Antarctic Science 16 (4): 569–584 (2004) © Antarctic Science Ltd Printed in the UK DOI: 10.1017/S0954102004002330

Management of Southern Ocean fisheries: global forces and future sustainability

J.P. CROXALL[1] and S. NICOL[2]

[1]*British Antarctic Survey, NERC, High Cross, Madingley Road, Cambridge CB3 0ET, UK*
[2]*Antarctic Marine Living Resources Program, Australian Antarctic Division, Channel Highway, Kingston, TAS 7050, Australia and Antarctic Climate and Ecosystems Co-operative Research Centre, Private Bag 80, Hobart, TAS 7001, Australia*
j.croxall@abs.ac.uk

Abstract: The marine resources of the Antarctic region are of global significance. In managing Southern Ocean marine resources, especially fisheries, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has adopted principles that aim: to balance harvesting and conservation; to protect the needs of dependent species, and to avoid changes that are irreversible in 20–30 years. CCAMLR has pioneered ecosystem approaches to fishery and environmental management, through the incorporation of precaution and uncertainty into its management procedures and by establishing an ecosystem monitoring programme using indicator species and processes. This pioneering application of precautionary and ecosystem approaches in the management of harvesting has met with some success, notably in applying conservative yield models for toothfish and krill stocks and in establishing strict rules for undertaking new and exploratory fisheries. However, toothfish management has been recently compromised by Illegal, Unreported and Unregulated (IUU) fishing which is driven by forces outside the Southern Ocean. Southern Ocean harvestable resources are also subject to other global forces such as environmental changes, and their management systems remain very vulnerable to rapid shifts in worldwide fishery economics, and to inadequate management in adjacent areas, particularly high seas. CCAMLR needs quickly to develop the basis of more flexible and effective management to cater for rapid shifts in capacity and demand. The complementary task, however, is to raise the management standard of other Regional Fisheries Management Organisations (RFMOs) to those of CCAMLR if global high seas marine resources are to be sustainable for the rest of this century.

Received 5 March 2004, accepted 17 May 2004

Key words: Antarctic fisheries, bycatch management, CCAMLR, ecosystem management, fishery economics, incidental mortality, krill, toothfish

Introduction

The history of the exploitation, management and protection of Antarctic marine resources differs rather little (except in timing) from that of marine systems elsewhere. The successional stages of prospecting, exploitation (somewhat restricted until new technologies were developed and new markets identified), over-exploitation, reactive management and proactive (precautionary) management are well evidenced by the history of harvesting of fur seals, penguins, whales, fin fish and krill in the Southern Ocean. By the late 1970s, just two centuries after the discovery of the resources of the region, the trophic cascade of exploitation (Fig. 1) had led to the near extinction of populations of Antarctic fur seals (*Arctocephalus gazella* (Peters)), several species of great whale and marbled rock cod (*Notothenia rossii* Richardson). The next targets were icefish (*Champsocephalus gunnari* L.), already over-exploited by 1980, and Antarctic krill (*Euphausia superba* Dana), which was a rapidly developing fishery at this time, and alone remains a major global resource.

In 1977 the contracting parties to the Antarctic Treaty, who had enjoyed considerable success in depoliticising governance and promoting scientific collaboration in respect of the Antarctic Continent, started to negotiate an international convention, primarily to prevent over-exploitation of Antarctic krill, widely perceived as the keystone species of Southern Ocean food webs. The resulting Convention for the Conservation of Antarctic

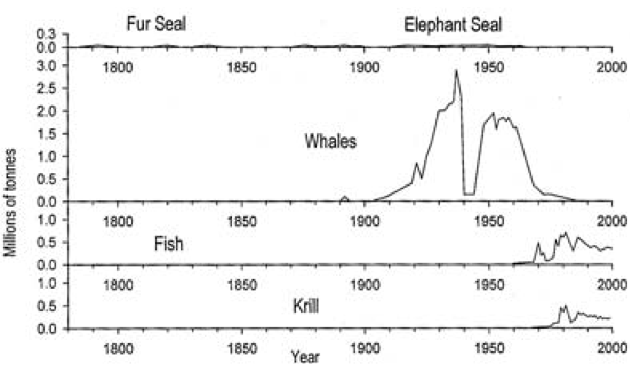


Fig. 1. Historical human harvesting in the CCAMLR Convention Area.

Table I. Article II of the Convention for the Conservation of Antarctic Marine Living Resources.

1. The objective of this Convention is the conservation of Antarctic marine living resources.

2. For the purposes of this Convention, the term "conservation" includes rational use.

3. Any harvesting and associated activities in the area to which this Convention applies shall be conducted in accordance with the provisions of this Convention and with the following principles of conservation:
  a) prevention of decrease in the size of any harvested population to levels below those which ensure its stable recruitment. For this purpose its size should not be allowed to fall below a level close to that which ensures the greatest net annual increment;
  b) maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources and the restoration of depleted populations to the levels defined in sub-paragraph (a) above; and
  c) prevention of changes or minimisation of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades, taking into account the state of available knowledge of the direct and indirect impact of harvesting, the effect of introduction of alien species, the effects of associated activities on the marine ecosystem and the effects of environmental changes, with the aim of making possible the sustained conservation of Antarctic marine resources.

Marine Living Resources, signed in 1980 and in force since 1982, applies to the whole Southern Ocean south of the Antarctic Polar Front, an area of 32 million km^2. Marine living resources includes all species in the Convention Area other than whales and seals for which there were existing Conventions. The Convention was the first in the marine environment to try to combine the requirements of sustainable harvesting with adequate protection for non-target species potentially affected by harvesting; indeed in three of its fundamental principles it was foreshadowing, by at least a decade, the widespread adoption of the precautionary principle and the need for ecosystem-based approaches to management of marine systems.

Thus, Article II of the CCAMLR Convention (see Table I) contains the requirements:

a. to balance the needs of sustainable harvesting with those of conservation;

b. to provide protection for dependent and related species, coupled with the restoration of depleted stocks and populations;

c. to avoid changes that are potentially irreversible within 2–3 decades.

However, the application of these principles proceeded slowly. In its early years CCAMLR focused mainly on procedural and organisational matters and on reactive management to try to control over-exploitation of fin fish stocks. Nevertheless some ground work for developing the approaches of precautionary management was established, as were monitoring programmes designed to provide baselines for assessing changes in krill-dependent species.

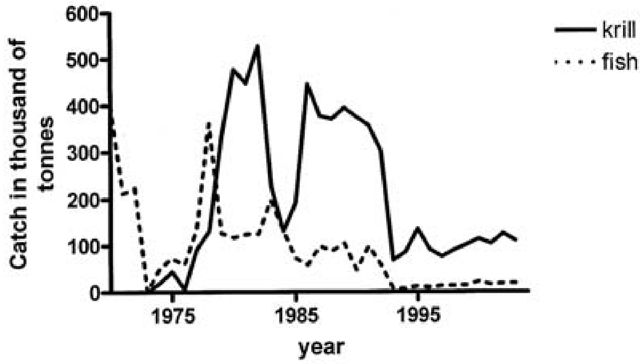


Fig. 2. The catch history of fish and krill in the CCAMLR Convention area. Data from CCAMLR Statistical Bulletins.

It should be recollected, however, that all CCAMLR's decisions (including those for fisheries management) must involve consensus between all 24 member states. Controversial measures can, therefore, take some time to be adopted, even in compromise form.

The early years of CCAMLR's establishment and operation, leading to the use and development of modelling techniques to facilitate precautionary approaches, have been described in some detail elsewhere (e.g. Kock 2000, Constable *et al.* 2000, Constable 2002). In this paper we:

a. briefly review the evolution of innovative management approaches for two currently harvested species: krill and toothfish, which exemplify very different types of problems and solutions,

b. assess the successes of, and main difficulties with, the approaches developed,

c. outline the global forces that affect Southern Ocean fisheries and their management,

d. identify lessons that may be of relevance to the widespread current attempts to develop ecosystem approaches to fisheries management elsewhere.

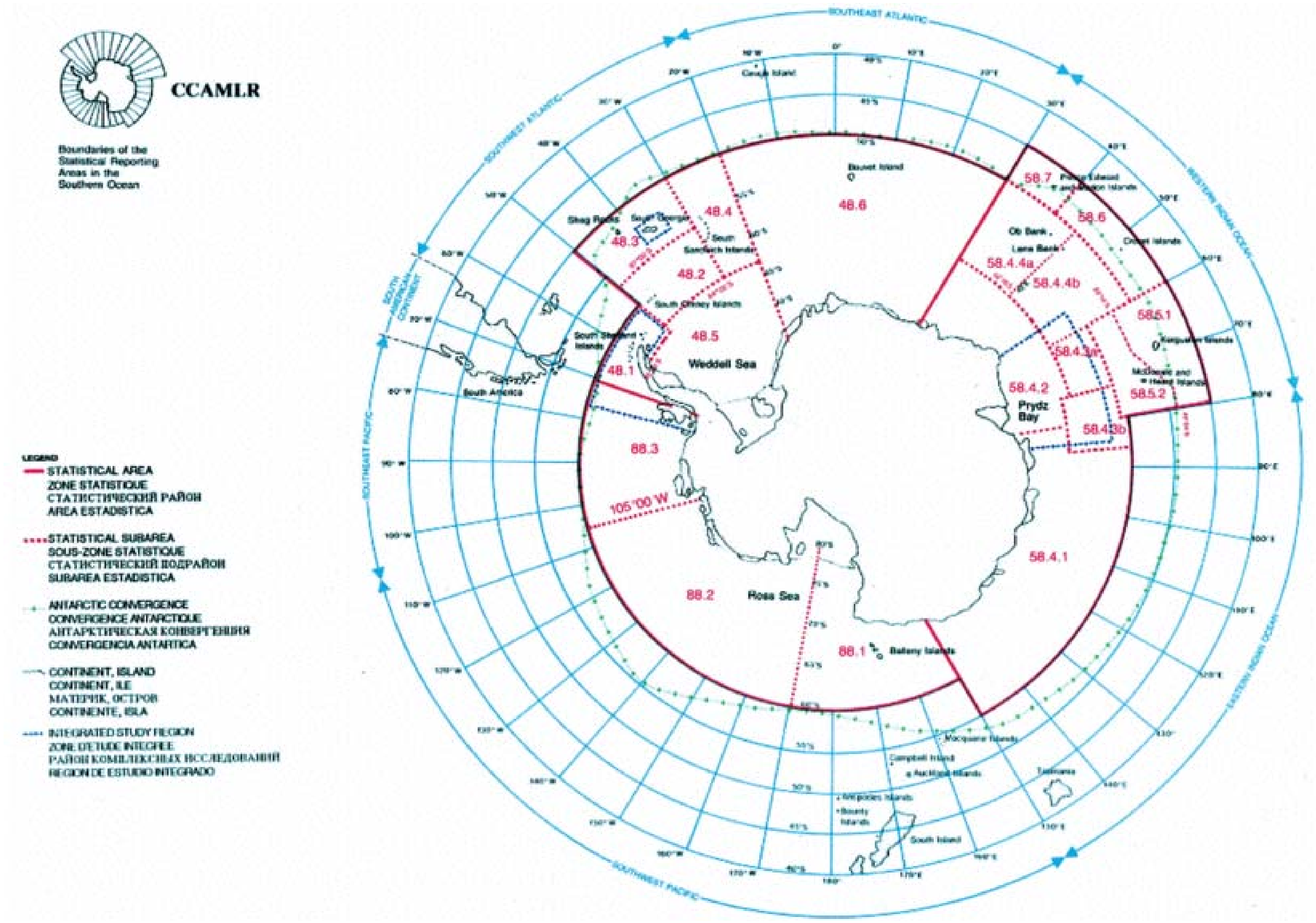
Krill fishery

The krill fishery has been the largest fishery in the CCAMLR Area since the late 1970s (Fig. 2). CCAMLR's approach to management of the krill fishery developed slowly through the 1980s (Miller & Agnew 2000, Hewitt & Low 2000, Ichii 2000). An initial focus was on the examination of potential measures of relative abundance of the krill resource. The standard fisheries measure, catch per unit effort (CPUE), was examined in depth in two commissioned studies for CCAMLR and it was concluded that the utility of this measure was limited for determining relative abundance, or changes in abundance, for the krill resource (CCAMLR 1989). The attention of the Scientific Committee then turned to other methods for determining appropriate harvesting levels for krill and this became a

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

major focus for the newly formed Working Group on Krill. The preferred approach to managing the krill fishery was the use of a simulation model modified from an approach developed by Beddington & Cooke (1983) – the Krill Yield Model (KYM: Butterworth *et al.* 1991). This approach required that an estimate of the initial, unexploited, biomass of the krill stock in the area be used. Fortunately, the results from the international research program which was co-ordinated in the early 1980s to investigate krill stocks in the Antarctic – Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) (El Sayed 1994) - were being analysed and these would prove to be the source of information used to set the first catch limits on the krill fishery in 1991 and 1992 (Nicol & Endo 1997).

The KYM has been developed into the Generalised Yield Model (GYM) which has been refined with time and which is also used to set precautionary catch limits for most fisheries in the Convention Area (Constable & de la Mare 1996). Precautionary limits are calculated from an estimate of the total biomass of the krill stock in an area obtained from an acoustic survey, an estimate of the rate of natural mortality (including natural predation), a model of how individual krill grow in weight during their lives, and an estimate of the inter-annual variability in recruitment



CCAMLR Statistical area	Biomass estimate	Precautionary catch limit	Year Conservation Measure adopted
Area 48 (South Atlantic)	44.3 million tonnes	Overall 4.0 million tonnes subdivided into: 0.832 million tonnes (48.4) 1.104 million tonnes (48.3) 1.056 million tonnes (48.2) 1.08 million tonnes (48.1)	2000
Division 58.4.1 (south-east Indian Ocean)	4.83 million tonnes	Overall limit 440,000 tonnes subdivided into: 0.277 million tonnes west of 115°E and 0.163 million tonnes east of 115°E.	2000
Division 58.4.2 (south-west Indian Ocean)	3.9 million tonnes	450 000 tonnes	1992

Fig. 3. Precautionary Catch Limits on the krill fishery. The CCAMLR Area with statistical divisions indicated and details of existing catch limits.

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

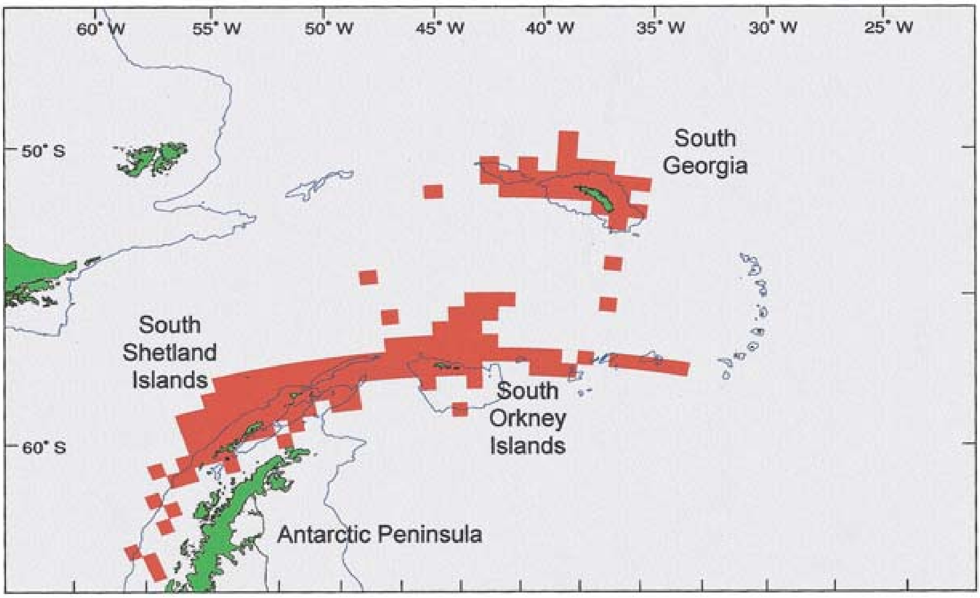


Fig. 4. Distribution of krill fishing areas in the Atlantic sector (Subarea 48) of the CCAMLR Area. Updated from Everson & Goss (1991) using CCAMLR data.

(Constable *et al.* 1996). This information is used to make a computer population model of a krill stock which is used to calculate a distribution of population sizes both in the absence of fishing and at various levels of fishing mortality. These distributions are used to determine an estimate of the proportion of the unexploited biomass that can be caught each year (γ). CCAMLR has also developed a three-part decision rule for determining this proportion which matches the aims of Article II:

1. choose γ_1 so that the probability of the spawning biomass dropping below 20% of its pre-exploitation median level over a 20-year harvesting period is 10%; and
2. choose γ_2 so that the median krill escapement in the spawning biomass over a 20 year period is 75% of the pre-exploitation median level.
3. select the lower of γ_1 and γ_2 as the level of γ for the calculation of the krill yield.

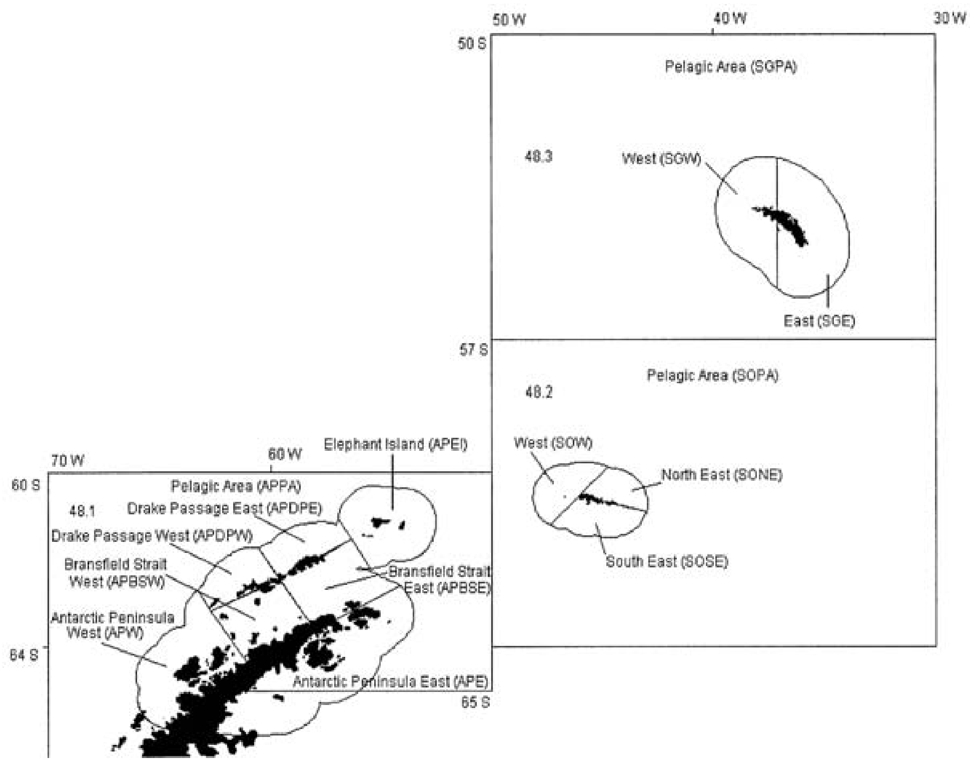


Fig. 5. The Small Scale Management Units within Statistical Subareas in the South Atlantic part of the CCAMLR Area. Subarea 48.3 centres on South Georgia (SG), Subarea 48.2 on the South Orkney (SO) Islands. Subarea 48.1 comprises the South Shetland Islands and adjacent parts of the Antarctic Peninsula (AP).

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

The requirements of predators of krill are taken into account through the process of the decision rules. In decision rule number 2 the level of 75% of the pre-exploitation biomass was chosen as an intermediate value between the case of single-species management where 50% escapement would be acceptable and the case where no fishing was permitted - 100% escapement. This value is subject to refinement as more information becomes available. Additionally, the incorporation of natural krill mortality into the model's formulation ensures that the needs of all predators are taken into account because they are assumed to be the prime cause of mortality in the krill population. This formulation, although a long way from the eventual implementation of an "ecosystem approach" to managing the krill fishery, is still novel in its incorporation of the spirit of Article II of the Convention into management decision rules. The development of a feedback management procedure for krill, which will incorporate a fully elaborated ecosystem approach, will occur over the next five years (Constable 2002).

The initial catch limits on krill (totalling 1.5 million tonnes per year) were established for the South Atlantic (subareas 48.1, 48.2, 48.3) in 1991. This was followed by the establishment of a catch limit (650 000 tonnes per year) on the krill fishery in the south-west Indian Ocean (Division 58.4.2) (Nicol & Endo 1997). Other parts of the CCAMLR Area had been fished, and continued to be fished in the 1990s, but these areas had not been surveyed for krill as part of BIOMASS so catch limits could not be set. In 1996 the first acoustic survey of a CCAMLR Division specifically designed for establishing a precautionary catch limit was conducted in Division 58.4.1 (the south-east Indian Ocean) (Nicol *et al.* 2000a). A catch limit (775 000 tonnes per year) was established in 1996 on the basis of this survey data, this was subsequently revised in 2000 and subdivided into two catch limits (277 000 tonnes per year in the west and 163 000 tonnes per year in the east), based on environmental data (Nicol & Foster 2003). In 2000, CCAMLR also sponsored a multi-nation survey of the South Atlantic to establish new precautionary catch limits in Area 48 where the fishery has operated predominantly (Hewitt *et al.* 2002). The results from this survey, carried out by vessels from Japan, UK, USA and Russia were used to establish a new catch limit for the South Atlantic of 4 million tonnes (Fig. 3). The new, higher, catch limit reflects more advanced techniques and methods and is not strictly comparable to the older survey results, so the difference cannot be interpreted simply as a change in biomass (Nicol & Foster 2003).

Notwithstanding the improvement in estimation of krill biomass and its use in redefining catch limits, these limits are set for enormous areas of ocean wherein the resource itself and especially the fishery are actually located at much smaller scales. Thus in the south-west Atlantic sector, the krill fishery operates in < 20% of the available area (Fig. 4). Given that in the South Orkney and South Shetland Island areas the fishery consistently operates in the same locations as the main feeding grounds of breeding krill-eating penguins and fur seals, the possibility that excessive quantities of krill could be removed from local areas to the detriment of dependent species was clearly a significant risk. To address this problem CCAMLR has begun the complex task of managing krill fishing at the scales most relevant to many of the natural environment-prey-predator interactions. The first step has been to define smaller and more ecologically realistic management areas – Small Scale Management Units (SSMUs) (Fig. 5). The next step is to quantify the spatial and temporal demands for krill by predators and fisheries, the main fluxes of krill into and out of these areas and the nature of potential competition between predators and fisheries. While this is being developed, the essential complementary step is to start testing potential decision rules and management procedures for minimising, on a precautionary basis, adverse interactions between these.

While distribution and demographic data relevant to managing the krill fishery were being collected, a parallel initiative, addressing ecosystem interactions involving krill-dependent species, was being developed. The basis of the CCAMLR Ecosystem Monitoring Programme was developed in 1984–87 and involved monitoring selected predator, prey and environmental indicators of ecosystem status (Croxall *et al.* 1988, Croxall 1989, 1994, in press, Agnew 1997). The variables involved mainly related to reproductive performance (on scales ranging from days to months) and demography (scales of one year upwards) of krill-eating predators. The aims of the programme were twofold:

a. to detect and record significant changes in critical

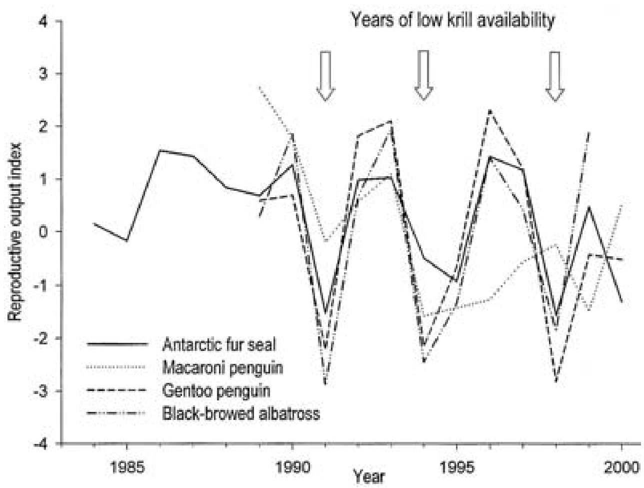


Fig. 6. Variation in reproductive output (essentially offspring raised per breeding pair) for krill-dependent top predators breeding at South Georgia. (Extended from Reid & Croxall 2001).

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

components of the ecosystem;

b. to distinguish between changes due to the harvesting of commercial species and changes due to environmental variability, both physical and biological.

A recent review, essentially 15 years after its inception (CCAMLR 2003a), concluded that the programme had enabled many important changes in the interactions between krill and its main predators to be detected, some of which suggested that major changes in aspects of ecosystem functioning may have occurred (see Fig. 6). However the programme had been unable to distinguish changes due to harvesting and those due to other, more natural causes, and this was deemed unlikely to be remedied given the resources available.

Furthermore, although the CEMP is one of the world's longest running - and most extensive - programmes monitoring population performance of land-based marine predators in relation to indices of prey and environment, CCAMLR is still trying to develop procedures for using these data to link directly to the management of krill. The recent development of rigorous and objective ways of combining the various types of indicators (Boyd & Murray 2001, de la Mare & Constable 2000) should facilitate this. It is hoped that these performance indicators, whose relationship to krill abundance are becoming increasingly well defined (Barlow *et al.* 2002, Reid & Croxall 2001, Reid *et al.* in press) can now be applied, in the context of precautionary management, to interactions within the Small Scale Management Units in ways that can lead directly, through appropriate decision roles, to appropriate modifications in fishing practice. One unexpected product of monitoring diet composition of predators has been the ability to provide new insights into krill population dynamics using predator samples (Reid *et al.* 1999, 2002), generating the possibility of predicting years of exceptionally low krill availability – with obvious implications for predators and fisheries alike.

As CCAMLR has been developing management procedures for the krill fishery, the fishery itself has experienced a period of turmoil. The initial exponential rise in krill catches in the late 1970s and early 1980s was halted by a sharp drop (Fig. 2), which has been attributed to technical processing difficulties, possibly associated with the discovery of high levels of fluoride in the krill shells, and to low krill availability in some areas. The catch recovered to levels of around 400 000 tonnes per year for much of the late 1980s and early 1990s before declining as the Soviet Union disaggregated (Nicol & Endo 1997). Since 1993 the catch has fluctuated around 100 000 tonnes per year with generally around 60% of this catch being taken by Japanese vessels. The fishery has reduced its geographic scope and is currently restricted to the South Atlantic. Catching occurs around South Georgia in winter and moves south as the ice retreats in spring and summer, moving north again in autumn. A recent trend has been for the fishery to operate further south in winter because of conditions of reduced ice cover (Nicol & Foster 2003).

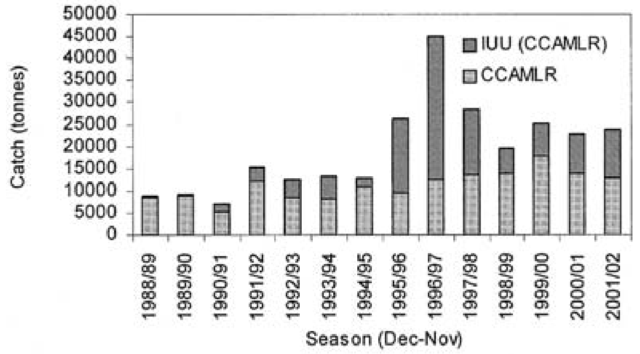


Fig. 7. Catches of toothfish *Dissostichus* spp. in the Convention Area. The CCAMLR catches are those from the regulated fishery as reported annually to CCAMLR. The estimates of IUU (illegal, unregulated and unreported) catches in the CCAMLR area are derived by CCAMLR from various sources (CCAMLR 2002, 2003).

At 120 000 tonnes a year, the krill fishery is not an insubstantial fishery in global terms and in the 1980s it was one of the world's top 20 fisheries in terms of tonnage landed. The current precautionary catch limits total nearly 5 million tonnes and if the fishery were exploited to this level it would be amongst the largest fisheries on the planet.

Toothfish fishery

In Southern Ocean fisheries, Patagonian toothfish (*Dissostichus eleginoides*) first appeared, as a shallow-water bycatch of juveniles, in trawl fisheries around South Georgia in the late 1970s. By the late 1980s the deep water (500–1000 m) habitat of the larger adults (reaching lengths over 2 m and weights in excess of 100 kg) could be targeted by using longlines. Typically each longline set involves deploying about 10 000 baited hooks on branch lines from the main longline weighted to sink to the sea floor. Surface buoys mark the ends of the lines which are retrieved 10–20 hours later. Directed fishing started around South Georgia in 1987 (Fig. 7) but the high market value of toothfish led to rapid expansion throughout the sub-Antarctic parts of the Convention Area in the 1990s and a subsequent southward extension of fishing into Antarctic coastal waters, mainly in the Ross Sea, where Antarctic toothfish (*Dissostichus mawsoni*) is the principal target.

Because toothfish are long-lived (30–50 years natural life-span) and slow growing, the rapid expansion of this fishery caused major concern. This was compounded by data from the fishery being insufficient for conventional stock assessment methods and the adults stocks being largely inaccessible to fishery-independent trawl surveys (Constable *et al.* 2000). To take account of the absence of assessments of the unexploited stock, and that fishing was

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

already in progress, CCAMLR developed two approaches for management, a Generalised Yield Model (Constable & de la Mare 1996) and regulations restricting the development of new fisheries (including existing fisheries moving into new areas).

The Generalised Yield Model builds on the approaches already developed for the Krill Yield Model. It also addresses the problems in toothfish assessment by using absolute estimates of the abundance of recruits and projecting these forward in the simulations. This enables the known catches to be directly discounted from the population and permits the long term annual yield to be assessed in tonnes, rather than as a proportion of an estimate of standing stock. Surveys around South Georgia provided a time-series of recruitment estimates enabling long term annual yields for South Georgia since 1995 to be calculated. Similar methods were also applied to the toothfish trawl fishery around Heard Island, albeit with a shorter time-series of recruitment data. In applying the decision rules for Patagonian toothfish there is essentially just one difference from the process for krill. As a large deep water predator, toothfish do not constitute key items in the diet of land-based predators; therefore the escapement value was set at 50% (rather than 75% as for krill). This level of escapement is still higher than more conventional fisheries management schemes which typically prescribe escapement levels of 20–30%. For toothfish, the assessment of long term (20 year) annual yields is a further example of a precautionary approach, taking account of stock fluctuations and incorporating many sources of uncertainty in to a single assessment.

However, these approaches, on their own, are potentially insufficient to deal with opening new fishing grounds in the absence of survey data, particularly estimates of recruitment. For toothfish, this is particularly exacerbated by the often restricted amount of toothfish habitat in such new areas, making stocks very vulnerable to over-exploitation. CCAMLR has so far dealt with this in two ways. First, estimates of recruitment from fished areas have been extrapolated to the new areas in proportion to the ratios of areas of seabed; the resulting yield estimates are then discounted by 60% to take account of the special uncertainties surrounding opening new fisheries. Second, catches in new areas are restricted to 100 tonnes per rectangle of 1° longitude by 0.5° latitude, to prevent all the allowed catch being taken in a small area. These regulations are to be maintained until sufficient research data, and especially on recruitment, are available for a full stock assessment to be carried out, at which time that particular fishing area would be treated in the same way as the existing established and assessed fisheries for toothfish.

Despite enacting these precautionary procedures, CCAMLR's management of toothfish has been severely compromised by difficulties relating to bycatch and incidental mortality of non-target species and by high levels of illegal, unreported and unregulated (IUU) fishing.

Incidental mortality and bycatch

At the close of the 1980s, incidental mortality of albatrosses breeding in the Convention Area associated with longline fishing for tuna in waters north of the Convention Area, was identified as potentially the most serious cause of their declines in population (Croxall *et al.* 1990, Brothers 1991). At the same time the first records were obtained of albatrosses killed by longline fishing around South Georgia (Dalziell & de Poorter 1993). As the toothfish fishery expanded, so did the seabird bycatch, involving giant petrels (*Macronectes* spp) and especially white-chinned petrels (*Procellaria aequinoctialis*), in addition to albatrosses (of several species). In 1994 CCAMLR established an *ad hoc* Working Group to advise on the problem, which recommended the use of a variety of practical measures designed to reduce seabird bycatch (see Table II). The scientific observers already assigned to longline fishing vessels to collect data on the fish catch, also started to record details of the seabird bycatch and report on the use of mitigating measures. Although these measures had some effect, their use was patchy and often inappropriate and levels of seabird bycatch continued to increase, reaching estimated levels (based on the quantified observer data) of nearly 6000 birds at South Georgia alone in 1997 (Fig. 8). CCAMLR then decided that, until the suite of mitigation measures were in use by all vessels at all

Table II. Main measures used by CCAMLR to minimise incidental mortality of seabirds associated with longline fishing.

Measure	Desired effect
No offal discharge	Avoid attracting birds
Streamer lines	Keep birds away from sinking longline
Weighted lines	Sink lines too fast for birds to access
Night setting	Albatrosses are diurnal
Closed seasons	Protect birds when breeding

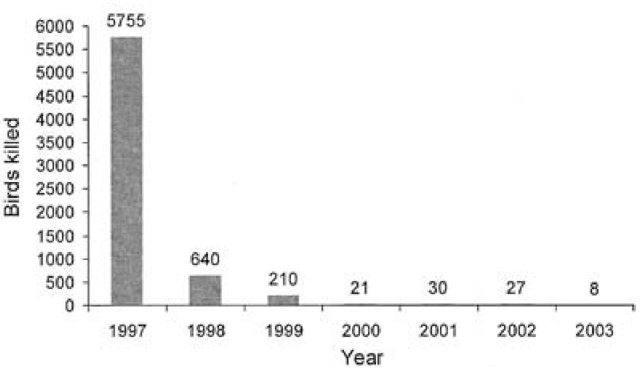


Fig. 8. Incidental mortality of seabirds by longline fishing for toothfish at South Georgia since 1997 (data from CCAMLR 2003a).

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

times, longline fishing should take place only outside the breeding seasons of the species most affected (black-browed albatross (*Diomedea melanophris*), giant petrels and white-chinned petrel), all of which migrate away from the toothfish fishing grounds in winter. This measure was immediately put into effect at South Georgia where it had the effect of a ten-fold reduction in seabird bycatch (Fig. 8). This was followed by further reductions, as the other measures were used consistently and correctly, with levels of seabird bycatch being essentially negligible (in terms of effects on the populations concerned) from 2000 onwards.

However, seasonal restrictions on longline fishing were not adopted within the South African and French EEZs in the Indian Ocean and seabird mortality levels remained high. In the South African EEZ, however, reduction in fishing effort, fishing further away from seabird breeding colonies and more effective use of mitigation, reduced bycatch to levels similar to those at South Georgia by 2002. In the French EEZs, however, over 10 000 white-chinned petrels are still being killed annually and new regulations and urgent studies are being implemented to try to rectify the problem (CCAMLR 2003a, 2003b). With this exception, CCAMLR – and notably the fishing interests represented therein – have proved able to address seabird incidental mortality in a manner more effective than in any other Regional Fisheries Management Organisation (RFMO).

In addition to its desire to manage fisheries in environmentally responsible, as well as sustainable, fashion, CCAMLR's concerns over seabird bycatch related also to the impact on their populations, particularly of albatrosses. For these long-lived seabirds, with low productivity and very low natural mortality rates (Weimerskirch *et al.* 1997, Croxall *et al.* 1998), even the mortality levels from the longline fisheries in the Convention Area were unsustainable for the populations involved (CCAMLR 2002). Given albatross demography, population decreases (e.g. Croxall *et al.* 1998) were, unless mortality levels became drastically reduced, irreversible within 20–30 years - in direct conflict with the provisions of Article II of the CCAMLR Convention. It is therefore ironic that, despite CCAMLR's success in addressing this issue, its seabird populations are still in peril – by continuing mortality from longline fisheries for tuna and allied species in waters to the north of the Convention Area (and where mitigation measures are still inadequate) and by IUU fisheries in the Convention Area. The latter, where vessels are unlikely to bother to use mitigation measures to avoid catching birds, are estimated to kill tens of thousands of seabirds in the Convention Area annually (CCAMLR 2003a).

CCAMLR's attention to bycatch issues has also extended to fish; many skates and rays are caught and killed or discarded due to toothfish longlining. Because the effect of this bycatch on the population concerned cannot currently be quantified, CCAMLR has adopted interim bycatch limits for these taxa, together with rules requiring fishing activities to move a specified distance once a threshold level of skate and ray bycatch has been reached (CCAMLR 2003a). CCAMLR has also considered the effects of bycatch of fish, particularly juveniles and larvae, in the krill fishery (Watters 1996); this is not currently a major issue but CCAMLR continues to monitor the situation.

IUU fishing

The threat posed by IUU activity to regulated toothfish fisheries is well documented (Agnew 2000, Constable *et al.* 2000, CCAMLR 2003a). IUU catches of toothfish were initially confined to the South Georgia region but by 1996 levels in the Indian Ocean may have reached 100 000 tonnes, well in excess of the aggregate global limit recommended for the regulated fisheries for the whole Convention Area.

To address this situation, threatening the complete collapse of toothfish stocks in most of the Convention Area, the Commission:

a) collaborated operationally and through information exchange to police its area more effectively – resulting in numerous arrests, fines and catch confiscation,

b) made the use of satellite-linked tracking systems (vessel monitoring systems (VMS)) mandatory for longline vessels fishing in the Convention Area. However to be fully effective this system needs to be operated centrally in real time, rather than through Flag State filters,

c) developed a catch documentation scheme (CDS) whereby only fish with certificates indicating legal capture in the Convention Area can be landed and marketed. This has enjoyed some success but, as with any such trade measure, many difficulties remain to be overcome.

These measures indicate the global nature of the problems facing the management of Southern Ocean resources. Despite these initiatives and especially the resolute policing of the main fishing grounds around sub-Antarctic islands, only at South Georgia (and in the Ross Sea) are IUU catches currently at insignificant levels, although there is evidence of reduction in levels elsewhere, which may augur better for the future. If not, many stocks of toothfish will soon become depleted to levels potentially prejudicial to their recovery. Given the serious threat posed by IUU fishing to the sustainability of its most valuable fishery and thereby to the reputation of CCAMLR, it is a particular concern that there is clear evidence that certain Members of the Commission, notably Uruguay and Russia, are unable adequately to regulate the activity of their flag vessels and/or to take appropriate actions, including via port state control, to

Table III. Potential timescales/reaction speeds of operation of different factors relevant to comprehensive management of fisheries.

Factor	Reaction speed	Spatial scale of effects	Comments
Management decisions:	< 1 year	generally regional	CCAMLR meets annually
Economics	< 1 year	local to global	
Shipbuilding:	< 5 years	global	
Stock change effects:	< 5 years	regional	Interannual variability can operate at shorter timescales
Changes in predators:	5–10 years	regional	
Politics:	< 1– >5 years	local to global	Inherently unpredictable
Science:	1–5 years	local to global	Time for scientific discoveries to be translated into management or technology
Technology:	1–5 years	local to global	Time for technological developments to be realised in the fishery
Climate change:	decades to centuries	global	

prevent their apparent complicity in IUU activity (CCAMLR 2003b).

Finally, it is worth observing that many features of CCAMLR's successes in fishery management have been greatly assisted by its scientific observer scheme. This arose out of the need to collect data with which to help manage specific fisheries but has now become an invaluable source of data and information on other topics such as bycatch, operational practice etc. It is greatly to the credit of all parties, especially the fishers, that observers are required – and accepted – on all vessels fishing for finfish in the Convention Area; the reluctance to have observers on krill fishing vessels is slowly being overcome.

Global forces that will influence Southern Ocean fisheries.

The Southern Ocean ecosystem, its fisheries and their management is affected by factors which range from local changes to global-scale processes. Management of fisheries requires some ability to predict changes, or at least to take the likelihood of potential changes into account. The range of global factors that affect fisheries and their management includes large scale climatic changes, more regional meteorological and oceanographic changes, ecological changes and economic and political developments. The ability to predict the scope and magnitude of these changes diminishes considerably as one moves from the physical to the ecological, and is more difficult still when economic and political forces are involved. These forces also operate on different temporal and spatial scales (Table III).

The physical environment

The immediate physical environment can have direct short and long term effects on Southern Ocean fisheries. In the shorter term, the krill fishery has recently altered its behaviour in the South Atlantic in response to changing winter sea ice conditions. The winter fishery used to be confined to the ice free waters of South Georgia but in recent years, in response to reduced winter ice conditions, the fishing fleets have remained in the South Orkneys and Antarctic Peninsula area throughout the year (Miller & Agnew 2000). Interannual changes in physical conditions can manifest themselves either directly, though mechanisms such as changes in sea ice extent or through the abundance of icebergs in the fishing grounds, but may also affect fisheries indirectly through the effect of physical changes on the biological systems. These could include adverse effects of increased UV-B on primary production as a result of the "ozone hole", changing ocean circulation patterns or variations in the wind field (Constable *et al*. 2003). Recruitment of krill has been linked to sea ice conditions off the Antarctic Peninsula (Loeb *et al.* 1997) and there is a complex relationship between changes in sea ice extent and both reproductive and larval success in krill (Hewitt *et al.* (2003). This is thought to be mediated through the sea ice affecting the food supply by acting as a habitat for ice algae, and as a water column stratifying agent during the melt season in spring which facilitates the development of the spring bloom. On longer timescales, there appears to be a relationship between the distribution of Upper Circumpolar Deep Water and the larval survival of krill (Hofman & Murphy 2004) and climate-related changes in the intrusion of this water mass onto the shelf may have long term effects on krill stocks. Recruitment of krill is one of the key parameters in the GYM used to manage the fishery, so changes that occur with time are critical to ensuring sustainable harvests. However, the current GYM includes stochastic recruitment variation rather than incorporating a function that is driven by physical variables, partly because the degree of predictability for the effects of physical variation on krill recruitment is low. Additionally, the global distribution and abundance of krill is difficult to measure (Nicol *et al.* 2000b), so the effect of large scale physical changes on the krill population is unknown and thus longer term trends cannot be incorporated into the management process.

More distant or more global physical processes also have direct and indirect effects on the Southern Ocean ecosystem. Global-scale atmospheric and oceanographic phenomena such as El Niño appear to affect sea ice processes in the Southern Ocean (Yuan 2004) and this has ramifications for the ecosystem (see above). The direct effects of ENSO in more northerly regions, such as its effects on pelagic fisheries in upwelling regions, leads to

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

fluctuations in the supply of fishmeal which can affect the market for meal derived from Antarctic krill (Tacon & Forster 2001).

The effect of long term global climate change on the management of Southern Ocean fisheries is difficult to predict. To incorporate such change into management models clearer relationships must be established between variations in physical and biological variables, so that some degree of predictability can be established. It is, however, axiomatic that unless the management system is capable of coping with the shorter term biological, economic, sociological and political forces that affect Southern Ocean fisheries, it is unlikely that there will be sustainable fisheries will survive into a future to be affected by global change.

Scientific and technological developments

Scientific and technological developments take time to be implemented by the fishing industry or to become incorporated into fisheries management practices. In the light of the BIOMASS experience, CCAMLR initially considered the conduct of large-scale krill biomass surveys as a forbidding undertaking; however, recent experience utilising better survey techniques and methodologies has indicated that such surveys can be conducted efficiently. It took 10 years for the acoustic survey results from the first international BIOMASS experiment (FIBEX) to be analysed to the point where they could be incorporated into a management model to set precautionary catch limits (Trathan *et al.* 1992). However, when the major CCAMLR acoustic surveys were carried out in the summers of 1996 and 2000, developments in technology and computing power meant that it was possible to present the biomass data to CCAMLR meetings within six months and to establish precautionary catch limits within nine months of these surveys being completed (Nicol *et al.* 2000a., Hewitt *et al.* 2002). This experience has prompted the Scientific Committee to recommended the surveying of much of the Convention Area for krill as soon as is practical (CCAMLR 2000, para 5.28).

The results of basic scientific research can also directly affect the fishery. In 1979, Soevik & Braekkan (1979) reported high levels of fluoride in krill. In the mid 1980s the krill fishery experienced a major decline, dropping from an all time high of 528 000 tonnes in 1981/82 to 229 000 tonnes in 1982/83 and 131 000 tonnes in 1983/84 (Fig. 2). This has been attributed to the conversion of the high levels of fluoride discovered in whole krill to unacceptably high levels of fluoride in krill products forcing a reassessment of the uses of krill products (Budzinski *et al.* 1985, Nicol & Endo 1997). Technological responses to the high fluoride levels in krill included rapid peeling (Budzinski *et al.* 1985), development of low fluoride products (Tenuta Filho & Alvarenga 1999) and re-orienting towards aquaculture where high fluoride levels are less problematic (Nicol *et al.* 2000c).

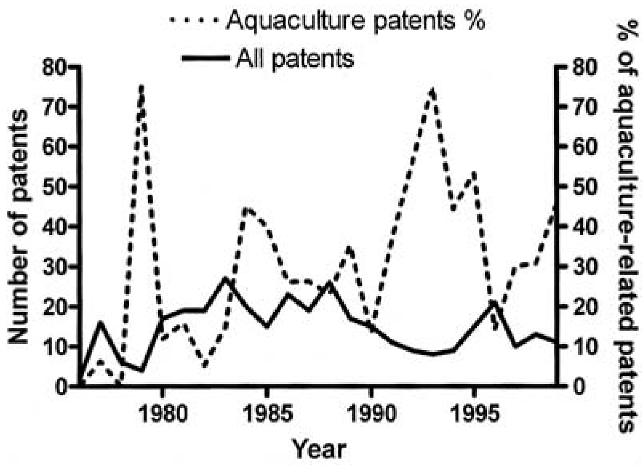


Fig. 9. Trends in the patenting of products and processes related to krill. The number of aquaculture-related patents is expressed as a percentage of all patents registered. Data from US Patent and Trademark Office, European Patent Office and Japanese Patent office (see text).

New manufactured products using krill are constantly under development and are becoming widely available and it is the development of new products and the marketing of these that will enhance demand for krill as a raw material (Nicol *et al.* 2000c). Krill hydrolysates have been developed as additives for aquaculture feed but they also have potential in the livestock and pet food markets (Nicol *et al.* 2000c). Krill oils are likely to be an expanding market in the nutriceutical, cosmetic and pharmaceutical fields, which will result in high-value products (Hamovitch 2002). Krill enzymes have a wide range of potential uses from novel medical applications (Mekkes *et al.* 1997) to their use restoring paintings (Makes 1992). Predicting these developments and their effect on demand for krill is difficult, but it is possible to detect some trends from analyses of patent databases.

A large number (376) of patents relating to krill have been registered in Europe, Japan and the USA, or through the WIPO (information from US Patent and Trademark Office: http://patft.uspto.gov, European Patent Office: http://www.european-patent-office.org/online/, Japanese Patent office: http://www.jpo.go.jp/). An initial assessment of krill-related patents was published recently (Nicol & Foster 2003) and most of these patents relate to the use of krill for human consumption (29.3%) although only 33.6% of these have been filed since 1988 (half way through the time series). Next most numerous are patents that relate to the production of fish feed or bait (21.3%), and a further 4.8% deal with either hydrolysates or pigments which are also used in aquaculture. Aquaculture-related patents show an increase in recent years with 64.3% of these being registered since 1988 (Fig. 9). Medical uses, which require small quantities of high quality krill, constitute 17% of all patents but of these 87.5% have been filed since 1988. Interestingly, the patenting of krill products and processes has proceeded unhindered over the last 25 years, independent of the emerging issues regarding biological prospecting in the Antarctic Treaty Area (Jabour-Green & Nicol 2003)

Many developments in krill processing have been directed towards addressing the requirements for the aquaculture industry. Aquaculture is the fastest growing agricultural sector with an annual growth rate of 11% and this is not being matched by an increase in the rate of supply of aquaculture feed (Rumsey 1993). Currently, aquaculture consumes 35% of the world's fishmeal production and 70% of the world's fish oil production. It has been the fastest growing food production sector for the last 20 years and currently 25% of fish consumed by humans comes from aquaculture. In 10 years aquaculture production will exceed wild fisheries production. In 2000 aquaculture production was more important than sheep and in 20 years aquaculture production will exceed world beef production. Although much of the current aquaculture production comes from herbivorous fish species, there is a trend for production to move from grazing species to carnivorous species and these need supplies of fish meal.

Much aquaculture feed currently comes from fishmeal yet the supplies of fishmeal from traditional sources are declining (Tacon & Forster 2001). Although alternative sources of animal based meal are being used (feathers, offal, animal fats, etc.) the use of such feedstuffs raises biosecurity issues which are being treated more seriously in the light of recent outbreaks of Bovine Spongiform Encephalitis (BSE – or "mad cow disease" resulting from ingestion of infected neural tissue in cattle feed). The demand for marine-based aquaculture feed is projected to grow and the advantages of using krill in aquaculture feeds are becoming more widely known (Nicol *et al.* 2000c). About half the annual krill catch is currently used as aquaculture feed for high-value fish species, such as salmon and sea bream. Cultured carnivorous fish need fish oils and, not surprisingly, thrive best when fed a diet that closely resembles their natural diet. Globally, traditional fisheries which supply fishmeal are declining and are also generally subject to fluctuations caused by short-term climatic events, there is an international effort to find supplies of fishmeal or fishmeal substitutes (New & Wijkstrom 2002).

The rapid growth of aquaculture and its demand for feed will soon begin to have an economic effect on industrial fisheries throughout the world. Other more political factors that will also come into play. For example, a recent EU directive reducing the permissible levels of artificial colouration in fish (and other animal) feed (EU Press Release DN: IP/03/123: 27/01/2003) and allied requirements in the United States to specifically label all farmed fish that contain artificial colourants (http://www.smithandlowney.com/salmon/pressrelease/) will speed development of natural sources of pigmentation for incorporation into aquaculture feeds. Such moves are also likely to generate a market for "naturally" coloured fish. Krill have been used for decades as a natural colouring agent for red sea bream in Japan (Nicol & Endo 1997) and salmon and trout reared with krill in their diet obtain the desired colouration without further additives (Arai *et al.* 1987). That krill also have a number of other desirable properties as an aquaculture feed, including their ability to flavour vegetable based protein feeds, thus enhancing their palatability to farmed fish (Nicol *et al.* 2000c), should ensure that krill products are able to be sold at a premium in the future.

Interest in krill as an aquaculture feed has led to proposals to harvest temperate species of krill in waters close to major aquaculture sites and to the development of new products based on species from outside the Southern Ocean. Availability of krill from Northern Hemisphere sources is restricted and this may put pressure on Antarctic krill stocks. The West Coast Canadian krill fishery is currently capped at 500 tonnes (Everson 2000). Exploratory krill fisheries have been proposed in Alaskan waters, off California and off the East Coast of Canada but have resulted in prohibitions on krill fishing in each of these areas (Anon 1997, 1998, 2000). Japanese coastal krill fisheries are probably near capacity at ~70 000 tonnes per year (Endo 2000). It seems unlikely that new coastal krill fisheries will develop because of conflict between developers, existing fishing industries, fishery managers and conservation groups. These fisheries were proposed to provide aquaculture feed and the prohibition of many fisheries on northern species of krill has meant that companies developing krill-based aquaculture feeds are restricted in their supply to krill harvested either in Japan or the Antarctic. Thus, well-meaning management actions in the Northern Hemisphere may come to have a profound effect on resources management in the Southern Ocean.

Technological developments are also likely to provide solutions to problems such as those posed by non-target bycatch of skates and rays and incidental mortality of seabirds. For seabirds, bait-casting machines (avoiding baited hooks sinking slowly in turbulent water), simple underwater setting devices (ensuring that hooks are set too deep for surface feeding seabirds to access) and longlines with lead weights integrated into the fibres (ensuring rapid sinking which avoids catching even seabirds with considerable diving capacity) are all now commercially available (Robertson *et al*. 2003). The last is likely to prove particularly important for demersal longline fisheries as in trials it has enhanced fishing performance (providing fresher bait and more time at fishing depth) and is therefore likely to be used in IUU as well as regulated fisheries. Although these advances are unlikely to reduce bycatch of non-target fish species, some of the new designs for hooks and other ideas being trialled to avoid catching turtles may

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

come to have wider application.

Economic forces

Economic forces act on a global scale and often with immediate effect. The collapse of the North West Atlantic cod fisheries had a dramatic effect on the value of table fish and this was translated rapidly into exploratory fisheries for alternative supplies (Pauly *et al*. 2000). This economic trend (fuelled by overfishing in another part of the globe) has almost certainly influenced much of the increase in IUU fishing in the Southern Ocean, with its consequent ecological effects (Agnew 2000). For several years, CCAMLR has recognised that its fisheries are driven by external economic forces and it has made repeated requests for information on economics and technology that will affect the development of the krill fishery. Unfortunately, such information has been difficult to obtain and only three papers have been submitted to CCAMLR's Working Group on Ecosystem Monitoring and Management (the main source of scientific advice to the Scientific Committee on management of the krill fishery) which deal with the economics and technology of the fishery. The Scientific Committee has historically avoided extensive discussion of economics on the grounds that its concern is strictly scientific. The Commission itself is concerned with much broader issues so is unable to adequately deal with topics such as economics.

In recent years, CCAMLR has shown itself capable of adopting a more comprehensive approach to management of the toothfish fisheries, including the use of trade-related measures such as the catch documentation scheme. This was developed by a subsidiary group of the Commission now the Standing Committee on Implementation and Compliance, which is now the main potential forum for the discussion of information from economic sources that may affect the development of fisheries. Thus, its terms of reference include requirements to provide technical advice and recommendations on means to promote the effective implementation of, and compliance with, conservation and management measures; and to provide the Commission with recommendations on appropriate interaction with other fisheries or conservation management, technical or scientific organisations on matters of relevance to the effective implementation of, and compliance with, conservation and management measures.

Direct information on the economics of the krill fishery e.g. the costs of fishing or the relative values of different products, is difficult to obtain although some analyses have been presented in the past (Budzinski *et al.* 1985). The price of frozen krill has been occasionally reported to CCAMLR. Their use of such data as indicators of fishing trends has been made difficult because information from major markets was not available (CCAMLR 2000, Annex 4 para 2.6) and because their submission has not been in a systematic fashion. Information on the economics of the krill fishery was presented at the 2001 meeting of CCAMLR WG-EMM (CCAMLR 2001, Paras 2.24–2.28) and drew attention to a US Department of Commerce analysis of krill markets in Japan, which gave some indications on the relative cost-effectiveness of the production of products such as meal and frozen krill. Although economic and market information on krill and other fisheries products is available from a number of commercial sources, the Commission has not had regular access to this information. Only limited economic information from a small number of sources has been available within CCAMLR and a more comprehensive approach would be required to produce economic information that might be useful in predicting trends in the fishery. Additionally, interpretation of such information would require access to specialists with marketing and economic skills who do not regularly attend CCAMLR meetings.

Managing change

One of the difficulties that CCAMLR has faced is the task of predicting when the krill fishery will expand and at what rate. In 2001/02 the krill fishery grew by some 20%, largely as a result of increases in catches by vessels from the Ukraine and the USA (CCAMLR 2002). It is difficult to assess whether this increase is the beginning of a trend or whether it is a one-off event. The US fishing company, 'Top Ocean', has provided CCAMLR with considerable information on its operations and on the economic forces behind the fishery (Jones & Hull 2003). This company aims to produce animal feed, human-grade meat and meal for aquaculture (Griffin 2002). The impetus for this venture is humanitarian rather than economic, aiming to provide low cost protein for human consumption with funding from the Family Federation for World Peace. This may open new markets for krill products but it may also affect fisheries for krill which have purely economic aspirations.

CCAMLR has established compulsory schemes for the notification of intended entrance into a number of its fisheries but not for krill. Thus information on trends in the krill fishery has been obtained through voluntary submission of Members' intentions for the following season. Additional information has been supplied through published articles and through economic information supplied by the Secretariat or by Members. There has been no formal mechanism for the provision of information on krill fishery trends nor is there any requirement for members to submit such information. However, at the 2003 meeting of CCAMLR, a scheme for the voluntary notification of detailed information on Members krill fishing plans was adopted (CCAMLR 2003b). This development may provide better year-to-year information on developments in the krill fishery but will only be

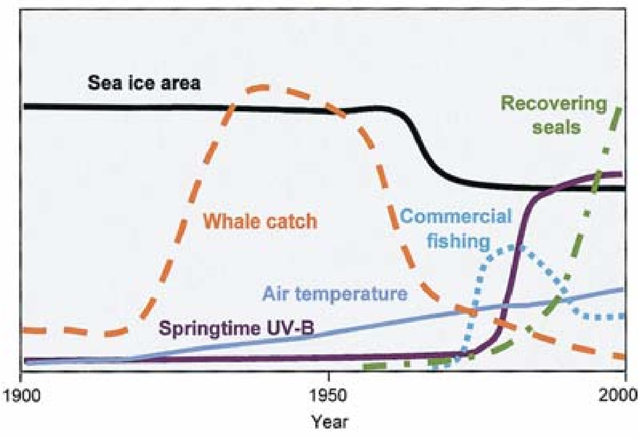


Fig. 10. Schematic illustration of the broad patterns of change observed in elements of the Southern Ocean ecosystem and environment. Changes indicated are from well documented sources but no attempt has been made to represent their magnitudes on a common scale.

indicative and may not be particularly useful in helping to predict longer term trends.

In the past, voluntary submission of information to CCAMLR on krill fishing intentions has generally been inadequate to predict trends. Additionally, this voluntary notification process provides no information on the potential for involvement in the fishery by vessels from non-member nations. Regulations requiring formal notification of krill fishing plans would greatly assist in the orderly development of the fishery. Although compulsory notification of new and exploratory fisheries for toothfish within the CCAMLR Area has not resulted in the accurate prediction of fishing effort (because many of the submitted notifications have not been implemented), such notification has allowed the establishment of precautionary regimes for the management of potential new and exploratory fisheries. Formal notification of intention to participate in the krill fishery by members might over time provide some indication of trends. Increased numbers of notifications per year, irrespective whether they are acted upon, could well signal increased interest in the fishery and this is exactly the advance warning that is required.

Notification is only part of the process of understanding the krill fishery and the forces that drive it. In other fisheries in the Convention Area scientific management and understanding has been greatly enhanced through the adoption of a number of Conservation Measures. These include the compulsory carrying of Scientific Observers, the use of vessel monitoring systems and the submission of detailed catch and effort information (CCAMLR 2003c). The krill fishery has been exempt from all of these Conservation Measures but for CCAMLR to make progress on understanding the dynamics of its largest fishery it will have to begin bringing krill into line with the regulations that it has deemed necessary for its other fisheries.

Conclusion

Harvesting of living resources in the Southern Ocean is the longest continuous human activity around Antarctica. It is also the activity that, in the period since humans first entered the Southern Ocean, has had the most devastating effect on natural systems on both long and short timescales. It is difficult to gauge the effect that the large scale removals of seals, whales and fish have had on the ecosystems of the region, but the first two of these almost certainly caused ecological changes greater than anything subsequently, at least until the current decades. Nowadays Antarctic marine systems are in a particularly dynamic phase (Fig. 10), with major changes in the physical environment, recovery (and probable overshoot) of some stocks (e.g. fur seals) from past exploitation and the impact of current harvesting all operating simultaneously. It is not surprising that many scientists believe that we may be observing changes at least partially co-incident with or caused by a regime shift in the Southern Ocean marine system (Loeb *et al.* 1997, Reid &

Table IV. Some successes and challenges for CCAMLR's management of krill and toothfish fisheries.

Successes	Challenges
Antarctic krill:	
Precautionary GYM	Acquisition of economic data to enable independent forecasting of fishery growth
Triggered decision rules	Incorporation of CEMP data into management advice
Catch limits in place before fishery expansion	
Monitoring (CEMP) programme for dependent species	Observer programme and VMS for krill fishing vessels
Recent definition of areas for management at more appropriate scales	Application of small scale management units
Patagonian toothfish:	
Within the CCAMLR area, good precautionary management of main stocks	Within the CCAMLR area, limited control of IUU outside South Atlantic
Reasonable control on fishery expansion into new areas	
	Outside CCAMLR area, bycatch measures inadequate to protect "CCAMLR" species.
Development of catch documentation scheme (CDS)	Improve implementation and efficiency of CDS
Compulsory use of vessel monitoring system (VMS)	Convert VMS to centralised system, rather than via Flag State filter
Within the CCAMLR area, seabird bycatch largely under control	Within CCAMLR area, skate and ray bycatch still concerns

https://doi.org/10.1017/S0954102004002330 Published online by Cambridge University Press

Croxall 2001, Croxall *et al.* 2002, Atkinson *et al.* 2001 and in press).

Although global forces, such as pollution and climate change, undoubtedly affect Antarctic ecosystems and may have profound long term effects, we can do relatively little to mitigate their influence in the shorter terms. In contrast fishing is currently the only major activity in the Antarctic region that actively sets out to exploit, and thus alter, the existing ecosystems. It is thus the major threat to the region and also the only significant tool available to manage the system. Management of ecosystems means managing human activities and CCAMLR has set a number of global precedents for environmental management, whilst other management bodies are still initiating approaches to concepts such as ecosystem-based approaches. Today's challenge for CCAMLR is to manage toothfish sustainably and without detriment to non-target species; it is also to lay the management foundations now to cope with the potential increased demand for krill. Table IV sets out some of the notable successes and salient challenges for CCAMLR in respect of management of krill and toothfish. It is noteworthy that, in both cases, however much CCAMLR can improve its own performance, it cannot succeed without both taking account of global and regional scientific, technological, economic and political changes or without collaboration on the part of other organisations managing fisheries, particularly in adjacent regions.

A recent assessment of the environmental performance of southern hemisphere Regional Fishery Management Organisations (RFMOs) (Small in press) concluded that CCAMLR has arguably the best record of all. Some of the main lessons from CCAMLR for other RFMOs are the need to:

a) implement precautionary approaches to sustainable harvesting;

b) take full account of the needs of dependent and related species;

c) subscribe to the philosophy – and help define the implementation – of ecosystem approaches to fishery and environmental management;

d) adopt appropriate mitigation measures to prevent, avoid or minimise bycatch and incidental mortality of non-target species;

e) require minimum consistent reporting standards of effort, catch and bycatch, linked to data collection and validation through appropriate levels of independent scientific observation.

Even these prescriptions will be insufficient, however, if governments lack the political will to make them work, and, in particular, to address a key issue in respect of high seas fisheries, that of eliminating IUU fishing. The future of the ecosystems of the Southern Ocean are, therefore, not just in the hands of CCAMLR. The resources, habitats, species and systems of this extraordinary region will, ultimately, only survive if there is concerted global effort to:

a) eliminate pirate fishing, particularly by outlawing flags of convenience;

b) develop new or vastly improved systems for the coordinated management and governance of high seas marine systems, incorporating appropriate principles and practices for ecosystem-based management in a changing world.

c) improve understanding of the linkages between the physical environment and biological productivity at all scales so that management of the living resources of the Southern Ocean can be based on greater scientific certainty.

Acknowledgements

The authors would like to thank the organizers of the meeting '*The Role of the Southern Ocean in Global Processes: An Earth System Science Approach* for inviting them to present the talk on which this paper is based. The comments of the three reviewers greatly improved the manuscript and their input, and that of the editor, is gratefully acknowedged.

References

Agnew, D.J. 1997. Review: the CCAMLR ecosystem monitoring programme. *Antarctic Science,* **9**, 235–242.

Agnew, D.J. 2000. The illegal and unregulated fishery for toothfish in the Southern Ocean, and the CCAMLR catch documentation scheme. *Marine Policy*, **24**, 361–374.

Anon. 1997. Ecosystems considerations for krill and other forage fisheries. *Canada Dept. of Fisheries and Oceans Maritimes Region, DFO Maritimes Regional Fisheries Status Report*, **97**, 1–5.

Anon. 1998. Fisheries of the Exclusive Economic Zone off Alaska; Forage Fish Species Category, 50 CFR Part 679, Vol. Federal Register/Rules and Regulations, 13 009–13 012.

Anon. 2000. California acts to protect ocean food chain. *Pacific Coast Federation of Fishermen's Association News Release,* 1.

Arai, S., Mori, T., Miki, W., Yamaguchi, K., Konsu, S., Satake, M. & Fujita, T. 1987. Pigmentation of juvenile Coho salmon with carotenoid oil extracted from Antarctic krill. *Aquaculture,* **66**, 255–264.

Atkinson, A., Whitehouse, M.J., Priddle, J., Cripps, G.C., Ward, P. & Brandon, M.A. 2001. South Georgia, Antarctica: a productive, cold water, pelagic ecosystem. *Marine Ecology Progress Series*, **216**, 279–308.

Atkinson, A., Siegel, V., Pakhomov, E. & Rothery, P. In press. Long-term decline in krill stock and increase in salps within the Southern Ocean. *Nature*.

Barlow, K.E., Boyd, I.L., Croxall, J.P., Reid, K., Staniland, I.J. & Brierley, A.S. 2002. Are penguins and seals in competition for Antarctic krill at South Georgia? *Marine Biology*, **140**, 205–213.

Beddington, J.R. & Cooke, J.G. 1983. The potential yield of fish stocks. *FAO Fisheries Technical Paper*, **242**, 47.

BOYD, I.L. & MURRAY, A.W.A. 2001. Monitoring a marine ecosystem using responses of upper trophic level predators. *Journal of Animal Ecology,* **70**, 747–760.

BROTHERS, N. 1991. Albatross mortality and associated bait loss in the Japanese longline fishery in the Southern Ocean. *Biological Conservation*, **55**, 255–268.

BUDZINSKI, E., BYKOWSKI, P. & DUTKIEWICZ, D. 1985. Possibilities of processing and marketing of products made from Antarctic krill. *FAO Fisheries Technical Paper,* **268**, 1–46.

BUTTERWORTH, D.S., PUNT, A.E. & BASSON, M.L. 1991. A simple approach for calculating the potential yield of krill from biomass survey results. *Selected Scientific Papers, 1991 (SC-CAMLR-SSP/8)*. Hobart, Australia, CCAMLR: 207–217.

CCAMLR. 1989. Report of the Workshop on the Krill CPUE Simulation Study (La Jolla, USA, 7 to 13 June 1989). *Report of the Eighth Meeting of the Scientific Committee (SC-CAMLR-VIII)*. Hobart, Australia, CCAMLR. Annex 4: 81-137.

CCAMLR 2000. *Report of the nineteenth meeting of the Scientific Committee* (SC-CCAMLR-XIX). Hobart: CCAMLR.

CCAMLR 2001. *Report of the twentieth meeting of the Scientific Committee*. (SC-CCAMLR-XX). Hobart: CCAMLR.

CCAMLR 2002. *Report of the twenty first meeting of the Scientific Committee*. (SC-CCAMLR-XXI). Hobart: CCAMLR.

CCAMLR 2003a. *Report of the twenty second meeting of the Scientific Committee*. (SC-CCAMLR-XXII). Hobart: CCAMLR.

CCAMLR 2003b. *Report of the twenty second meeting of the Commission*. Hobart: CCAMLR.

CCAMLR 2003c. *Schedule of Conservation Measures in force*. Hobart: CCAMLR.

CONSTABLE, A.J. 2002. CCAMLR ecosystem monitoring and management: Future work. *CCAMLR Science*, **9**, 233–256.

CONSTABLE, A.J. & DE LA MARE, W.K. 1996. A generalised model for evaluating yield and the long term status of fish stocks under conditions of uncertainty. *CCAMLR Science*, **3**, 31–54.

CONSTABLE, A.J., DE LA MARE, W.K., AGNEW, D.J., EVERSON, I. & MILLER, D. 2000. Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic MarineLiving Resources. *ICES Journal of Marine Science,* **57**, 778–791.

CONSTABLE, A. J., NICOL, S. & STRUTTON, P.G. 2003. Southern Ocean productivity in relation to spatial and temporal variation in the physical environment. *Journal of Geophysical Research Special Issue on Southern Ocean Variability*, **108**, 6-1–6-21

CROXALL, J.P. 1989. Use of indices of predator status and performance in CCAMLR fishery management strategies. *CCAMLR Selected Papers,* **1989**, 353–365.

CROXALL, J.P. 1994. BIOMASS - CCAMLR relations: past, present and future. *In* EL-SAYED, S.Z., *ed*. *Southern Ocean Ecology: the BIOMASS Perspective*. Cambridge, UK: Cambridge University Press, 339–353.

CROXALL, J.P. In press. Monitoring of predator-prey-environment interactions using multiple predator species: the South Georgia experience. *In* BOYD, I.L. & WANLESS, S., *eds*. *Management of marine ecosystems: monitoring change in upper trophic levels*. Cambridge: Cambridge University Press.

CROXALL, J.P., MCCANN, T.S., PRINCE, P.A. & ROTHERY, P. 1988. Reproductive performance of seabirds and seals at South Georgia and Signy Island 1976–1986: implications for Southern Ocean monitoring studies. *In* SAHRHAGE, D., *ed. Antarctic Ocean and resources variability*, Berlin: Springer, 261–285.

CROXALL, J.P., ROTHERY, P., PICKERING, S.P.C. & PRINCE, P.A. 1990. Reproductive performance, recruitment and survival of wandering albatrosses *Diomedea exulans* at Bird Island, South Georgia. *Journal of Animal Ecology*, **59**, 775–796.

CROXALL, J.P., PRINCE, P.A., ROTHERY, P. & WOOD, A.G. 1998. Population changes in albatrosses at South Georgia. *In* ROBERTSON, G. & GALES, R., *eds. Albatross biology and conservation*. Sydney, Australia: Surrey Beatty, 69–83.

CROXALL, J.P., TRATHAN, P.N. & MURPHY, E.J. 2002. Environmental change and Antarctic seabird populations. *Science*, **297**, 1510–1514.

DALZIELL, J. & DE POORTER, M. 1993. Seabird mortality in longline fisheries around South Georgia. *Polar Record*, **29**, 143–145.

DE LA MARE, W.K. & CONSTABLE, A.J. 2000. Utilising data from ecosystem monitoring for managing fisheries: development of statistical summaries of indices arising from the CCAMLR ecosystem monitoring programme. *CCAMLR Science*, **7**, 101–117.

EL-SAYED, S.Z. 1994. History, organization and accomplishments of the BIOMASS Program. *In* EL-SAYED, S.Z., *ed. Southern Ocean ecology: the BIOMASS perspective*. Cambridge: Cambridge University Press, 1–8.

ENDO, Y. 2000. Management of krill in Japanese waters. *In* EVERSON, I., *ed. Krill biology, ecology and fisheries.* Oxford: Blackwell Science, 284–299.

EVERSON, I. 2000. Management of krill fisheries in Canadian waters. *In* EVERSON, I., *ed. Krill biology, ecology and fisheries.* Oxford: Blackwell Science, 338–344.

EVERSON, I. & GOSS, C. 1991. Krill fishing activity in the southwest Atlantic. *Antarctic Science*, **3**, 351–358.

GRIFFIN, N. 2002b. Top ocean looks south. *Pacific Fishing*, April 2002, 32–34.

HAMOVITCH, E. 2002. Tapping krill. *Montreal Business Magazine* (July–August), 86–87.

HEWITT, R.P. & LOW, E.H.L. 2000. The fishery on Antarctic krill: defining an ecosystem approach to management. *Reviews in Fisheries Science,* **8**, 235–298.

HEWITT, R.P., WATKINS, J.L., NAGANOBU, M., TSHERNYSHKOV, P., BRIERLEY, A.S., DEMER, D.A., KASATKINA, S., TAKAO, Y., GOSS, C., MALYSHKO, A., BRANDON, M.A., KAWAGUCHI, S., SIEGEL, V., TRATHAN, P.N., EMERY, J.H., EVERSON, I. & MILLER, D.G.M. 2002. Setting a precautionary catch limit for Antarctic krill. *Oceanography,* **15**, 26–33.

HEWITT, R.P., DEMER, D.A. & EMERY, J.H. 2003. An 8-year cycle in krill biomass density inferred from acoustic surveys conducted in the vicinity of the South Shetland Islands during the austral summers of 1991/92 through 2001/2002. *Aquatic Living Resources*, **16**, 205–213.

HOFMANN, E.E. & MURPHY, E.J. 2004. Advection, krill, and Antarctic marine ecosystems. *Antarctic Science*, **16**, 487–499.

ICHII, T. 2000. Krill harvesting. *In* EVERSON, I., *ed. Krill biology, ecology and fisheries.* Oxford: Blackwell Science, 228–261.

JABOUR-GREEN, J. & NICOL, D. 2003. Bioprospecting in areas outside national jurisdiction: Antarctica and the Southern Ocean. *Melbourne Journal of International Law,* **4**, 77–111.

JONES, C.D. & HULL, M. 2003. The US commercial krill fishery in Area 48: development, fishing patterns and decision making. WG-EMM-02/18. *CCAMLR Scientific Abstracts*, **2002**.

KOCK, K.-H., *ed.* 2000. *Understanding CCAMLR's approach to management*. www.ccamlr.org/pu/E/pubs/am/toc.htm.

LOEB, V., SIEGEL, V., HOLM-HANSEN, O., HEWITT, R., FRASER, W., TRIVELPIECE, W. & TRIVELPIECE, S. 1997. Effects of sea-ice extent and krill or salp dominance on the Antarctic food web. *Nature*, **387**, 897–900.

MAKES, F. 1992. *Enzymatic examination of the authenticity of a painting attributed to Rembrandt. Krill enzymes as diagnostic tool for identification of "The Repentant Magdalene"*. Gothenburg: Institute of Conservation of the University of Gothenburg, 66 pp.

MEKKES, J.R., LE POOLE, I.C., DAS, P.K., KAMMEYER, A. & WESTERHOF, W. 1997. *In vitro* tissue-digesting properties of krill enzymes compared to fibrinolysin/DNAse, papain and placebo. *International Journal of Biochemistry and Cell Biology*, **29**, 703–706.

Miller, D.G. & Agnew, D.J. 2000. Krill fisheries in the Southern Ocean. *In* Everson, I., *ed. Krill: biology, ecology and fisheries*. Oxford: Blackwell Science, 300–337

New, M.B. & Wijkstrom, U.M. 2002. Use of fishmeal and fish oil in aquafeeds: Further thoughts on the fishmeal trap. *FAO Fisheries Circular No. 975, FIPP/C975.*

Nicol, S. & Endo, Y. 1997. *Krill fisheries of the world*. Rome: FAO Fisheries Technical Paper 367, 100 pp.

Nicol, S., Pauly, T., Bindoff, N.L. & Strutton, P.G. 2000a. "BROKE": a biological/oceanographic survey of the waters off East Antarctica (80–150°E) carried out in January–March 1996. *Deep-Sea Research II*, **47**, 2281–2298.

Nicol, S., Constable, A. & Pauly, T. 2000b. Estimates of circumpolar abundance of Antarctic krill based on recent acoustic density measurements. *CCAMLR Science,* **7**, 87–99.

Nicol, S., Forster, I. & Spence, J. 2000c. Products derived from krill. *In* Everson, I., *ed*. *Krill biology, ecology and fisheries*. Oxford: Blackwell Science, 262–283.

Nicol, S. & Foster, J. 2003. Recent trends in the fishery for Antarctic krill. *Aquatic Living Resources*, **16**, 42–45.

Pauly, D., Christensen, V., Froese, R. & Palomares, M.L. 2000. Fishing down aquatic food webs. *American Scientist*, **88**, 46–51.

Reid, K., Watkins, J.L., Croxall, J.P. & Murphy, E.J. 1999. Krill population dynamics at South Georgia 1991–1997, based on data from predators and nets. *Marine Ecology Progress Series*, **177**, 103–114.

Reid, K. & Croxall, J.P. 2001. Environmental response of upper trophic level predators reveals a system change in an Antarctic marine ecosystem. *Proceedings of the Royal Society,* **B268**, 377–384.

Reid, K., Murphy, E.J., Loeb, V. & Hewitt, R.P. 2002. Krill population dynamics in the Scotia Sea: variability in growth and mortality within a single population. *Journal of Marine Systems*, **36**, 1–10.

Reid, K., Croxall, J.P. & Murphy, E. In press. Monitoring krill population variability using seabirds and seals at South Georgia. *In* Boyd, I.L. & Wanless, S., *eds. Management of marine ecosystems: monitoring change in upper trophic levels*. Cambridge: Cambridge University Press.

Robertson, G., Moe, E., Haugen, R. & Wienecke, B. 2003. How fast do demersal longlines sink? *Fisheries Research,* **62**, 385–388

Rumsey, G.L. 1993. Fish meal and alternate sources of protein in fish feeds. Update 1993. *Fisheries*, **18**, 14–19.

Small, C. In press. *An evaluation of the environmental performance of southern hemisphere Regional Fishery Management Organisations, with particular attention to bycatch and incidental mortality of seabirds*. Cambridge: BirdLife International.

Soevik, T. & Breakkan, O.R. 1979. Fluoride in Antarctic krill (*Euphausia superba*) and Atlantic krill (*Meganyctiphanes norvegica*). *Journal of the Fisheries Research Board of Canada,* **36**, 1414–1416.

Tacon A.G. & Forster, I.P. 2001. Global trends and challenges to aquaculture and aquafeed development in the new millennium. *In International aquafeed directory and buyers guide 2001*. Turret RAI, Uxbridge, UK, 4–25.

Tenuta Filho, A. & Alvarenga, R.C.C. 1999. Reduction of the bioavailability of fluoride from Antarctic krill by calcium. *International Journal of Food Sciences and Nutrition,* **50**, 297–302.

Trathan, P.N., Agnew, D.J. Miller, D.G.M., Watkins, J.L., Everson, I., Thorley, M.R., Murphy, E., Murray, A.W.A. & Goss, C. 1992. *Krill biomass in Area 48 and Area 58: recalculations of FIBEX data.* Selected Scientific Papers, 1992 (SC-CAMLR-SSP/9). Hobart, Australia: CCAMLR, 157–181.

Yuan, X. 2004. ENSO-related impacts on Antarctic sea ice: a synthesis of phenomenon and mechanisms. *Antarctic Science*, **16**, 415–425.

Watters, G. 1996. By-catch of fishes captured by the krill fishing vessel *Chiyo Maru No. 2* in Statistical Area 58 (January to March 1995). *CCAMLR Science*, **3**, 111–123.

Weimerskirch, H., Brothers, N. & Jouventin, P. 1997. Population dynamics of wandering albatross *Diomedea exulans* and Amsterdam albatross *D. amsterdamensis* in the Indian Ocean and their relationships with longline fisheries: conservation implications. *Biological Conservation*, **79**, 257–270.