the Southern Ocean ecosystem. For example, Antarctic krill predators range from the crab-eater seals that live on the sea ice in the South to the black-browed albatrosses that frequent the warmer oceans to the North[28], and from these seabirds that barely penetrate the surface waters of the ocean to the brittle-stars of the seabed[43]. Their influence on the primary production and nutrient cycling that underpin most ecological functioning means that they affect many more species than just their direct predators. However, this influence is highly variable in both space and time.

Fig. 3 illustrates temporal variability in the mean density of Antarctic krill in a 8000km^2 survey area to the northwest of South Georgia[52]. Local Antarctic krill density can shift dramatically within a single year and between years. Much of this variability is driven by variability in ocean conditions, which influence the success of every stage of the Antarctic krill life cycle[30,3]. The extreme seasonality of the high latitudes can mean that the physical conditions necessary for primary production are available for only two or three months of the year, resulting in dramatic shifts in food availability throughout Southern Ocean foodwebs[31]. This seasonality interacts with the well known interannual variability in the ocean conditions of the southern hemisphere characterised by periodic warming of the tropical eastern Pacific during El Niño events. This variability propagates quickly through the atmosphere and more slowly through the Southern Ocean via the Antarctic Circumpolar Current which flows around the continent from West to East[53].

Fig 2: Carotenoids from Antarctic krill give this penguin guano its distinctive pink colour, which can be used to identify penguin colonies, like this Adélie penguin colony on Paulet Island, in satellite images (photograph by Norman Ratcliffe).

This variability in physical conditions inevitably affects the organisms living in the Southern Ocean: Conditions switch between favourable and hostile and populations rise and fall over time. In addition to this natural variability, the Southern Ocean ecosystem is also responding to changes driven by human activities. The first significant disturbance was the seal harvesting which began in the late 1700s and persisted until the early 1900s, by which time Antarctic fur seals were virtually extinct on accessible sub-Antarctic islands such as South Georgia, and Southern elephant seal populations were also much diminished[54]. These species survived in less accessible southern areas and they gradually recolonised the sub-Antarctic islands as human attention shifted to the great whales[54,55].

Mori & Butterworth[56] describe the removal of whales and seals from the Southern Ocean as "*largest human induced perturbation of [any] marine ecosystem in the world*". Laws[57] speculated that these removals released 150 ty^{-1} of Antarctic krill for consumption by other predators. This could partially explain the recovery of Antarctic fur seals. We have less information about the fortunes of other Antarctic krill predators during this era. Trivelpiece et al.[58] suggest that penguin populations increased until the 1970s as a result of reduced competition with whales for food. Statistics from fishing expeditions to sub-Antarctic islands in the early 1970s suggest that annual catches exceeded present day estimates of total biomass[52,59,60], which could indicate that the fish populations were artificially elevated. This removal of fish biomass also affected the ecosystem. It is plausible that species such as Antarctic fur seals, which both prey on fish and compete with them for Antarctic krill, have suppressed the recovery of fish populations[61].

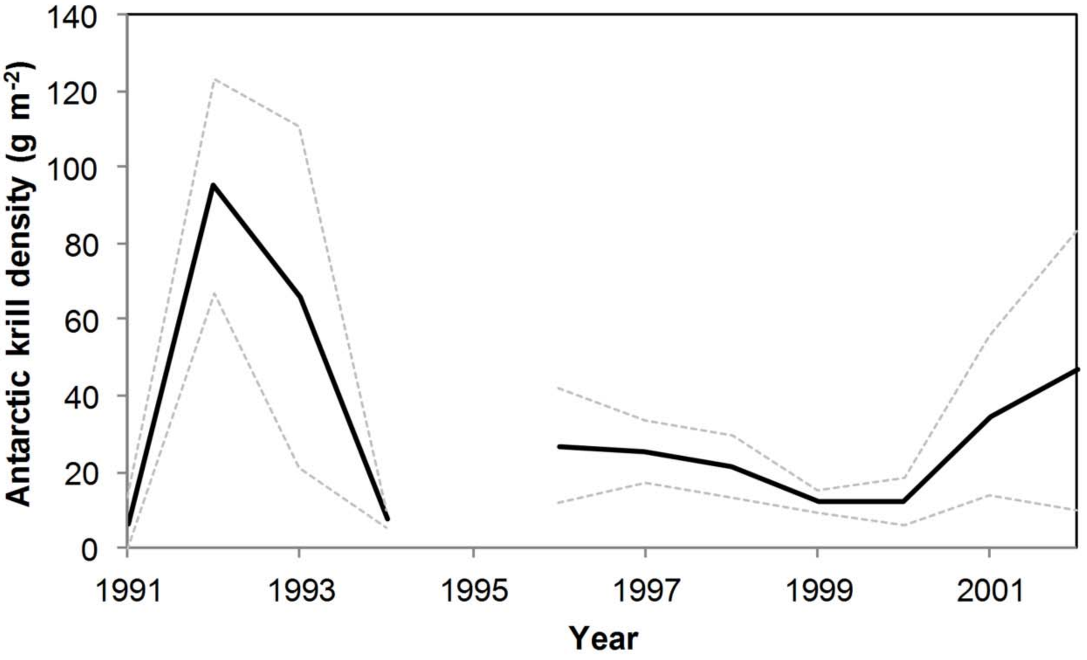

Fig 3: Interannual variability in estimated Antarctic krill density at a scale of 8000km^2: mean and 95% confidence intervals.

Historical harvesting of seals, whales and fish has clearly disrupted the Southern Ocean ecosystem. Seal populations may have recovered to or even beyond their historical levels, but most baleen whale populations are still depleted as are many fish stocks. Comparison of the number of individual Antarctic krill caught in standardised nets suggests that Antarctic krill densities in the SS-DP declined significantly from >100m^{-2} to <10m^{-2} between 1976 and 2004[62].The same analysis identified other areas where Antarctic krill densities did not change or increased, but the results suggest an overall reduction in Antarctic krill abundance. Several studies have reported correlations between the extent and duration of winter sea ice and the abundance of Antarctic krill in the SS-DP [63,64], but these relationships are not consistent for all sectors of the Southern Ocean[65]. Interannual and spatial differences in krill abundance are also linked to the availability of food and to sea temperature[39,66,67].

The size of each new cohort of Antarctic krill must depend to some degree on the size of the parental generation. Antarctic krill begin to breed in their third or fourth year and each female spawns upto 9 times per year, producing upto 8000 eggs each time[25]. However, successful hatching of these eggs might depend on whether they are released in the correct habitat[68] and survival to adulthood is likely to depend on many factors including the availability of food and appropriate habitat at critical life stages, and successfully avoiding predation and disease. Very little is understood about the relationship between the sizes of successive generations.

Climate change is yet another potential cause of variability and disturbance in the Southern Ocean. Although the accumulation of greenhouses gases in the atmosphere is expected to cause widespread warming, the presence of the ozone hole has so-far prevented this effect around Antarctica[69]. The ozone hole has, however, caused an intensification of westerly winds associated with rapid regional warming of areas such as the Antarctic Peninsula and the localised retreat of some ice shelves[69]. Sea temperature records also indicate localised warming. For example mean summer temperatures at South Georgia have increased by 0.9°C in 8 decades[70]. The influence of greenhouse gases relative to the ozone hole is likely to increase over coming decades and plausible forecasts suggest that 3°C warming across the Antarctic could occur by the end of the century[69]. This, in turn, would affect sea temperatures and sea ice cover, which could decrease by 33%[71], and is therefore likely to impact the Antarctic krill population and the wider ecosystem in which it exists. However, current predictions of these impacts are highly uncertain[46,66,67].

Observations of Antarctic krill density are usually made for small parts of the vast area over which the population is dispersed. Density changes at these small scales are due to the combined effects of changes in overall abundance, changes in demographic structure and changes in spatial distribution. It is difficult to assess the relative importance of these different influences and therefore the extent to which a localised change in density reflects a large-scale change in abundance.

In summary, Antarctic krill is an important part of the Southern Ocean ecosystem, affecting many other species through its interactions with both phytoplankton and predators, and through its role in nutrient cycles. The ecosystem is highly variable in space and time, and change is one of its defining characteristics. These changes result from a combination of natural and anthropogenic influences. These points apply in a general sense to most of the of LC-ω-3-rich lower trophic level species such as sardine and anchovy that channel energy to diverse groups of predators and support substantial but variable fisheries in upwelling systems off Africa and South America. There is much uncertainty in our understanding of Antarctic krill, which is due in part to a mismatch between the available data and the time and space scales over which changes affect Antarctic krill populations.

Fishery

The earliest reported exploratory fishing for Antarctic krill occurred in 1961/62 (fishing seasons are usually expressed in this format because they straddle the end of one year and the beginning of the next) and by 1973/64 annual catches exceeded 10kt[33]. The maximum reported annual catch (528kt) occurred in 1981/82. Soviet vessels caught 93% of this maximum, and 70% was from taken from the SS-DP (specifically statistical subareas 48.1 to 48.3: Figs 1 & 5)[72]. The collapse of the Soviet Union caused a dramatic decline in catches as Soviet vessels withdrew from the fishery, leaving Japan as the main fishing nation. Japan reduced effort in the early 2000s, and Japanese catches fell from an average of 67kt y^{-1} between 1985/86 and 2002/3 to 29kt y^{-1} between 2003/4 and 2009/10. Norway entered the fishery in 2005/06 and is now the main fishing nation, having taken 56% of the reported catch in 2009/10, while South Korea took 22%. Although reported annual catches remain substantially below the 1981/82 maximum, there has been a recent increase such that the 2009/10 catch (212 kt) was 185% of the post-Soviet average. 83% of all reported catch and >99% of post-Soviet catch was taken from subareas 48.1 to 48.3[72].

Nicol et al.[73] identify the following Antarctic krill products: peeled tail meat for human consumption; processed meat for use as a food additive; meal or meat for use in aquaculture; sport fishing bait; aquarium feed; chitin; lipids and enzymes. Foster et al.[74] identified 812 "Antarctic krill related" patents lodged between 1976 and 2009, 43% of which were lodged after 1978. Between 1976 and 1981, the majority of patents related to harvesting and processing methods but since 1981 the majority of patents relate to products for aquaculture or human use. Since 2007, over half of all patents relate to products for human use. Patents for human use products related exclusively to food use between 1976 and 1982. Since then an increasing proportion of these patents relate to medical use, which accounted for 38% of all patents lodged between 1999 and 2008. These trends illustrate the development of interest in Antarctic krill products and the recent focus on "nutraceutical" products, which include enzymes and chitin as well as LC-ω-3. Tou et al.[75] describe Antarctic krill as a "*rich source of high-quality protein*" with low fat and high levels of ω-3s and antioxidants. Overall levels of polyunsaturated fatty acids in Antarctic krill are higher than those in shrimp and salmon[75]. The DHA content of the three taxa is comparable, but the EPA content of Antarctic krill is higher[75]. Overall the EPA and DHA content of Antarctic krill is about 0.4% although this varies with season, age, and processing speed[75].

The fishery uses mid-water trawl nets with mouth openings of 300–1000 m^2 [76]. Originally these nets were brought on board the vessel for emptying when they were filled with catch[76]. Some vessels now empty the nets by pumping the contents onboard and some use a continuous pumping system which brings catch on board while the vessel is towing the net[76,77]. Most vessels are equipped with factories and process the catch to some degree at sea[76].

Management

Much of the Southern Ocean is “High Seas” and it does not fall under any national jurisdiction. Nonetheless, harvesting activities are governed by a system of international treaties. These include the 1946 International Convention for the Regulation of Whaling and the 1972 Convention for the Conservation of Antarctic Seals[34]. The 1980 international Convention on the Conservation of Antarctic Marine Living Resources covers the harvesting of fish and invertebrates[34]. It is implemented by CCAMLR which first met in 1982 and currently consists of 25 members. A further 9 states are party to the Convention but not members of CCAMLR[78].

The CCAMLR Convention is notable as “the first international convention involving fisheries to include wide-ranging conservation principles based on the ecosystem approach” [34]. Importantly, CCAMLR aims to support “rational use” [3] (which could be rephrased as “sustainable fishing”). CCAMLR’s decisions must be made on the basis of scientific evidence[3,34] (Fig. 4). It has adopted the precautionary approach to minimise risk in conditions of uncertainty[79].

Practical management of the Antarctic krill fishery must address two main issues: Firstly how much Antarctic krill the fishery can catch[34] and secondly where it can operate[80]. There are additional issues including appropriate fishing methods and gears, conduct and data collection[81].

The approach to Antarctic krill fishery management has mainly developed for subareas 48.1 to 48.4, which the remainder of this section will therefore focus on, although the principles may be applied to other parts of the Southern Ocean.

An initial estimate of how much Antarctic krill is available is necessary to establish how much can be caught. Assessing the size of the Antarctic krill stock in the 3,470,000km^2 covered by subareas 48.1 to 48.4 is a considerable task. There were two attempts to do this for a similar area in 1981[82] and 1983/84[83] and a definitive survey in 2000[84]. An area of approximately 2,065,000km^2, between the sea ice and the Antarctic Polar Frontal Zone was divided into seven strata (blocks of habitat with coherent characteristics) and each of four research vessels surveyed a number of narrow strips, called transects, in its allocated strata[84]. The survey method used shipboard sonar equipment to transmit sound waves in a vertical beam beneath the vessel and to record the signal reflected by objects in the water column. Expert analysis of these data is necessary to identify Antarctic krill swarms and assesses their biomass. The analysis extrapolates transect biomass to estimate the biomass within strata and combines the stratum estimates to estimate biomass for the whole area. The method for estimating Antarctic krill biomass from the raw acoustic data was in its infancy at the time of the initial analysis[85]. Methodological improvements since then have led to a number of reanalyses of the same data and reappraisals of how much biomass was present in 2000[84,85,86]. The initial estimate, published in 2000, was 44.29 Mt[87], but the current, revised estimate is 60.3 Mt[88]. The process is prone to uncertainties at each stage: identifying Antarctic krill swarms; converting the raw acoustic data to transect biomass; and extrapolating the transect biomass to the large unsurveyed areas between transects. The survey method excludes Antarctic krill in the upper 15 to 20m of the water column[84], and in 40% of subareas 48.1 to 48.4. Furthermore some extrapolation methods give much higher biomass estimates[85], suggesting that the survey results might underestimate biomass. Atkinson et al.[89] estimated that 28% of the global Antarctic krill stock occurs in the survey area, which implies that the biomass of Antarctic krill in the entire Southern Ocean was about 215 Mt in 2000.

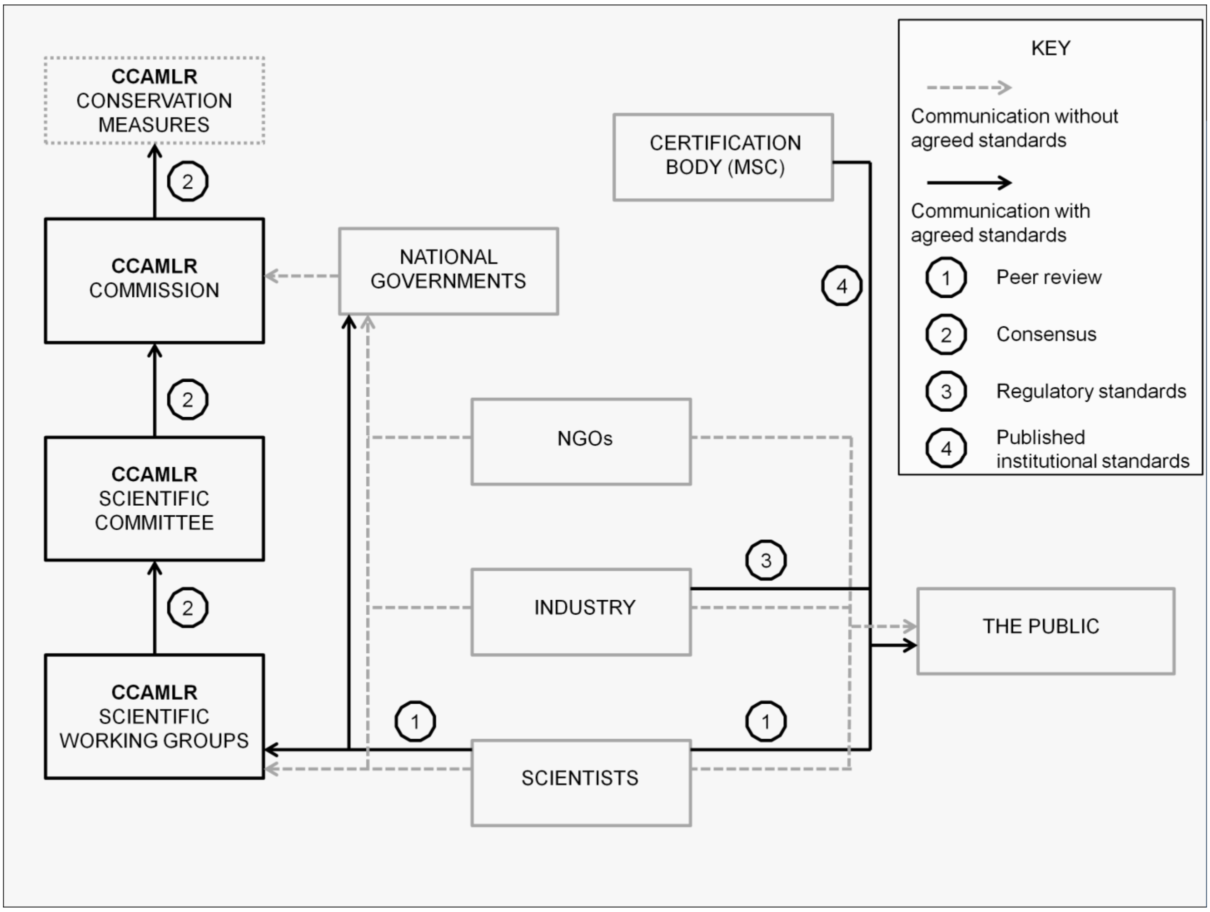

Fig 4. Interactions within CCAMLR leading to the Conservation Measures used to regulate the Antarctic krill fishery; and between stakeholders, indicating the different standards of evidence or agreement applied to these communications.

CCAMLR sets a notional catch limit (known as the "precautionary catch limit") as a fraction of the survey estimate of "unexploited" biomass[33,34,35]. Analysts identify this fraction using a computer model that simulates the effects of fishing on the Antarctic krill stock and assesses the impacts of different catch levels[30,34]. The model and its application in setting catch limits account for uncertainties in understanding of how Antarctic krill populations vary over time, and for variability in many of the known population processes[30,34]. Given this uncertainty it would be impossible to predict exactly how the population will change in the future. CCAMLR therefore uses a process called Monte Carlo simulation where the model is run many times with many different combinations of values for the various processes that it incorporates. This gives many possible population projections, which are combined with a range of annual catch levels expressed as fractions of the unexploited biomass.

CCAMLR uses multiple population projections from the model to identify catch levels consistent with two outcomes that are, in turn, considered to be consistent with CCAMLR's objectives for the target stock and related species[34]. Outcome one is where the biomass of adult Antarctic krill (those capable of producing offspring) falls below 20% of its initial level in 10% of population projections[34]. In the absence of clear information about the adult biomass required to maintain stable recruitment, but with evidence that the population varies naturally from year to year, the 20% level was considered to be a limit below which there is a significant risk that the population might not be able to replace itself. Outcome two is where the median adult biomass after 20 years is 75% of the median after 20 years from a reference set of projections without any fishing[30,34]. This could be restated as exploitation to (a median of) 75% of the unexploited biomass. Smith et al.[90] studied simulations of five fished ecosystems and concluded that exploitation to 75% of unexploited biomass allows reasonable catch rates while achieving "much lower impacts on marine ecosystems" than "conventional" exploitation rates.

The model usually identifies two catch levels, one for each outcome, and CCAMLR selects the lowest of these to set the precautionary catch limit. The current precautionary catch limit for subareas 48.1 to 48.4 is

$$B_0 * \gamma_2 = 60.3 * 0.093 = 5.61\text{Mt}$$

where B_0 is the survey estimate of biomass and γ_2 is the catch level consistent with outcome two[88]. This addresses the issue of how much the fishery can be allowed to catch, but the precautionary catch limit is notional as it does not resolve the issue of where the fishery should be allowed to operate within subareas 48.1 to 48.4.

The fishery has always concentrated its efforts on and around island shelves[76], which are where Antarctic krill predators such as penguins and fur seals also concentrate their foraging effort during the summer offspring rearing season[46,80]. CCAMLR has selected the precautionary catch limit to reserve an appropriate amount of Antarctic krill for predators at the large scale. However, it recognises that there is a risk that the catch could be concentrated in smaller areas and that this could deprive predators of prey in their foraging areas. Although concern about predators has largely focused on birds and seals, fish probably consume more krill than both of these groups[32,46]. CCAMLR has considered various solutions to the problem of localised competition with predators, including dividing the fishery up into smaller spatial units and setting catch limits for each of these units[6,80]. However, the solution that it adopted in 1991 is much simpler: It imposed an interim catch limit (known as the “trigger level” because this is the catch level at which a revised, spatially-structured management scheme must be implemented) of 620kt y^{-1} [35]. That is, the actual catch limit is only 11% of the current precautionary catch limit. According to computer simulations this is equivalent to reducing the stock by 2% of unexploited biomass[91], which is less than 10% of the depletion allowed by Smith et al’s[90] reference point. Smith et al’s[90] results suggest that upto 11% (mean + 95% CI) of groups (collections of species) could suffer population declines of >40% if the target species were reduced by 25% of unexploited biomass, but no more than 1.5% of groups would suffer such declines if it were reduced by 2%.

The 620kt y^{-1} trigger level approximates the sum of the maximum annual catches recorded in each subarea. There is no evidence that these catches impacted predator populations. In 2009 CCAMLR adopted a further restriction on how much of the trigger level could be caught in each subarea[35], which should help to prevent excessive concentration of the catch in a single subarea in the event of a shift away from the historical distribution.

Fisheries management requires frequent updating in response to changing conditions and new information. Over recent years CCAMLR has recognised a number of issues which it is working to address. Firstly, catch statistics are not based on the raw weight of Antarctic krill removed from the sea. Rather, this raw weight is estimated by applying conversion factors to the weight of processed products[88,91]. Secondly, the fishing process probably kills more Antarctic krill than are brought aboard fishing vessels, including Antarctic krill that sustain damage while passing through the mesh of fishing nets[88,91]. Both of these issues lead to uncertainty in estimates of mortality (i.e. how much Antarctic krill is killed by fishing). Even with this uncertainty, the total amount of Antarctic krill currently killed per year is likely to be much less than the trigger level (Fig. 5). Nonetheless, CCAMLR will need to take this uncertainty into account if future catches approach the trigger level[88,91].

A third issue is that more information on changes in Antarctic krill populations has accumulated since CCAMLR established its management approach. This information suggests that natural variability could mean that there is a high (>10%) probability of adult biomass dropping below 20% of the unexploited level in some years, so that outcome one is impossible to achieve even with no fishing[91]. Furthermore, a climate-driven population decline is a plausible scenario that is not accounted for in the current management approach[30] or indeed in CCAMLR’s objectives[3]. Finally, the current approach is based on an 11-yearprojection of biomass observed during 2000.This fact alone challenges the validity of the current precautionary catch limit.

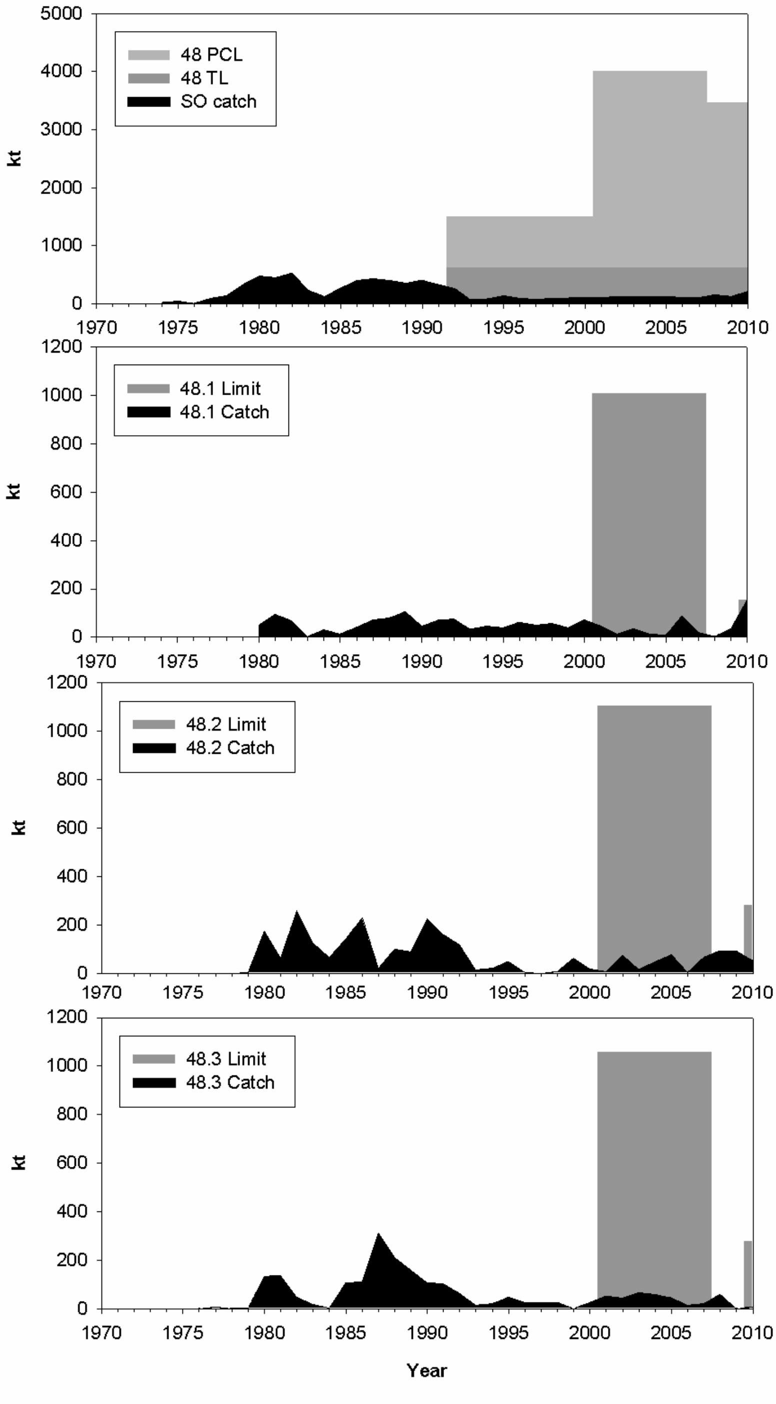

Fig 5: Antarctic krill catches and catch limits. SO catch = catch for the entire Southern Ocean; 48 PCL = precautionary catch limit for subareas 48.1 to 48.4; 48 TL = trigger level (actual catch limit) for subareas 48.1 to 48.4. The lower three panels show subarea-specific catches and catch limits. The total reported catch to 2010 for subarea 48.4 is 61t (not shown).

Data indicating the state of the harvested resource, the fishery, and the wider ecosystem are an essential part of fisheries management. CCAMLR collects catch data[76], and has a programme of work to address the uncertainties in mortality estimates[88,91]. Various national programmes monitor a suite of ecosystem components and make the data available to CCAMLR[33,34]. These data include local estimates of krill density (e.g. at the scale of 80 by 100 km [92]) and the condition of predator populations[33,34]. Scientific observers are a further important source of data on such things as the biological characteristics of the catch, bycatch and incidental mortality, gear configuration and operational characteristics, and sightings of illegal vessels[93]. There is an argument for using observers who are independent of both the company that owns the fishing vessel and the nation to which it is registered. Observer data are particularly important when uncertainty is a major issue and where there is no systematic fishery-independent method of assessing the status of the stock. Vessels in the Antarctic krill fishery were not obliged to carry observers until the 2009/10 fishing season. CCAMLR currently requires that at least 50% of vessels carry observers and that these observers sample at least 20% of the hauls set by the vessel. CCAMLR intends to arrange to analyse the data collected in the first few years of this observer programme so that it can then "adopt a well-designed program for systematic observer coverage in the Antarctic krill fishery" [81].

CCAMLR's scientific working groups are assessing how best to use catch, observer, and ecological monitoring data to support CCAMLR's objectives[91]. However the current state of data and its use in fishery management highlights some important issues. Firstly, the data and scientific expertise required to support the management of the Antarctic krill fishery is rarely directly funded by CCAMLR or the fishing industry. Rather it is provided by members through national science programmes. There is an inevitable tension between the objectives of these programmes and those of CCAMLR, and the ability of members to provide this input has noticeably diminished during recent years. This system sometimes provides focused data collection to address a CCAMLR-specific issue, such as the estimate of Antarctic krill biomass in 2000. It is notable that this system has not provided a more recent assessment of the stock size. CCAMLR has little capacity to collect new types of data[35]. The reliance on donated science constrains CCAMLR's management approach. Understanding of the state of the ecosystem and how it responds to fishing pressure is likely to remain highly uncertain, and it will continue to be necessary to limit catches to precautionary levels. Secondly, CCAMLR requires consensus to implement new management and data collection measures, which can mean that change is often slow in practice[34], as illustrated by the welcome but very slow progress in developing an observer programme.

In summary, current Antarctic krill catches are lower than the historical maximum due to reduced demand since the late Soviet era. CCAMLR's current management measures are appropriate for the current level of demand and state of knowledge. The current catch limit (the trigger level) is equivalent to reducing the Antarctic krill stock by about 2% and, as such, is highly precautionary and will maintain the fishery's status as under-exploited. Nonetheless, this catch limit is an interim measure pending a decision on the spatial management of the fishery. New measures are needed to deal with any potential increase in demand, updated understanding of Antarctic krill population changes, and the questionable validity of the current precautionary catch limit. CCAMLR is vulnerable to the vagaries of national science funding and it can be slow to make progress even when provided with high quality scientific advice.

SUSTAINABILITY

The concept of sustainability is not mentioned in the CCAMLR Convention which, nonetheless, specifies objectives that correspond with the recognised goals of sustainable fisheries management. The impetus for developing these goals came from recognition that over-exploitation can reduce the productivity of fish stocks. Initially there was a tendency to consider fish stocks in isolation from the rest of the ecosystem[18]. A stock's perceived value lay in its ability to provide catch and the objective of management was to maximise both the catch and the catch per unit fishing effort in the long term[18]. This involves sacrificing some potential catch in the present to ensure that there is catch in future. All species eventually go extinct, so "the long term" is distinct from "perpetuity".

Increasing awareness of the risks associated with catch maximisation caused a shift in focus towards preventing long-term damage to the stock's productivity[15,18,94]. Over recent decades fisheries management has become increasingly informed by recognition that fish stocks exist within complex ecosystems[6,11,15,18,35,90,94]. Fishing can damage parts of the ecosystem other than the target stock, and the productivity of the target stock depends on the health of the ecosystem. The objectives of sustainable management have therefore expanded to include preventing long-term damage to the wider ecosystem[10,11,12,15,35,94].

Unfortunately many of the world's marine fisheries have damaged both the productivity of their target stocks and the wider ecosystem[15]. Other human activities (such as pollution) can also damage marine ecosystems and therefore the productivity of fish stocks. Also the effects of these other activities can amplify the impacts of fishing[95,96], meaning that fisheries management has to consider these other effects. Climate change is a salient example of an anthropogenic effect that can damage marine ecosystems[96]. Some predictions suggest that climate change could cause serious population declines in many species in the foreseeable future[97]. This suggests that the objectives of fisheries management might need to be revised again to account for severe effects that are beyond the control of fisheries managers.

It is apparent that the meaning of sustainable is not fixed nor universally agreed. The WCED definition[4] fits well with the objectives of fisheries management described above. However it does not provide any guidance on the specifics such as the acceptable levels of risk associated with a particular activity. The word "sustainable" is also part of the general vocabulary and is sometimes used to mean things that do not refer to the future. For example, in a recent article on a British newspaper's website, the word refers to the humane treatment of farm animals and seems to be used as a synonym for "ethical" [98].

In July 2010 the US grocery chain Whole Foods cited "sustainability issues" as its reason for withdrawing Antarctic krill oil products from sale[99]. Articles appeared on the internet[100] and even in the academic literature[101] claiming that the Antarctic krill fishery is not sustainable. These pronouncements followed in the wake of the eco-labelling organisation the Marine Stewardship Council's (MSC) certification of Norwegian fishing company Aker Biomarine's Antarctic krill fishing operations. According to the MSC, this certification shows that the fishery is "well managed and sustainable"[102].

The fact that different participants in this controversy were able to simultaneously claim that the Antarctic krill fishery both is and is not sustainable illustrates the linguistic uncertainty in the word "sustainable". The MSC defines fishing activities as "sustainable for the fish population" if they "operate so that fishing can continue indefinitely and [are] not overexploiting the resources"[102]. Jacquet et al.[101], on the other hand, state that "much of the Antarctic krill caught is destined not for consumer purchase but for fishmeal, to feed factory-farmed fish, pigs and chickens. We propose that any fishery undertaken for fishmeal should not be viewed as responsible or sustainable". The other sources cited above do not offer any indication of what they mean by "sustainable". This is particularly problematic in the case of Whole Foods whose statement reads "Until it evaluates the sustainability of its supply, the chain will refuse to sell this omega-3 supplement"[99]. Such an evaluation will certainly benefit from a clear set of criteria by which to assess sustainability.

Jacquet et al.'s[101] novel, product-focused interpretation of "sustainable" says nothing about the Antarctic krill stock's ability to replenish itself, how much is caught, where it is caught, or how the fishery impacts the stock or the Southern Ocean ecosystem. It labels as unsustainable any fishery that produces fishmeal but it does not provide any guidance on how to make a fishery sustainable.

Another group claims that the management of the Antarctic krill fishery "cannot be considered precautionary" [103] (but see [104]). This group also neglected to explain the standards they used to test whether management is or is not precautionary or to identify management measures that would pass such tests.

The Antarctic krill fishery is one of only 3% of global fisheries that are under-exploited[14,20,21]. It is one of the few fisheries that have a management approach committed to limiting impacts on the both the target stock and the wider ecosystem. Judging by Smith et al.[90], the risk of ecological impact associated with the catch limit (trigger level) is minimal. The FAO describes the CCAMLR management regime as "strict and effective"[14] and the Antarctic and Southern Ocean Coalition (ASOC) of conservation groups describe current management measures as "precautionary" [104]. The main conservation groups behind claims that the krill fishery is not sustainable or precautionary are also members of ASOC[105], which suggests a lack of consensus within that community.

One of the world's few under-exploited fisheries has been singled out as exemplifying an unsustainable fishery, and this has created a perception that the Antarctic krill fishery has a particular problem with "sustainability issues". This perception continues to be fed, for example, by a "research report" claiming that "climatic warming, a targeted Antarctic krill fishery and recovering whale and fur seal populations have depressed Antarctic krill abundance by almost 80 percent in the Southern Ocean" [106], despite an absence of evidence to support the claim made against the fishery. This perception affects markets for Antarctic krill products as demonstrated by Whole Foods' policy on these products.

There are some important lessons from this controversy. The first is that reference to the concept of sustainability is a powerful tool for influencing opinion. Sustainability is widely considered to be a good thing. The word "sustainable" itself seems to carry authority. A pronouncement that something is or is not sustainable implies technical understanding and evidence. However, because there is no requirement to conform to a particular definition or to provide evidence to a particular standard, "sustainable" can mean almost anything the user wants it to. As such, the word "sustainable" is as ambiguous and prone to misuse as the word "green".

The second lesson is that arguments against the Antarctic krill fishery reflect valid human concerns. The main concern seems to be with the welfare of penguins and other "flagship" species that "garner public support and affection"[107]. The Antarctic krill fishery has a tangible link with these species, while the over-exploited fisheries of the world mainly impact "cold bloodied" species that are hidden from view beneath the surface of the ocean and appear to be less useful for garnering public support. The second concern is with modern food production methods. Jacquet et al's[101] view of the Antarctic krill fishery is informed primarily by their opposition to factory farming. There is also widespread concern about the prevalence of processed foods. This is associated with the opinion that diet supplements, such as omega-3 products, represent an after-the-fact remedy to problems associated with an "unnatural" diet. Finally, fishing for Antarctic krill is seen as the culmination of the process of "fishing down marine foodwebs"[108] whereby the human race sequentially exhausts stocks of larger predatory fish until there is nothing to left exploit but the small species that feed directly on phytoplankton.

Both of these lessons are relevant to the objective of providing a sustainable increase in the availability of LC-ω-3. This objective, as stated, does not provide any criteria by which to assess sustainability. Without such criteria it will not be possible to demonstrate sustainability and it will be difficult to robustly answer critics with their own (not necessarily stated) criteria. Clear criteria will also provide a solid focus for dialogue about other stakeholders' objectives and criteria. Also, attitudes about what is sustainable incorporate a wide range of considerations, many of which the WCED did not discuss. It will be necessary to decide which of these considerations to address when devising sustainability criteria. In my opinion, such criteria should be devised in collaboration with the wider group of stakeholders. The apparent commitment to sustainability by both opponents and proponents of the Antarctic krill fishery implies that such collaboration is possible.

In summary, there is no consensus about the meaning of the word "sustainable", but it is widely used as a tool to influence public opinion, sometimes without substance. There is little tangible evidence to support the view that the Antarctic krill fishery is not sustainable by any definition other than that of Jacquet et al.[101], which appears to have been formulated for the specific purpose of criticising this fishery. The fishery is well managed compared to Smith et al's[90] reference point and it is under-exploited according to the FAO. It is also amongst the minority of current fisheries that have a management approach committed to limiting impacts on both the target stock and the wider ecosystem. The controversy over Antarctic krill suggests that a diverse group of stakeholders are committed to sustainability. This could imply a willingness to cooperate in ensuring that any increase in the availability of LC-ω-3 is sustainable and environmentally responsible.

NEXT STEPS

The GSNHHB did not identify a mechanism for achieving a sustainable, environmentally responsible increase in the availability of LC-ω-3. The elements of such a mechanism should include:

(1) Sources of LC-ω-3;

(2) A set of criteria with which to evaluate sustainability and environmental responsibility;

(3) Governance systems to ensure that management of the sources is compatible with the sustainability criteria; and

(4) A further governance system to ensure that the supply chain uses only sources that conform to these sustainability criteria.

Sources

Marine fisheries are currently the main source of EPA and DHA consumed by humans. Aquaculture is often presented as an alternative to capture fisheries, but in reality the total catch required to support fish farming in the developed world exceeds the production of these fish farms[15]. An alternative aquaculture model producing low value herbivorous species might help to improve the availability of fish to the "least endowed people, particularly in the rural areas"[109].

Current global annual fish landings contain about 325kt of EPA and DPA (see Table 1 for assumptions). This is equivalent to 1g d^{-1} for 890 million people (about 13% of the world population[110]). The precautionary catch limit for Antarctic krill in subareas 48.1 to 48.4 contains sufficient EPA and DHA for 1% of the world population (about the population of the UK), while the trigger level is sufficient for 0.1%. Extrapolation of the precautionary catch limit to the entire Southern Ocean suggests that Antarctic krill could provide sufficient EPA and DHA for 3.5% of the world's population. The catch limit for subareas 48.1 to 48.4 could increase beyond the trigger level if certain conditions are met. The prospects for developing a substantial Antarctic krill fishery elsewhere, along with the knowledge and infrastructure needed for appropriate management, are limited at present.

Table 1: Crude calculation of the total EPA + DHA content in global marine fisheries landings.

Category	Species	EPA + DHA (% in serving)	Type of conversion factor	Conversion factor	EPA + DHA (%)	Category average EPA + DHA (%)	2009 landings (kt)	EPA + DHA (t)
Diadromous fish	Salmon	1.25	FFB	2.40	0.52	0.52	1,547	8,085
Marine fish	Tuna	0.89	FF	1.67	0.54			
	Sardines	1.58	FGH	1.18	1.34			
	Mackerel	1.12	FFB	2.60	0.43			
	Herring	2.07	FFB	2.67	0.78			
	Halibut	0.82	FFB	2.57	0.32			
	Cod	0.22	FFB	2.85	0.08			
	Haddock	0.24	FFB	2.92	0.08			
	Flounder	0.49	FFB	2.70	0.18	0.47	65,164	304,583
Freshwater fish						0.49	19	96
Crustaceans	Antarctic krill	0.45	W	1.00	0.45			
	Lobster	0.28	FHP	3.50	0.08			
	King crab	0.41	FMO	5.81	0.07			
	Shrimp	0.32	FGP	2.35	0.14	0.18	5,321	9,759
Molluscs	Oyster	0.79	FS	9.00	0.09			
	Clam	0.28	FS	9.00	0.03			
	Scallop	0.20	FS	9.00	0.02	0.05	6,187	2,910
Total							78,239	325,433

% in serving from [113], except Antarctic krill from [75]; Conversion factors (live mass to serving mass) averaged sfrom [114]; Category average EPA + DHA is a simple average of listed species, except freshwater fish which is the average of marine and diadromous fish; landings from [115]. Abbreviations: FF=Fresh, fillets; FGH = Fresh, gutted, head off; FFB= Fresh, fillets, boneless, skin off; W=Whole; FHP= Frozen, head off, peeled; FMO= Frozen, meat only; FGP= Fresh, gutted, peeled; FS = fresh, shucked.

Garcia & Grainger[109] discuss possible future trends in marine capture fisheries. Although they consider both optimistic and pessimistic scenarios, they do not suggest that it is possible to increase landings beyond current levels. Indeed their “best case scenario” involves a decrease in catches as society reduces pressure on natural resources. According to the FAO, 15% of global fisheries are under-exploited or moderately exploited[14]. These fisheries could support limited increases in production but, unless effective management is established before any substantial increase in catch, they could rapidly become over-exploited.

The objective of increasing the availability of LC-ω-3 in a sustainable and environmentally responsible way implies an initial focus on ensuring that current sources meet the relevant sustainability criteria followed by a concerted effort to identify new (non-fishery) sources that also meet these criteria.

Sustainability criteria

The ecosystem approach recognises the interdependence of mankind, individual living resources, and the ecosystems in which they exist. This implies that sustainability criteria must account for both the wider impacts of human activities and the diversity of human needs. These principles are logical and widely supported[12,13] including by some of the organisations that oppose the Antarctic krill fishery[111,112]. It is not possible to simultaneously maximise all of the benefits that mankind obtains from ecosystems. It is therefore necessary for stakeholders to identify their objectives and work together to establish acceptable trade-offs between these objectives.

Fisheries management is a complicated process involving a wide range of individuals and organisations. The ecosystem approach is potentially even more complicated because it involves the coordination of multiple management bodies responsible for different activities or objectives. The management of the Antarctic krill fishery is relatively straight forward because there are few other human activities in the Southern Ocean. Nonetheless this ecosystem has a wide range of attributes that benefit mankind in different ways. These include the benefits to human health derived from the LC-ω-3 in Antarctic krill; the benefit of other Antarctic krill products including foodstuffs; the economic benefits to those involved in the Antarctic krill fishery and distribution chain; the biodiversity value of the unique wildlife that feed on Antarctic krill; the economic benefit of wildlife tourism; the quality of life of those who appreciate this wildlife *in situ* or via films and other media; and the benefits of a functioning ecosystem that contributes to global chemical cycles and climate regulation.

Cooperation to establish trade-offs offers better prospects for achieving both conservation and a well managed supply of fishery products than entrenched positions on either side. Opposition to all fishing in the Southern Ocean is unlikely to be successful. This is partly because CCAMLR's commitment to "rational use" clearly allows regulated fishing and partly because without regulated fishing it is difficult or impossible to control unregulated fishing, especially in remote areas. Conversely, opposition to controls on fishing will be counterproductive for numerous reasons including the incontestable fact that unregulated fishing results in over-exploitation. In the case of Antarctic krill, catches cannot increase beyond the trigger level without agreement on new controls. Furthermore, the public have become increasingly aware of the need for appropriate management and transparency. Failure to deliver this can therefore lead to exclusion from lucrative markets.

Any trade-offs between objectives for Antarctic krill must be made within the framework CCAMLR's conservation principles. These principles do not define operational objectives, including the acceptable limits of fisheries impacts on the Antarctic krill stock or the level of protection that should be provided for predators. CCAMLR has devised operational objectives concerning acceptable impacts on the Antarctic krill stock, but it has not reached agreement on the level of protection for predators beyond the interim use of the trigger level and subarea catch limits. The operational catch limit cannot therefore increase beyond the trigger level until there has been progress on the issue of predator protection.

Resolving the predator protection issue to the satisfaction of all stakeholders requires a process for establishing trade-offs, which is likely to include:

(1) Clear statements of each stakeholder's objectives. Ideally these will include some metric by which achievement of the objective can be measured. They could also include "limit reference points"[94] defining a level that this metric should be maintained above. Example objectives could include "maintain catch limits above the equivalent of X tonnes of LC-ω-3 per year" or "maintain penguin populations above Y% of expected biomass in the absence of fishing".

(2) A method for evaluating the potential to achieve each of these objectives given potential strategies for managing human activities[6]. In the case of fisheries, these strategies could include annual catch limits, gear restrictions, spatial and temporal restrictions, and adjustment of catch limits and restrictions based on information about the state of the ecosystem. Ideally this method would provide an evaluation of the probability of failing to meet each objective (i.e. a risk assessment) and would be subject to agreed standards of evidence.

(3) A decision about a mutually acceptable management strategy, or acceptable levels of risk, on the basis of information provided by step 2.

This process could be iterative as the detail of the objectives, the range of management strategies to consider and the perception of acceptable levels of risk might be revised in response to step 2. Ideally the management strategy should include monitoring to assess the state of the metrics used to describe objectives, and an agreed remedial response in the event that a limit reference point is breached. It should also be precautionary, meaning that it should prioritise maintaining the ecosystem in a healthy state defined by the relevant limit reference points.

The process requires clarity about objectives, standards for assessing the achievement of objectives, and standards of evidence. At present, the public receives a confusing array of information and opinions with very different standards of evidence (Fig. 3). In my opinion, clarity is preferable to unsubstantiated claims about what is and is not sustainable. Such clarity should help the public to better understand the issues and develop informed opinions. The community of stakeholders interested in medical products derived from living resources includes those with expertise in regulatory issues. Regulation of medical products involves standards of evidence and an application of the precautionary approach (medicines are not granted licences until they are demonstrated to be both safe and effective). Cooperation between these stakeholders and experts in ecosystem uncertainty might help to develop analogous standards within living resource management.

It is not possible to suggest detailed sustainability criteria until stakeholders have identified their objectives, but some of the elements already exist. Objectives for over-exploited fisheries should include recovery. Sustainability criteria should take into account existing criteria governing sources of LC-ω-3, such as CCAMLR's conservation principles. These principles include preventing changes to the ecosystem that are not reversible over decadal timescales. This is analogous to one of the main goals of the ecosystem approach, which is to preserve ecosystem resilience[12].

Governance

Governance does not necessarily imply legal powers. Nonstate, market driven governance systems[19], including the MSC, are becoming increasingly important. The important attributes of governance systems include clear standards, transparency about the reasons for decisions, and effective assessment and monitoring processes.

Many current or potential sources of LC-ω-3 have existing governance systems. To achieve a sustainable, environmentally responsible increase in the availability of LC-ω-3 it will be necessary to support effective governance and encourage change in ineffective systems. This means entering into dialogue or partnership with the relevant governance organisations including CCAMLR. More effort is needed to develop CCAMLR's conservation principles into a set of operational objectives that can be used to manage catches above the trigger level. Stakeholders with an interest in increased catch limits should work with other stakeholders to identify objectives, and with scientists to develop the risk assessments and candidate management strategies identified in step 2 of the process described above. It is also important to engage with the fishing industry and with those decision makers who have previously had difficulty agreeing to evidence-based proposals to modify regulation or monitoring of Southern Ocean fisheries. These parties are likely to benefit from increasing demand for Antarctic krill products. However, increasing the catch beyond the trigger level is only feasible with additional regulation and monitoring. Furthermore, a reluctance to act affects the public perception of the governance system and the "sustainability" of the source.

In the majority of fisheries, the focus will be on the recovery of the stock or more efficient use of existing catches rather than an increase in catch limits. Approximately 15% of the global fisheries catch is discarded (i.e. dumped back in the sea)[15]. This is either because the catch is not sufficiently valuable to be worth landing (sometimes because it might take up storage space or quota that could be used for more valuable catch), or because it is not legal to land. Arguably using this part of the catch for a tangible human benefit, such as LC-ω-3, is preferable to discarding.

The development of a governance system to ensure that the entire LC-ω-3 supply chain uses only "sustainable" sources is a major challenge raised by GSNHHB's commitment to a sustainable increase in availability, although it is beyond the scope of this chapter to consider further. When developed, such a governance system could be a powerful means of ensuring effective governance and management of the individual sources of LC-ω-3.

Generalities

The principles are broadly similar for most potential sources of LC-ω-3. Critical questions concern how much of a resource can be taken, where, and how. It will not be possible to maximise all of the different benefits from the resources used in LC-ω-3 production. Consider a plant crop that produces the appropriate types of LC-ω-3. This will require agricultural land, fertilisers, pesticides, industrial plants, and energy. Each of these could be put to alternative uses. The agricultural land and fertilisers could, for example, be used to produce higher yielding calorie-rich crops which address a more fundamental need for people in the developing world. A decision to prioritise the production of LC-ω-3 could simply increase the demand for agricultural land resulting in an increase in environmental damage. Therefore an approach that identifies objectives and evaluates risk is essential to establish the trade-offs between these different types of land use.

The previous paragraph raises two critical issues in the subject of sustainability. The first is energy use. The production and distribution of LC-ω-3 is bound to consume energy. There is near consensus that the use of fossil fuels is both environmentally damaging and constrained by a non-replenishing supply. Climate change is one of the main threats to ecosystem resilience and it requires effective global governance across many sectors to resolve. Secondly, human population growth puts increasing pressure on natural resources. The fact that the fisheries production of the entire world can supply only about 13% of the human population with the recommended dose of LC-ω-3 illustrates the finite nature of natural resources. Garcia & Grainger[109] predict that "global *per capita* consumption from marine resources will decrease, simply because [the] human population [will continue to grow]". These facts provide important context for the challenge of establishing sustainability criteria.

CONCLUSION

The GSNHHB's stated commitment to sustainability and environmental responsibility is a positive first step, which must be followed by the many practical steps that are necessary to achieve this objective. These steps include establishing criteria by which sustainability and environmental responsibility can be evaluated; supporting effective governance of LC-ω-3 sources; encouraging the remediation of over-exploited fisheries and efficient use of fisheries by-products; and ultimately developing an overall governance system to ensure that the supply chain uses only sources that conform to agreed sustainability criteria. Most of these steps involve engagement and cooperation with other stakeholders, including those who oppose the methods used to produce LC-ω-3. One of the potential benefits of successful engagement is the widespread application of the ecosystem approach to fisheries.

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