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Reconciling Fisheries with Conservation: Three Examples from the Southern Ocean

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Abstract.—Preservation of ecosystem structure is the guiding principle by which the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) endeavors to manage the harvests of living resources of the Southern Ocean (with the notable exception of marine mammals). The experiences of CCAMLR with regard to fisheries on Antarctic krill *Euphausia superba*, mackerel icefish *Champhsocephalus gunnari* and Patagonian toothfish *Dissostichus eleginoides* are reviewed. The unifying paradigm employed by CCAMLR is the application of a precautionary approach, which explicitly incorporates uncertainty in the analysis of risk of exceeding defined management criteria. Each fishery, however, presents a unique set of circumstances and unresolved concerns. While the current fishery for krill is small compared to the precautionary limit established by CCAMLR, fishing effort concentrated near colonies of land-breeding krill predators may pose a threat in addition to those posed by the broader-scale influence of climatic cycles and trends on krill production. Management of the fishery on mackerel icefish relies on frequent surveys and short-term population projections because of high variability in natural mortality and is further complicated by the dual role of icefish as both consumers of krill and alternative prey to krill predators. While CCAMLR management of the fishery on toothfish is based on longer-term projections and has demonstrated success in addressing incidental mortality of seabirds, large-scale misreporting of catches, particularly in the Indian Ocean sector, threatens to compromise the viability of the fishery. These concerns are discussed in the context of CCAMLR's long-term goal of feed-back management schemes, whereby conservation measures are adjusted in response to ecosystem monitoring.

Introduction

The history of exploitation of Antarctic marine living resources spans over two centuries. Intense and sporadic cycles of harvest began in the late 18th century when Antarctic fur seals were hunted to near extinction. The harvest of elephant seals, southern right whales, and some species of sub-Antarctic penguins followed in the 19th century. More recently, through the mid-20th century, increased whaling pressure caused the collapse of many of the great whale populations while explor-

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atory harvests of ice seals were initiated (for reviews see McElroy 1994; Kock 1994; Agnew and Nicol 1996). Today, all of the formerly exploited marine mammal populations are protected, but controlled harvesting in the Southern Ocean continues with fishing for krill, finfish, and crabs. With the single exception of cetaceans, the conservation of all living resources in the Southern Ocean is currently regulated under the umbrella of the Antarctic Treaty system.

The Antarctic Treaty came into force in 1961 when the 13 original Parties agreed to 1) ban military activities from the continent, 2) allow open access to their installations by other parties, and 3) neither acknowledge nor deny existing territorial claims by seven of the parties. While these terms were remarkable in their scope and precedence, they did not provide a framework for resolving many of the issues encumbered by human activities. These details were left to a series of protocols and conventions negotiated by the parties in subsequent years such as the Agreed Measures for the Conservation of Antarctic Flora and Fauna (1964), the Convention for the Conservation of Antarctic Seals (1972), the Protocol on Environmental Protection to the Antarctic Treaty (1991), and the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR).

The terms of CCAMLR were negotiated in the late 1970s when concern was expressed over the rapid rise in the harvest of Antarctic krill *Euphausia superba* and its central role in the pelagic marine ecosystem, as well as the decline of several finfish stocks (for reviews see Lagoni 1984; Stokke 1996, Vicuna 1996). Like the Antarctic Treaty, the terms were deceptively simple and precedent setting. The essence of the Convention is expressed in Article II, which states that the Convention is a conservation agreement but that conservation shall include "rational use." Rational use is further stipulated to be conducted so as to 1) prevent the abundance of a harvested species from falling below that which would ensure stable recruitment; 2) maintain ecological relationships between harvested and dependent species; and 3) minimize risk of change to the ecosystem that cannot be reversed in two or three decades. Article II also stipulates that environmental influences, both physical and biological, be considered in the estimation of risk of change to the ecosystem.

With these terms, CCAMLR became the first international fisheries agreement to specify that resource management shall be based on both a precautionary approach (in accordance with the mandate to minimize risk of change to ecosystem) and an ecosystem approach (in accordance with the mandate to consider both trophic interactions and physical forcing).

The Convention also specified a consensus based decision process, which afforded Members with fishing interests the power to veto any conservation measures that they considered to be overly restrictive. Other specifications included the establishment of a permanent Secretariat in Australia, the repository Member of the Convention, a policymaking body (the Commission) and a consultative body (the Scientific Committee). The structure was intended to allow the Commission to make informed decisions based on the best available science. These decisions are adopted by consensus and become legally binding on members after 180 d. There are currently 24 signatory members plus another 10 states acceding to the terms of the Convention.

During the first 10 years of the Convention's history, confrontational attitudes prevailed and few conservation measures were adopted. Although conservation-oriented members outnumbered fishing members, consensus was

required for action and there was a general resistance to any fishery restrictions. Furthermore, the annual harvest of krill was small relative to the estimates of consumption by krill predators and there was little scientific information available on which to assess the status of krill stocks and related ecosystem components. Instead the Scientific Committee and Commission used stock-specific approaches to focus on some of the more severely depleted finfish fisheries in dire need of regulation. It was during this period, however, that CCAMLR established an ecosystem monitoring program (CEMP), whose objectives were to detect change in the krill-centric ecosystem, and attribute the cause of change to either the action of the fishery or environmental variation.

Since the early 1990s, the effectiveness of the Convention has improved dramatically. A precautionary catch limit for krill was adopted. Management procedures are in place for seven assessed and three exploratory finfish fisheries. A catch documentation scheme has proven to be effective in controlling illegal international trade in Patagonian toothfish. And measures for mitigating catastrophic by-catches of seabirds adopted by CCAMLR are considered to be pioneering and have been widely emulated. The reasons for this positive change are manifold and interrelated. Large-scale krill harvesting did not develop as expected. Other fisheries did develop and more members found themselves with interests in both conservation and harvest. And political and economic disruptions in the fishing states (Russia and the Ukraine) of the former Soviet Union reduced their influence.

Consequently, work toward defining and implementing the far-reaching terms of the Convention has progressed substantially. The general approach adopted by CCAMLR for each fishery is to 1) develop operational definitions of the resource management guidelines contained in the Convention; 2) develop conservation criteria that quantify the definitions; 3) assess the risks of exceeding the criteria; and 4) adopt decision rules for controlling the fishery based on the assessment. Risk assessments have attempted to incorporate uncertainty regarding both the processes regulating population growth and the estimation of parameters, such that as more is known about the systems in which these resources are imbedded the less restrictive the regulatory controls will be (for reviews see Miller and Agnew 2000; Constable et al. 2000; Hewitt and Linen Low 2000).

Here we present three case studies of fisheries management by CCAMLR: the Antarctic krill, mackerel icefish *Champsocephalus gunnari* and Patagonian toothfish *Dissotichus eleginoides*. For each resource, brief overviews are presented of the fishery, the relevant natural history, assessment methods, and the management procedure. Also described are circumstances unique to each fishery and the concerns that remain to be resolved.

Antarctic Krill

Of the 85 species of euphausiids worldwide, Mauchline and Fisher (1969) list nine that are the most important in terms of their numbers and function in marine ecosystems. Of these nine species, Antarctic krill is the largest, the longest lived, and constitute the greatest biomass. They enjoy a circumpolar distribution throughout the Southern Ocean, although the highest densities appear to be associated with permanent large-scale cyclonic gyres (Amos 1984). These gyres are in turn associated with topographic features that influence the eastward flowing Antarctic Circumpolar Current and create exchanges with the East Wind drift, the latter flowing westward closer to the continent. The largest con-

centration of krill is present in the southwest Atlantic sector of the Southern Ocean (Marr 1962), along with large numbers of krill-consuming birds, seals, and whales. It is in this region, also known as the Scotia Sea, that the greatest geographic overlap exists between krill and their vertebrate predators (Laws 1977).

The importance of krill to the natural economy of the Antarctic marine ecosystem is impressive. Numerous colonies of krill predators, including fur seals, penguins, and other seabirds, are found throughout the South Shetland, South Orkney, South Georgia, and South Sandwich archipelagos—a string of island groups lying along the Scotia Ridge, which stretches from the tip of the Antarctic Peninsula, half-way across the Atlantic sector, and curves back toward the tip of South America defining the Scotia Sea. These land-breeding predators rely on ample concentrations of krill within their foraging ranges to sustain them and their offspring during the critical summer breeding season. Croll and Tershy (1998) estimated that 830,000 metric tons (mt) of krill are required during the summer months to maintain current population levels of penguins and seals breeding in the South Shetland Islands. Boyd (2002) estimated more than 10 times this amount was required by land breeding krill predators at South Georgia. Pelagic predators may consume more, but regional estimates are scarce. Everson (1984) estimated the annual consumption of krill throughout the Southern Ocean by baleen whales at 43 million mt, by seals at 128 million mt, by birds at 33 million mt, possibly 100 million mt by squid, and an unknown but substantial quantity by fish. Taken together these numbers indicate that a reasonable estimate of annual consumption of Antarctic krill by natural predators is between 150 and 300 million mt (Miller and Hampton 1989; Everson and de la Mare 1996).

The fishery on Antarctic krill began in the 1970s and quickly expanded to annual catches of 300,000–500,000 mt during the mid-1980s and early 1990s. Catches declined after 1992, coincident with political changes in the Soviet Union, and have since averaged approximately 100,000 mt per year. Currently six members participate in the fishery, producing products ranging from those destined for direct human consumption, to protein concentrates, pharmaceutical derivatives, chitin products, meal, and aquaculture feed. With the exception of the early exploratory years, all of the harvest has been taken from the Scotia Sea, in particular near the continental shelf breaks surrounding the South Shetland, South Orkney, and South Georgia island groups.

It has long been appreciated that krill are not evenly distributed throughout the Scotia Sea (Stein and Rakusa-Suszczewski 1984; Siegel 1988, Makarov et al. 1988; Miller and Hampton 1989). Their distribution is highly contagious with individual animals organized into swarms and layers that may extend tens of meters vertically and hundreds of meters horizontally. The swarms are grouped into clusters, and the clusters are associated with zones of water convergence, eddies, and gyres (Witek et al. 1988). Krill appear to move eastward through the Scotia Sea with the Antarctic Circumpolar Current, although the relative importance of passive transport versus active migration (either to maintain or change position) is not well understood. Likely sources of immigrants are the Bellingshausen Sea to the west and the Weddell Sea to the south. Within the Scotia Sea, krill spawn in the vicinity of the South Shetland and South Orkney Islands. Although they are abundant further to the north and east near South Georgia, they do not reproduce successfully there.

In the early 1990s, concerned about the potential effects of a rapidly expanding and un-

regulated krill fishery, CCAMLR employed a simple harvest control law, first proposed by Gulland (1971), and later refined by Beddington and Cooke (1983), whereby it is assumed that a fixed proportion of the unexploited biomass of a stock may be harvested on a sustainable basis. The terms of Article II of the Convention were given operational definitions and quantitative criteria. The first is to ensure that the population size remains large enough to produce a stable number of recruits. Accordingly, the probability that the spawning biomass in any one year falls below 20% of unexploited median spawning biomass should be 10% or less. The second is to ensure that relationships between harvested and dependent species are maintained. Accordingly, the median level of spawning biomass should be 75% or greater of the unexploited median spawning biomass. The third is to prevent changes to the ecosystem that cannot be reversed over 20 or 30 years. Accordingly, risks are to be evaluated over a 20-year time period.

Risks are evaluated by simulating hundreds of population trajectories using values of abundance, recruitment, growth, and mortality drawn from appropriate statistical distributions. An age-structured population model is used to generate distributions of population biomasses, both unexploited and exploited at various fishing levels. The first criterion is examined by comparing the distribution of lowest population biomasses over the period of each population trajectory and noting the fishing level at which 10% of this distribution is below 20% of the median unexploited biomass. The second criterion is examined by comparing the distribution of population biomasses at the end of each trajectory and noting the fishing level at which the median of this distribution is 75% of the median unexploited biomass. The third criterion is met by extending the trajectories over 20 years. The lower of the two fishing levels is accepted as the most precautionary.

In 1991 CCAMLR adopted a precautionary catch limit for krill in the Scotia Sea after conducting a risk assessment using an estimate of preexploitation biomass generated from acoustic data collected during the first international BIOMASS experiment (FIBEX) in 1981 (Trathan et al. 1995). A second multinational, multiship survey was conducted in 2000, and an updated estimate of krill biomass in the Scotia Sea (44.3 million mt), an estimate of acceptable fishing level (0.091), and a revised precautionary catch limit for krill (4 million mt) were adopted by CCAMLR (Hewitt et al. 2002, 2004a). The Commission further subdivided the catch limit in approximately equal proportions among four large FAO statistical areas encompassing the South Shetland, South Orkney, South Georgia and South Sandwich archipelagos. However, the Commission remained concerned that localized depletion of the krill resource could occur if all of the catch was taken within a small proportion of one of these areas and mandated that the total catch in the Scotia Sea shall not exceed 620,000 mt before the precautionary catch limit had been subdivided into small-scale management units.

The Commission's concern reflected an awareness of the assumptions implied in the procedure used to determine a precautionary catch limit. That is, a freely distributed population, evenly distributed predation pressure, and randomly determined recruitment. Evidence generated from fine-scale catch data, CEMP indices, krill surveys conducted in the vicinity of CEMP monitoring sites, and complementary studies suggests that these assumptions are not valid.

Virtually all of the krill catch is currently concentrated within 100 km of known breeding

colonies of krill predators, primarily Antarctic fur seals and Adelie, gentoo, chinstrap, and macaroni penguins. This implies a complete overlap between the area of fishing operations and the foraging ranges of these predators. Seasonal variability in fishing operations may mitigate potential interactions (e.g., the krill fishery near South Georgia has been conducted principally during the winter months when sea ice precludes access to the South Shetland and South Orkney areas) but concern remains that competition between krill trawlers and natural predators may be intense under certain conditions. Krill biomass densities within the foraging range of land-breeding predators in the South Shetland Islands have been shown to vary tenfold between years (Hewitt et al. 2003). The ratio of predator demand to standing stock of krill at South Georgia is several times higher than that at the South Shetland Islands (Everson and de la Mare 1996; Trathan et al. 1995; Boyd 2002) and reproductive failures among krill predator populations have been associated with low levels of krill density (Brierley et al. 1999; Croxall et al. 1999; Boyd and Murray 2001).

Evidence from monitoring also suggests that krill reproductive success may be dependent on multi-year changes in the physical environment (Loeb et al. 1997; Nicol et al. 2000; Brierley et al. 1999; White and Peterson 1996; Naganobu et al. 1999). During periods of equator-ward excursions of the southern boundary of the Antarctic Circumpolar Current, the development of sea ice is more extensive, populations of salps *Salpa thompsoni* (a pelagic tunicate postulated to be a competitor with krill for access to the springtime phytoplankton bloom) are displaced offshore, and both krill reproductive output and survival of their larvae are enhanced. During periods of poleward excursions of the southern boundary of the Antarctic Circumpolar Current, the development of wintertime sea ice is less extensive, salps are more abundant closer to shore, and krill reproductive success is depressed. These interactions may be confounded by a warming Antarctic Peninsula over the last 50 years (Vaughan and Doake 1996).

In principal CCAMLR has adopted a feedback approach to management of the krill fishery, by which management measures are adjusted in response to ecosystem monitoring. However, such a management procedure has yet to be fully developed and the procedure for establishing a precautionary catch limit outlined above was adopted as an interim measure. Full development of a management scheme based on monitoring will require: 1) delineation of small-scale management units to better address spatial heterogeneity; 2) elaboration of alternative management procedures including management objectives, required observations, assessment methods and decision rules; 3) operational models that capture relevant interactions between krill, their predators, the environment and the fishery which can be used to test the effectiveness of alternative management procedures; 4) enhancement of CCAMLRs ecosystem monitoring program; and 5) high resolution, real-time monitoring of the behavior of fishing vessels.

Fortunately, much of this work is currently in progress and preliminary results are encouraging. A window of opportunity may exist while the human demand for krill is relatively low, to establish a feedback management procedure based on ecosystem monitoring. If CCAMLR is able to take advantage of this opportunity the fishery will develop in reaction to an established management scheme rather than the reverse.

Mackerel Icefish

Commercial interest in the mackerel icefish began in the 1950s when Norwegian scientists began investigating species of potential importance around South Georgia (Olsen 1954, 1955). This was not followed up until a decade later when exploratory vessels of the former USSR began a series of exploratory fishery cruises into the Southern Ocean in the 1960's. Although the primary target at that time was krill (Moiseev 1970), this heralded the commencement of major fisheries for finfish (Everson 1984b).

Up to that time it had been assumed that the northern limit of the Antarctic Treaty Zone would be a reasonable descriptor for Southern Ocean fisheries. Unfortunately the bulk of these fisheries was taking place in waters around South Georgia and Kerguelen, islands that are well north of 60°S but oceanographically still within Antarctic waters. This meant that the catches were included in FAO Areas 41 (Southwestern Atlantic Ocean) and Area 51 (Western Indian Ocean) and since the species were unknown for these areas they were reported as unspecified demersal percomorphs (Everson 1977). Although the bulk of these early catches were marbled rockcod *Notothenia rossii*, some were almost certainly mackerel icefish although, unfortunately, the amounts are unknown. In the absence of any controls on the extent of the fisheries in those early years, considerable concern was expressed that these catches were unsustainable.

Icefish belong to that group of vertebrates, Channichthyidae, that are unique by virtue of having no hemoglobin or functional erythrocytes. Mackerel icefish are restricted almost entirely to the ice shelves of the peri-Antarctic zone: South Georgia, the South Shetlands, and South Orkneys in the Atlantic sector and Heard, McDonald, and Kerguelen in the Indian Ocean sector. They are rarely found in water deeper than about 400 m. The presence of extensive areas of deep water between most of these localities means that the populations in each are more or less isolated and as such have been treated as separate stocks for management purposes. The standing stock in all of these localities has declined partly because all have been subject to significant levels of commercial fishing over the past 30 years. Over the same period, there have been other changes in the ecosystem and it is important to consider these in an overall analysis.

In a recent review, Kock and Everson (2003) considered the following additional factors affecting the abundance of mackerel icefish:

- The role of mackerel icefish as prey for some top-level predators,
- The role of mackerel icefish as predators of krill,
- Changes in krill abundance, and
- Changes in low-Antarctic ecosystems caused by regional warming in parts of the Southern Ocean.

Although preyed upon by a number of species, the dominant predators of mackerel icefish are Antarctic fur seal *Arctocephalus gazella*, black-browed albatross *Thalassarche melanophrys*, gray-headed albatross *Diomedea chrysostoma* and gentoo penguin *Pygoscelis papua*. Two points warrant consideration in an assessment of the impact of these predators. Firstly, there is the question of the abundance of the predators and in that context there is known to have been a significant and continuous increase in fur seals over the period while the population sizes of the avian predators have remained more or less stable

or else have been in slow decline. From this perspective, assuming a constant predation pressure, the greatest change would have come from the impact of fur seals. The second point regarding predation pressure relates to the dietary preference of the predators. The dietary composition of all the predators listed above does vary in response to the availability of a preferred item. Thus, when krill abundance is low within the foraging range or foraging depth of fur seals or black-browed albatross, they tend to eat more mackerel icefish. Over the 30 years of the mackerel icefish fishery, there has been an increasing impact due to predation by fur seals in addition to that caused by variation in the availability of krill.

The dominant component in the diet of mackerel icefish in the low-Antarctic regions, the localities of all current fisheries, is euphausiids, *E. superba* in the Atlantic sector and *E. vallentini* in the Indian Ocean. The energy content and conversion efficiency of euaphsuiids and mysids as food for mackerel icefish is considered to be higher than that for the hyperiid amphipod *Themisto gaudichaudii*, the major prey species eaten when krill are scarce. Arising from this, a condition index, the ratio of observed mass to expected mass of an individual fish, varies with the availability of krill (Everson and Kock 2001). The availability of krill as food is also thought to affect the development rates of the gonads of mackerel icefish in the period leading up to spawning (Everson et al. 2000). Thus it is clear that the availability and type of food, by affecting condition and reproduction, is likely to affect survivorship and, potentially, subsequent recruitment.

The effects of predation on mackerel icefish and their feeding status outlined above comprise the forms of biological control in the system. Being central to the system, the ecology of krill also has an effect. This has been studied in greatest detail in the Atlantic sector, a region in which two forces are dominant. The first is the extent to which krill are carried on the circum-polar current to the vicinity of South Georgia providing what are often termed "good" and "poor" krill years. The second component is longer term changes arising from global warming.

The key components in this context are growth and mortality rates considered in the light of variation in standing stock.

Age determination has always been a problem with mackerel icefish because they do not possess scales and the fine structure within otoliths has proven difficult to interpret. Although some studies have used age estimates from otoliths, these have required corroboration through length-density analyses. Arising from this, there is a great deal of variation in the estimated parameter values that have been used for assessments (Everson 2003). The parameter values for the von Bertalanffy growth equation in current use are as follows

Locality	K	L_∞ (cm)	t_0 (years)
South Georgia	0.17	55.76	–0.580
Heard Island	0.323	45.7	+0.358

This indicates that at South Georgia growth is slower than at Heard Island but leads to a greater maximum size. It is not clear why such a difference should be present because comparative studies have not been undertaken. There is no reason to suppose that there are differences at the species level between the two localities, hence the differences are most likely ecological. Another key point is that at neither site are fish older than about 5 or 6 years frequently found indicating that growth is likely to be fairly rapid and natural mortality high.

Some limited information is available from which estimates of natural mortality can be made prior to the onset of commercial fishing. Using several different methods, Everson (1998) estimated a natural mortality coefficient (*M*) of 0.48 for the preexploitation stock. Compared to other fish species with similar growth characteristics, this value appears high, a feature that is in line with other Antarctic fish species as noted by Pauly (1980).

A major decline in the standing stock around 1991 has meant that there has been relatively little commercial interest in fishing at South Georgia over the past decade. Accordingly, the most recent estimates of total mortality, which can be derived directly from age–class strength, are likely to provide a reasonable proxy for natural mortality. Rather surprisingly, nearly all the recent estimates are much higher than the 0.48 estimated for the preexploitation stock. Independent estimates for the 1999–2000 season gave values of 0.71 and 0.87 while for the 1996–97 season there were values of 1.56 and 1.19 respectively. Such differences are thought to be related to changes in predation pressure, particularly by fur seals. Krill availability may also have an influence as the higher values of *M* are associated with poor krill years.

As a result of a series of surveys over almost 20 years, it has been possible to follow the changes that have occurred around South Georgia. In the 1980s, years when commercial fishing was active, much of the year-to-year variation was assumed to be related to the commercial fishery. Unfortunately, in 1991 there was a major reduction in standing stock which might have been fishery related. However, the large interannual variations that have been observed in more recent years cannot be attributed to commercial fishing.

A species such as mackerel icefish which is relatively fast growing and for which length–density distributions provide good indications of year–class strength might be thought to be suitable for conventional cohort analysis. Unfortunately, the high interannual variation in *M* has made it impossible to resolve such analyses and, with the almost complete absence of commercial fishing throughout most of the 1990s, alternative approaches to assessment were required.

The unexplained and high variation in *M* and standing stock indicate the need for a precautionary approach that caters for as much uncertainty as possible. The most important component in applying the precautionary approach is to ensure that the uncertainty associated with the chance of a high *M* between the most recent survey and the commencement of fishing is incorporated into the management advice.

These ideas have been incorporated into a short-term projection model. The criterion applied was to calculate the fishing mortality that would result in a probability of no more than 5% that the spawning stock after fishing would be less than 75% of the level which would have occurred in the absence of any fishing.

Patagonian Toothfish *Dissostichus eleginiodes*

Currently the most economically important species in the Southern Ocean is the Patagonian toothfish *Dissostichus eleginoides* a species within the family Nototheniidae. The current worldwide demand and high unit price for Patagonian toothfish presents considerable challenges for CCAMLR when attempting to implement a sound management regime.

Catches of this species were first reported in the Convention area in the mid 1970s, though there has been evidence of some take by the Soviet fishery near the end of the 1960s (Kock 1992). The long-line fishery for toothfish was introduced at South Georgia and Kerguelan near the end of the 1980s, at which time the yields increased considerably. Currently, toothfish is fished primarily using long-line gear, although in limited areas trawl gear has been employed as well as pots. Since the mid-1990s, reported catches in the Convention area from all gear types have been on the order of 12,000–13,000 mt, with a high of 16,394 during the 1999–2000 fishing season (CCAMLR 2003a). Catches since the late 1990s have been taken primarily around South Georgia in the Atlantic Sector, Kerguelen, and McDonald and Heard Islands in the Indian sector, with lesser amounts taken around Crozet, Prince Edward, and Marion Islands.

The geographic distribution of the Patagonian toothfish is circumpolar, occurring along slope waters in the Pacific off Chile from 30°S to Cape Horn (Fischer and Hureau 1985); in the southern Atlantic along the coast and slope waters of southern Patagonia and Argentina; the islands and banks in sub-Antarctic waters including South Georgia, Malvinas/Falkland Islands; Shag Rocks and the islands of the Scotia Arc (Gon and Heemstra 1990); and to south of South Africa and south of New Zealand including the sub-Antarctic waters of the Indian Ocean and Macquarie Island on the Indo-Pacific boundary of the Southern Ocean (Lloris and Rucabado 1991). Southernmost records of the species occur near the Antarctic Peninsula (Fischer and Hureau 1985). The bathymetric range extends to 2,500–3,000 m. A species similar in many regards to Patagonian toothfish is the Antarctic toothfish, *D. mawsoni*. While superficially similar to the Patagonian toothfish, the Antarctic toothfish has a more high Antarctic coastal distribution while the Patagonian toothfish is more likely to be encountered on seamounts associated with sub-Antarctic archipelagos near or outside the Antarctic convergence (Smith and Gaffney 2000). There is evidence that the two species ranges may overlap in certain places.

There are several characteristics of the life history of Patagonian toothfish that make the species vulnerable to overexploitation through nonoptimal harvesting practices. The production of large yolky eggs (Everson 1984b) implies that fecundity of Patagonian toothfish is comparatively low, with potential fecundity ranging from 238,000–546,000 eggs (Kock 1992). In addition, Patagonian toothfish mature at a relatively late age, with age at first spawning from 8 to 10 years of age (Kock 1992). They likely spawn on the slopes of South Georgia and the Kerguelan Islands (Kellermann and Kock 1988; Kellermann 1990; Koubbi et al. 1990). The species, along with most Antarctic Nototheniid fish, mature at about half of their maximum length (Kock and Everson 1998), although there remains uncertainty over size at sexual maturity.

The species is relatively slow growing and long lived. Estimates of age and growth have been made based on samples taken in the southwest Atlantic (Zakharov and Frolkina 1976), the Kerguelen Islands (Hureau and Ozuf-Costaz 1980), and regions in the Indo-Pacific boundary of the Southern Ocean (Horn 1998). Due to the longevity and slow growth of the species, aging of otoliths and scales is imprecise. Zakharov and Frolkina (1976) estimated a 20–25 year longevity, though it is widely believed that these fish likely live to be 40–50 years old, or older. Estimates of natural mortality for all stocks of Patagonian toothfish are currently very poorly understood. At South Georgia and Heard Island, natural morality is approximated as half of the cur-

rent best estimate of the growth parameter *K*. There is a considerable need to conduct further research toward better estimates of this important population parameter, and the processes that influence it.

The Patagonian toothfish is an opportunistic carnivore that mainly feeds on fish, cephalopods, and crustaceans. However, it has been observed that the dietary habits are influenced by biogeographical differences, local availability of food items, depth and predator size (Goldsworthy et al. 2002; Pilling et al. 2001). This species is preyed upon by a variety of bird and marine mammal species, including albatrosses (Cherel et al. 2002) and seals (Green et al. 1998).

The current assessment methodology adopted by CCAMLR as the basis for setting total allowable catches is based on an estimate of long-term annual yield (Constable and de la Mare 1996; Constable et al. 2002). This estimate factors in life history characteristics, recruitment projections from recruitment trawl surveys, changes in the fishing patterns of the commercial fleet, and in the case of South Georgia, an adjustment using standardized catch rates. The long-term approach evaluates different levels of projected catch that satisfy adopted decision rules pertaining to the estimated median spawning stock biomass over the lifetime of the cohort. Because Patagonian toothfish is a long lived species, this projection has been carried out to 55 years in recent assessments.

There are two decision rules adopted by CCAMLR to evaluate a long-term precautionary yield for Patagonian toothfish. These are 1) the probability that the spawning stock biomass during the projection period falls below 20% of the median preexploitation spawning biomass should be 10% or less and 2) the ratio of the median spawning biomass to the median preexploitation spawning biomass should be 0.50 or greater. The estimate of precautionary long-term yield is that which first triggers either of these decision rules. Total allowable catches are set in a similar manner for each management area within the Convention area.

This approach to setting long-term yields does not directly take other components of the Antarctic ecosystem into account, with the exception of the second decision rule specifying an escapement of fish biomass that can potentially be used towards maintenance of the ecosystem. However, conservation measures for this fishery other than long term annual yield provide considerable safeguards to other components of the ecosystem. These include measures that shut the fishery down or move it to a different location if incidental bycatch of skates or rattails exceeds a prescribed level, line weighting requirements and other required seabird mitigation measures, and area or seasonal closures to protect seabirds during their breeding season.

A major component of the management of this species is based on the incidental mortality of seabirds. Declines in seabird populations in the Southern Ocean have been linked to longlining operations (Prince et al. 1997; Weimerskirch et al. 1997; Ashford and Croxall 1998). Seabirds in jeopardy include several species of endangered albatross. Thus, CCAMLR has imposed a number of required seabird mitigation measures for the Patagonian toothfish fishery. Recent evidence suggests that these measures, when fully implemented, have considerably reduced seabird bycatch in the legal fishery. Nevertheless it is likely that seabird mitigation measures are not employed by illegal fishers. Thus, the illegal catch of *Dissositchus* spp. may substantially disturb the Southern Ocean ecosystem.

A primary threat to Patagonian toothfish in the Convention area is illegal, unreported, and unregulated (IUU) fishing and trade in this species, particularly in the Indian Ocean sector. Despite conservation measures imposed by CCAMLR, a considerable proportion of catches taken in CCAMLR waters and sold in international markets since 1996 has been the result of illegal exploitation. For example, the estimated unreported catch of Patagonian toothfish in CCAMLR waters during the 2002–03 fishing season was around 10,070 mt, about 39% of the total *Dissostichus* spp. catch (CCAMLR 2003b). During the previous year, about 44% of the total take in the Convention area was illegal. With the annual value of the illegal catch in the hundreds of millions of U.S. dollars, there continues to be an incentive to harvest this species illegally.

Current management and conservation measures for Patagonian toothfish include precautionary total allowable catch limits by each management area, area and season closures, a catch documentation scheme, mandatory coverage by satellite-based vessel monitoring systems, mandatory observers on each vessel, prohibition of directed fishing except in accordance with specific conservation measures, a requirement that members prohibit landings from nonparty vessels that have been sighted in CCAMLR waters without proof that fish were transhipped or caught outside CCAMLR waters, an agreement to assess the potential viability of trade restrictive measures against nations whose vessels violate CCAMLR conservation measures, and vessel identification and marking requirements. The seriousness of illegal fishing for Patagonian toothfish, as well as the threat to undermining the CCAMLR management measures, is well understood.

Although the management regime for Patagonian toothfish is not based on directly factoring in elements of the Antarctic ecosystem, the multifaceted approach employed by CCAMLR for this species appears to be ecologically suitable based on several factors. The prey species of Patagonian toothfish are not harvested commercially, none of the predator species are exploited (with the indirect exception of incidental mortality by vessels not using seabird mitigation measures), and the species is long lived and less impacted by short term changes in the ecosystem that may impact krill and mackerel icefish. Nevertheless, the high worldwide demand and considerable economic value continue to foster illegal fishing practices which challenge the successful sustainable management of this species.

Concluding Remarks

The hallmark of the CCAMLR approach to resource management is an assessment of the risks of exceeding defined management criteria. The tool of choice for risk assessment in the CCAMLR forum has been a simulation population model with input parameter values specified as probability distribution functions and output specified as distributions of the relevant reference criteria. One implication of this approach is that high levels of uncertainty lead to broad distributions and conservative management. Conversely, more data will contribute to higher precision and less restrictive management.

One advantage of this approach is that the process of setting management objectives and acceptable levels of risk can be accomplished in a political forum. The assessments and application of decision rules can then be accomplished in a scientific forum. This allows the analysis of risk and the provision of advice to proceed with less ambiguity (Constable et al. 2000).

CCAMLR has made good progress in defining and implementing the far-reaching terms

of the Convention. The first specification of Article II of the Convention, that is to prevent the level of a harvested population from falling below that which would ensure stable recruitment, has been interpreted as the protection of a threshold level of spawning biomass. The second specification of Article II, that is to preserve ecological relationships, has been interpreted as the protection of a threshold level of escapement.

The specific criteria are somewhat arbitrary and can be adjusted as more information becomes available regarding the population dynamics of the harvested resource, the response of the ecosystem to removals of the resource, and the influence of exogenous factors. The overall framework is also flexible and can accommodate restatement of management objectives and reformulation of the criteria used to ensure that the objectives are met. What does remain constant is the explicit incorporation of natural variability in population parameters and uncertainty in their estimation, in the evaluation of risk associated with various harvest rates.

The three case studies outlined here illustrate the application of the CCAMLR approach to resource management as well as the unique aspects of each fishery:

•In the case of the krill fishery, evaluation of risk was accomplished on a region-wide basis. Although the total harvest in a region may be acceptable, concern remains regarding the spatial concentration of land-breeding predators and fishing pressure in the same localized area at the same time. These predators act as central place foragers during the breeding season and may be vulnerable to localized depletions of their prey field. On a broader scale, concern remains regarding the incorporation of climatic cycles and long-term trends on krill production into a management procedure.

•In the case of the mackerel icefish fishery, estimation of the risk of exceeding a single criterion, that is preservation of a threshold spawning biomass, is complicated by the high variability in natural mortality and the need for short-term population projections. The application of an ecosystem approach will require the development of conceptual definitions of the role of icefish in an ecosystem model where they are consumers of krill, alternative prey to krill, and the target of a fishery.

•In the case of the Patagonian toothfish fishery, evaluation of risk was accomplished using a long-term yield model and reasonable parameter distributions. Although escapement is set at a relatively low value, the principal impact of the fishery has been on seabird populations via long-line bycatch. Mitigation measures have substantially reduced this impact, but IUU fishing threatens to undermine the conservation of threatened seabirds, as well as the rational management of the fishery and the effectiveness of the Convention.

With regard to development of the preferred management approach of CCAMLR, that is, a scheme whereby conservation measures are adjusted in response to indices generated from monitoring critical ecosystem processes, it would appear that the krill fishery provides the most reasonable expectation of success. The costs may be considerable, however. The operational framework will require additional development and testing. The existing ecosystem monitoring program will require expansion in terms of what is measured and the network of monitoring sites. More stringent reporting and observer requirements for fishing vessels will need to be imposed. And most importantly, the fishery may be restricted from operating in its traditional fishing grounds under certain circumstances (Hewitt et al. 2004b).

It is reasonable, however, to expect that these costs may be absorbed in a fishery developing under controlled conditions. On the other hand, if the human demand for products derived from krill increases rapidly, Members may experience increasing pressure to appease competing economic interests and political agendas. In addition, interest in fishing for krill might be generated in states that are not members of CCAMLR, further complicating the political landscape. This is why it is important for CCAMLR to take advantage of the current window of opportunity. If the krill fishery were to expand, a management procedure would be in place to minimize its impact on the krill-centric ecosystem. Even if the fishery did not develop further, the experience gained could be of value to other fisheries worldwide which share one or more common traits (e.g., targeted on a prey species, regulated by international agreement, the agreement is committed to preserving integrity of the ecosystem, and the kinds of information and rules for its use are evolving as more is learned about the system). For further discussion on the possible economic, political, and ecological consequences of developing krill fisheries see Nicol and Endo (1999) and Hewitt and Linen Low (2000).

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