Sustainable Management in the Southern Ocean: CCAMLR Science

Denzil Miller

Denzil Miller, Institute for Marine and Antarctic Studies, University of Tasmania, Private Bag 129, Hobart, TAS, 7001 Australia. Correspondence: denzilgmiller@gmail.com.

ABSTRACT. The Antarctic Treaty System promotes science as the basis for conserving and managing Antarctic resources. The 1980 Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention) further advocates science, as well as a precautionary approach and ecosystem perspective to manage harvesting of Antarctic marine living resources. This review presents case studies to illustrate the CAMLR Commission's (CCAMLR) use of science, precaution, and an ecosystem approach to managing Antarctic fisheries. The case studies illustrate CCAMLR's use of small-scale management units, bycatch measures, spatial management measures, and ecosystem-directed initiatives. These various studies highlight the value of science to CCAMLR's management efforts and the utility of CCAMLR as a model of large-scale marine ecosystem management.

INTRODUCTION

The 1959 Antarctic Treaty stands alone as an instrument of conflict prevention, strategic accommodation, and political cooperation, largely because of the sovereignty accommodations in Article IV (Zumberge and Kimball, 1986). Most notably, Articles II and III of the Antarctic Treaty provide for "freedom of scientific investigation in Antarctica" and promote "international cooperation in scientific investigation." Consequently, the freedom of scientific investigation in Antarctica may be viewed as a key element in the Antarctic Treaty's promotion of peace, cooperation, and the progress of all humankind.

However, things were not always this way. During the nineteenth and twentieth centuries, sealers and whalers hunted fur seals (*Arctocephalus gazellae*), elephant seals (*Mirounga leonina*), and the great whales (predominantly baleen whales, *Baleonoptera* spp.) in the Southern Ocean nearly to extinction.[1] Indeed, the Antarctic Treaty responds to this history by seeking to preserve and conserve the Antarctic's living resources (Article IX, paragraph 1(f)).

Two subsequent agreements underscored the Antarctic Treaty's conservation "ethic": the 1964 Agreed Measures for the Conservation of Antarctic Fauna and Flora (Agreed Measures) and the 1972 Convention for the Conservation of Antarctic Seals (CCAS). The latter aims to "promote and achieve the objectives of protection, scientific study and rational use of Antarctic seals, and to maintain a satisfactory balance within the ecological system." Together, the

Antarctic Treaty, Agreed Measures, and CCAS became the founding elements of the Antarctic Treaty System (ATS).[2]

Extensive harvesting of finfish in the Subantarctic during the late 1960s and mid-1970s and an emerging interest in large-scale krill (*Euphausia superba*) exploitation raised concerns about fisheries sustainability in the Antarctic Treaty area (south of 60°S) and beyond. In response, Recommendation VIII-10 from the 1975 Eighth Antarctic Treaty Consultative Meeting (ATCM VIII) noted the need to "promote and achieve within the framework of the Antarctic Treaty, the objectives of protection, scientific study and rational use of [Antarctic] marine living resources." Again, the importance of science was recognised as a basis for the protection and rational (i.e., sustainable) use of such resources.

In 1977, the Scientific Committee on Antarctic Research (SCAR) and the Scientific Committee on Oceanic Research (SCOR) sponsored the Biological Investigations of Marine Antarctic Systems and Stocks (BIOMASS) program to "gain a deeper understanding of the structure and dynamic functioning of the Antarctic marine ecosystem as a basis for the future management of potential living resources" (El-Sayed, 1994:3). Together with three United Nations Food and Agriculture Organisation reports (Eddie, 1977; Everson, 1977; Grantham, 1977), BIOMASS highlighted the importance of krill as a keystone species in the Antarctic marine ecosystem.

Growing recognition of the ecosystem role of krill heightened concerns that its large-scale exploitation could have severe repercussions for Antarctic birds, seals, and whales that depend on it (Mitchell and Sandbrook, 1980). Over the next eight years, BIOMASS sponsored substantial research (including the first large-scale acoustic assessment of krill abundance in 1981, the First International BIOMASS Experiment) to investigate the ecosystem vulnerability of unsustainable krill harvesting (El-Sayed, 1994).

At the same time, Recommendation IX-2 from the Ninth Antarctic Treaty Consultative Meeting (1977) called on Treaty Parties to contribute to scientific research on Antarctic marine living resources, observe interim guidelines on their conservation, and schedule a special meeting to establish a conservation regime for these resources. This Second Special Antarctic Consultative Meeting comprised a series of meetings from 1978 to 1980 and concluded with the signing of the Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention, hereinafter referred to as the "Convention" unless otherwise indicated) in Canberra on 20 May 1980.[3] The Convention entered into force on 7 April 1982.

Although developed under the Antarctic Treaty's patronage, the CAMLR Convention stands alone as a legally binding agreement, and its attached Commission has its own legal personality.[4] The Convention applies to a broader area than the Antarctic Treaty and sets the northern boundary of the Antarctic marine ecosystem as the Antarctic Convergence, now known as the Antarctic Polar Front (Convention Article I) (Figure 1). The convergence is a circum-Antarctic, biogeographic boundary where cold, northward-flowing Antarctic waters sink beneath warmer southward-moving subtropical waters. South of the convergence, krill is the dominant species (Miller and Hampton, 1988) and therefore key to understanding and managing the Antarctic ecosystem.

Article I of the CAMLR Convention identifies Antarctic marine living resources as "populations of fin fish, molluscs, crustaceans and all other species of living organisms, including birds, found south of the Antarctic Convergence." The Antarctic marine ecosystem is defined as the "complex of relationships of Antarctic marine living resources with each other and the physical environment."

In the remainder of this paper, I use case studies to illustrate the crucial role of science in addressing the Convention's key objectives. It will be shown that science has come to underpin CCAMLR's standing as "the leader to follow" (Willock and Lack, 2006) in sustainable management of marine living resources.

CONVENTION OBJECTIVES AND THE ROLE OF SCIENCE

CONVENTION OBJECTIVES

The Convention's primary objective is "the conservation of Antarctic marine living resources" (Article II, paragraph 2), with the term "conservation" being considered to include "rational use." Article II, paragraph 3, indicates that any harvesting and associated activities in the Convention area should be conducted in accordance with the Convention and with the principles of conservation outlined in paragraphs 3(a) to 3(c). These principles include

- "prevention of decrease in the size of any harvested population to levels below those which ensure its stable recruitment";
- "maintenance of the ecological relationships between harvested, dependent and related populations of Antarctic marine living resources"; and

FIGURE 1. The CCAMLR area, showing boundaries, statistical areas, and fishing grounds.

- "prevention of changes or minimisation of the risk of changes in the marine ecosystem which are not potentially reversible over two or three decades."

The potential changes specifically identified include direct and indirect impacts of harvesting, the effects of alien (i.e., introduced) species, and the effects of environmental change(s). Under Article II, the management approach adopted by CCAMLR is characterised as being

- "precautionary," which means that CCAMLR collects data as it can, then weighs the extent and effect of uncertainties and gaps (i.e., "deficiencies") in such data before taking a management decision; and

- based on an "ecosystem" approach, which ideally takes into account the delicate and complex relationships between organisms (of all sizes) and physical processes (such as currents, sea temperature, etc.) that constitute or impact the Antarctic marine ecosystem.

The Convention thus not only regulates fishing for target species but also aims to ensure that "harvesting activity" does not compromise other species or harm the environment.

Since the Convention's entry into force, the ecosystem and precautionary approaches in Article II have both directed and challenged CCAMLR's conservation efforts (Constable et al., 2000; Miller, 2002). The ecological

uncertainties associated with full and effective implementation of the Convention's provisions have forced innovative thinking to provide a holistic, scientific, and ecologically based approach to regulate fishing on target resources and minimise the indirect effects of harvesting on the Antarctic marine ecosystem as a whole.

THE ROLE OF SCIENCE

Article IX, paragraph 1(f), requires that CCAMLR Conservation Measures (CMs) be formulated, adopted, or revised on "the basis of the best scientific evidence available" subject to the provisions of paragraph 5 in the same article.[5] For that purpose, CCAMLR must take full account of any relevant measures or regulations adopted by the ATCM or by existing fisheries commissions that manage target species that enter the Convention area. This requirement raises questions as to what scientific evidence is required and how that evidence is to be integrated into the CCAMLR management process.

THE SCIENTIFIC BASIS FOR CCAMLR MANAGEMENT

General Basis

The term "scientific evidence" in Convention Article IX, paragraph 1(f), implies that scientific information, or advice, should be formally presented to CCAMLR for management purposes. In 1990 (CCAMLR, 1990: paragraph 7.6), the Commission clearly endorsed this assumption and agreed that "it should regard the Scientific Committee as the source of the best scientific evidence available," an agreement that effectively endorses the provenance of the Scientific Committee's scientific advice.[6]

One of the first scientific challenges faced by CCAMLR was to use a spatially explicit, iterative, interactive, and scientific process to describe the scale-dependent organization of species such as krill (Figure 2). To that end, CCAMLR's approach to fishery management can be viewed as a series of interdependent ecological associations of which fishing (Miller, 2000), individual species, and their ecological interactions are bound in space and time. By specifically accounting for key ecological factors, this approach facilitates assessment of "ecosystem status" and "health," as well as the scientific and systematic development of sustainable management measures for krill in particular (Everson, 2002).[7]

Much has been written about CCAMLR's management approach (e.g. Agnew, 1997; Constable et al., 2000; Constable, 2002; Everson, 2002; Miller, 2002), and Figure

3 summarises its early evolution for the krill fishery. Nevertheless, the question of how to manage fisheries in an ecosystem (i.e., multispecies) context is an ongoing and difficult issue, as well as one that particularly vexes CCAMLR (Constable, 2005).

CCAMLR Ecosystem Monitoring Program

The CCAMLR Ecosystem Monitoring Program (CEMP) was initiated in 1985 (Agnew, 1997) to improve CCAMLR's understanding of potential interactions between fisheries, harvested species, and the environment. To follow an ecosystem-based management approach, Constable (2002) has indicated (Figure 4) that CCAMLR should take explicit account of harvesting on target, dependent, and related species. To that end, CEMP focuses on monitoring key life history parameters of selected dependent, or "indicator," species likely to be affected by the availability of harvested species (Agnew, 1997; Miller, 2007).

Therefore, CCAMLR must not only take into account the best available scientific information in their quest to meet the Convention's objectives, but also specifically allow for incomplete knowledge of ecosystem function(s) and uncertainty in the available information (Miller, 2007). To the extent possible, actual resource use is preceded and/or accompanied by surveys to assess resource potential, to monitor resource status, and to provide for associated analyses of ancillary data. The approach is not to manage the Antarctic marine ecosystem per se but, rather, to regulate human activities (i.e., harvesting) in that system. Science is the means to achieve this operationally (Butterworth, 1986), a point well illustrated by the temporal and spatial confines of "biophysical" interactions and the "fishery" illustrated in Figure 2.

CCAMLR's scientifically based management approach relies on four key actions to achieve the conservation principles outlined in Convention Article II, paragraph 3: (1) development of operational objectives ("measures") to determine the desired/agreed status for relevant species or ecosystem features, (2) development of methods to assess ecosystem status, (3) elaboration of decision rules to control harvesting in a manner that meets the Convention's objectives, and (4) development of methods to address uncertainty (including ecosystem functional ["physical world"] uncertainty). The outcomes of such an approach aim to establish scientific consensus in such a way that the consequence of various management actions can be identified and clearly understood.

To be effective, the CCAMLR management approach relies on clearly identified scientific requirements. In effect,

FIGURE 2. The spatial and temporal structure of krill distribution in relation to other Antarctic marine ecosystem components, the physical environment, and the fishery (after Miller, 2002).

FIGURE 3. The CCAMLR's management approach to address Convention Article II objectives (after Miller, 2002). See text for explanation of various acronyms and activities.

it highlights the need, mandated by Article II, to (1) apply correct and timely decisions consistent with CCAMLR conservation principles, (2) undertake monitoring of sufficient power to prevent harvests from negatively affecting dependent predators, (3) allow sufficient time to detect and rectify harvest-induced changes in the ecosystem within two or three decades, and (4) refine precautionary assessments of harvested stock yield to account for new estimates of key demographic parameters. The approach also requires that (5) the precautionary yield of a target species such as krill is equally divided into small-scale management units (SSMUs) of appropriate scale to improve predictive power and spread any risk of irreversible ecosystem changes and (6) the development of operational objectives for nonharvested species to account for

uncertainties is associated with ecosystem function and dynamic relationships among predators, particularly between predators and prey. All these considerations require scientific definition, elaboration, and monitoring.

The overall CCAMLR management procedure thus comprises a set of rules to adjust harvest levels on the basis of scientifically objective assessments (Kock, 2000). These rules are sufficiently rigorous and flexible to ensure that the conservation objectives illustrated have a high probability of being met. In practice, the status ("health") of the Antarctic marine ecosystem is effectively observed through monitoring (i.e., via CEMP). Ideally, regular assessments account for uncertainty associated with ecosystem function as well as potential relationships between monitoring and key ecosystem components and properties, including

FIGURE 4. An ecosystem-based approach to manage effects of fishing on dependent and related species (adapted from Constable, 2002, with permission). Assessments (solid boxes) lead to decision rules for adjusting harvest controls to meet operational objectives. The physical world (dashed boxes) reflects ecosystem's actual state as observed by monitoring (e.g., via CEMP). Assessments take into account the uncertainty about how the physical world functions as well as how the monitoring program and physical world are related.

the physical environment. Full elaboration of the latter remains an important priority for CCAMLR in terms of fulfilling Convention Article II requirements.

CASE STUDIES

The case studies below outline CCAMLR's approach to managing krill and finfish fisheries; they include aspects of ecosystem management and protection. In each case the scientific aspects of the various approaches are emphasised. Although Convention Article II objectives address an essentially "new management ethos" and "conservation ethic" (Hewitt and Linen Low, 2000), the various case studies clearly show that CCAMLR has not relied on a single management approach alone. Rather, associated decisions are scientifically driven, iterative, and ongoing in an effort to address the key conservation challenges being faced. These challenges include

- assessing and monitoring harvested populations;

- defining and quantifying ecological interactions between harvested and other species (either dependent on or related to them); and
- estimating levels of depletion in order to effectively monitor restoration of depleted populations.

FISHERIES MANAGEMENT

Finfish

Large-scale finfish harvesting preceded the Convention's entry into force and many stocks in the Convention area were seriously depleted by 1982 (Kock, 1992). Therefore, the first task CCAMLR faced was to seek scientific advice on sustainable catch levels for species other than krill (Agnew, 1997; Miller, 2002). Such advice initially came from available fishery data, and to determine catch limits, CCAMLR used Beverton and Holt's (1957) approach to estimate the maximum sustainable yield. By 1987, CCAMLR had begun to develop other measures to set fishing levels (Scientific Committee for the Conservation

of Antarctic Marine Living Resources [SC-CAMLR], 1987). The introduction of $F_{0.1}$ (see Hilborn and Walters, 1992, for description) followed as a management standard for selected finfish species in the Convention area and fishery independent scientific survey data were used to "tune" estimates of stock yield (Kock, 2000).

In cases where stock assessments are data-scarce or where estimates of yield are largely uncertain, CCAMLR has come to mandate fishery-independent surveys as a prerequisite for opening any fishery. It also applies measures that ensure that fishery development proceeds at a pace commensurate with the ability to collect essential data for management (Sabourenkov and Miller, 2004).

During the early 1990s, CCAMLR became concerned that a management approach based on fishing mortality (F) alone might undermine Article II conservation principles if available yield(s) are not maximised and recruitment of young animals is compromised. As a consequence, CCAMLR began developing model-based approaches for dealing with uncertainty "unambiguously and unanimously" (Constable et al., 2000). These approaches are based on the conviction that spawning stock "escapement" is vital in determining sustainable levels of F (Kock, 2000). They use scientifically based, stochastic projection methods to incorporate and account for uncertainty in key biological parameters and to allow for random recruitment fluctuations (Constable et al., 2000).

Krill

For various reasons, the CCAMLR scientific community quickly realised that a single-species management approach for the krill fishery would be unlikely to safeguard ecosystem health, given the species' low trophic status, disparate distribution, and interactions with other species (Beddington and May, 1980; Miller, 2002). Recognising its management challenges, SC-CAMLR and the

Committee developed an empirically based management procedure for krill comprising three inter-related elements (Miller, 1991): (1) collection and compilation of essential data, (2) analysis of such data to determine target stock status, and (3) ongoing action to align management objectives (including evaluation of analysed data and implementation of appropriate action).

The above procedures facilitated development of general concepts for implementing Article II provisions. These were accepted by SC-CAMLR and the Commission as being to

- keep the krill biomass at a level higher than might be the case if only single-species considerations are of concern so as to ensure sufficient krill escapement to meet reasonable predator requirements;
- accept that krill dynamics have a stochastic component and therefore focus on the lowest biomass that might occur over a future period, rather than on a mean biomass at the end of the period as might be the case in a single-species context; and
- ensure that any reduction of food to predators which may arise from krill harvesting does not affect land-based predators with restricted foraging ranges disproportionately compared to predators present in pelagic habitats.

The above concepts also provided the basis for the 1994 adoption of pre-agreed decision rules for setting annual krill yield (Table 1) over time. These rules were based on Beddington and Cooke's (1983) approach as modified by Butterworth et al. (1991). The modified approach is known as the krill yield model (KYM) and calculates annual krill yield (Y) as a proportion (λ) of estimated pre-exploitation biomass (B_0). Initially, the KYM allowed for more refined determinations of λ, using recruitment variability information from survey data, with particular attention being paid to the relationship between such

TABLE 1. CCAMLR three-part decision rule for selecting the proportionality coefficient γ value to set krill precautionary catch limits where yield (Y) is calculated as a proportion (γ) of preexploitation biomass (B_o) such that $Y = \gamma B_o$ (SC-CAMLR, 1994).

Rule	Proportionality Coefficient	Action
1	γ_1	γ is chosen so that the probability of the spawning stock biomass dropping below 20% of the preexploitation median level over a 20-year harvesting period is 10%
2	γ_2	γ is chosen so that the median krill escapement over a 20-year harvesting period is 75%
3	lower of γ_1 or γ_2	The lower of γ_1 and γ_2 is selected as the level for γ for the calculation of krill yield

variability and natural mortality (M) (de la Mare, 1994a, 1994b).

The KYM-attached decision rules use a 75% krill escapement level as the midpoint between making no allowance for krill predator needs (i.e., treating krill as a single-species fishery with 50% escapement) or providing complete protection for predators (i.e., no fishery) (Miller and Agnew, 2000). Exploring the functional relationships between krill and its predators thus remains high on CCAMLR's agenda with respect to direct, and indirect, interactions between the krill fishery, krill, and other species. Only with more complete knowledge of such functional relationships will it be possible to define krill escapement more precisely.

Generalised Management of Fisheries

Building on the KYM approach, Constable and de la Mare (1996) recognised that it was specifically tailored to assumptions concerning krill growth, fishing seasons, and the timing of spawning. Furthermore, yield could only be determined as a proportion of the estimated B_o. Therefore, Constable and de la Mare developed a more generally structured model (general yield model [GYM]) (Table 2) to allow flexibility in assessment of krill growth patterns, natural mortality, spawning, and fishing. The decision rules outlined in Table 1 were thus recast as general principles indicating that (1) escapement of the spawning stock is sufficient to avoid the likelihood of declining recruitment and (2) reserves of exploited harvest stock abundance are sufficient to fulfil dependent species (usually predators) needs. Stock trajectories can then be calculated from estimated levels of absolute recruitment (R) in relation to fishing mortality (F).

Although the GYM was specifically tailored for finfish assessments, its outputs for krill were remarkably similar to those of the KYM (Constable and de la Mare, 1996). Therefore, from 1994 onward, CCAMLR has used the GYM to determine long-term annual yields for harvested stocks in absolute terms rather than as a proportion of B_o. Examples of CMs formulated using the generalised approach include CM 51-01 (krill fishing in CCAMLR Statistical Area 48) as well as CMs 41-20 and 41-03 for toothfish (*Dissostichus eleginoides*) fishing in the same area.[8]

The CCAMLR continues to refine the scientific basis of its finfish fishery management approach. More recently, it has sought to integrate diverse data sets within a generalised stock assessment "package" (Hillary et al., 2006; Candy and Constable, 2008). Such data include multiple fisheries catch-at-age proportions, fisheries-independent research survey data, and mark-recapture data from different fisheries. These techniques will undoubtedly improve future management efforts. Similarly, advances in determination of krill age, growth, and maturation (Brown et al., 2010; Virtue et al., 2010) have again raised interest in exploring age-based assessments of the species' annual productivity and yield.

Illegal, Unreported, and Unregulated Fishing

Illegal, unreported, and unregulated (IUU) fishing has seriously undermined CCAMLR's efforts to manage the Patagonian toothfish (*Dissostichus eleginoides*) fishery in the Indian Ocean (Agnew, 1999; Miller, 2007). As a result, total toothfish removals and fishery-related mortality (F) from the CCAMLR area are largely uncertain. In response, CCAMLR began to develop a standard methodology to estimate IUU catches in the Convention area (CCAMLR, 2005: pars. 8.3, 8.4) in 2005. In 2007, CCAMLR agreed to continue using the traditional method developed by SC-CAMLR for estimating IUU catches, which is based on

TABLE 2. Variation of the krill yield model and its later modification into the general yield model (after Miller, 2002).

Formula	Key features	Source
$Y = 0.5MB_o$	0.5 too high due to uncertainties in estimating natural mortality (M) and recruitment (R)	Gulland (1971) formulation
$Y = \lambda B_o$	Used for determining CCAMLR krill precautionary catch limits with λ applied as a single proportionality constant	Butterworth et al. (1994)
$Y = \gamma B_o$	Refinement of above with absolute recruitment (R) and natural mortality (M) being subsumed into a single calculated constant γ. The stock is tracked stochastically over a 20-year period with an appropriate yield level being selected by a three-part, conservatively applied decision rule to designate the γ value (see Table 1)	Constable and de la Mare (1996)

vessel sightings and other information (CCAMLR, 2007: paragraph 10.51). More recently, CCAMLR has agreed to continue development of other methods, such as an index to determine the density of licensed vessels fishing on particular grounds. Clearly, procedures are needed to refine IUU vessel identification as well as systematically and objectively determining breakdowns in compliance with CCAMLR CMs.

ECOSYSTEM EFFECTS

General Effects

The SC-CAMLR recognised that krill fishing may cause intolerable variations in the trophic dynamics of Antarctic marine ecosystems (SC-CAMLR, 1995: Annex 4; Constable et al., 2000). Although the KYM approach implicitly accounted for this possibility, CEMP was predicated on the assumption that the information it obtained could be used to predict the impact of different harvesting strategies and thereby provide an opportunity to avoid any serious deterioration in ecosystem health. To that end, CEMP would seek to improve understanding of relationships between fisheries, target species, and target species predators.

Over the past decade, the CCAMLR scientific community has sought to develop predictive models of such relationships to refine the decision rules used in conjunction with the KYM and GYM. These predictive models have provided a new basis for setting catch limits that do not pose significant risks to ecosystem predators (e.g., Constable, 2001, 2005; Hill et al., 2007). Such efforts are ongoing and important physical and biological interactions have been identified (SC-CAMLR, 1995, Annex 4). However, models estimating krill availability to predators remain limited (e.g., Murphy et al., 1988; Murphy, 1995), and those examining the consequences of different levels of such availability are rare (e.g., Butterworth and Thomson, 1995; Mangel and Switzer, 1998). One notable advance has been the development of a framework (e.g., Constable, 2005) to evaluate krill management procedures in an ecosystem context. The framework is particularly noteworthy because it allows and, indeed, facilitates explicit assessment of uncertainty in the modelled systems.

Despite such advances, the explicit linkage of CEMP-derived predator information, krill availability, and fishing activity remains elusive in the formulation of CCAMLR CMs aimed at fully addressing all the objectives of Convention Article II. As highlighted by Reid et al. (2008), work is still required to

- detect the effects of fishing on any process/ecosystem component in an operationally useful way and with respect to an agreed reference point(s),
- remain cognisant of appropriate trade-offs between CEMP aims and prevailing uncertainty about ecosystem function, and
- promote a realistic appreciation of CEMP's ability to provide data relevant to a specific management objective for the krill fishery or krill-associated predators.

Small-Scale Management Units

The CCAMLR krill CMs require precautionary catch limits to be subdivided into smaller spatial management units known as SSMUs (Figure 5).[9] A set of candidate options have been proposed for such subdivision in CCAMLR Area 48 (West Atlantic; Constable and Nicol, 2002; Hewitt et al., 2004). Hill et al. (2007) have compiled parameters for various available krill ecosystem dynamic models to assess options based on plausible limits for parameter values. This complex work continues despite the perception that the krill fishery is expanding now and will continue to expand in the future. The studies involved may help resolve some of the concerns identified by Everson (2002) regarding fishery, krill, and predator interactions, as well as a reduction in krill availability due to shifts in the species' distribution (SC-CAMLR, 1990, 1994; Murphy, 1995).

Once krill catches reach a "trigger," the total allowable catch set in CCAMLR CM 51-01 is to be subdivided into smaller areas (including SSMUs). Anticipating growth in the krill fishery, SC-CAMLR and the Committee advised that the 620,000 tonne trigger in CM 51-01 could be concentrated in a single area (SC-CAMLR, 2009: pars. 4.26, 4.28). However, this would increase the risk of significant adverse impacts on krill-dependant predators, especially those that are land based (SC-CAMLR, 2009: pars. 3.126–3.132). With that concern in mind, SC-CAMLR and the Committee have advised the Commission to spatially distribute krill fishing effort to avoid large catches in restricted areas as the trigger level is approached. Five models have been provided to distribute the krill trigger level over CCAMLR Statistical Area 48 (SC-CAMLR, 2009: table 1). Drawing on this approach, the Commission agreed to an interim measure (CM 51-09) to distribute the trigger level proportionately between Statistical Subareas 48.1 and 48.4 (CCAMLR, 2009: pars. 12.60, 12.61). This interim measure will lapse at the end of the 2010/2011 fishing season but will be kept under review by SC-CAMLR and the Commission.

FIGURE 5. Small-scale management units (SSMUs) in CCAMLR Statistical Area 48.1. From SC-CAMLR (2002: Annex 4, Appendix D, fig. 37).

Bycatch

The SC-CAMLR and the Commission also have been concerned about fisheries bycatch. Fortunately, CCAMLR's management of seabird bycatch during toothfish longline fishing (CM 25-02) has been a notable success (Miller, 2007). The number of seabirds incidentally caught has been dramatically reduced from tens of thousands in the CCAMLR area a decade and a half ago to a few individual birds. Similar measures have reduced the entanglement of seals and other animals (CCAMLR, 2009: paragraph 6.4) in fishing devices (e.g., nets and pots) as well as marine debris. Scientific observers appointed under the CCAMLR International Scheme of Scientific Observation play an important role in monitoring incidental seabird bycatch, deploying mitigation devices, and educating fishers to the dangers of fisheries-induced mortality caused by the direct effects of fishing activity on nontarget species.[10]

A notable exception to the above has been in the French exclusive economic zone around Kerguelen and the Crozet Islands, where more than 1,000 birds were taken annually (SC-CAMLR, 2008: paragraph 5.3) until

a dramatic improvement in the application of mitigation measures over the past two years (CCAMLR, 2009: paragraphs 6.5–6.8).

Other measures to monitor and mitigate fishery bycatch include reporting procedures (e.g., CM 41-08, Annex 41-08A, paragraph iv), bycatch limits or proportions (CM 41-02, paragraphs 6 and 7), and "move-on" rules when bycatch is encountered (CM 41-02, paragraph 8). One of SC-CAMLR's scientific working groups evaluates these measures periodically to provide appropriate advice as needed. Directed scientific studies continue to assess the species that are, or may be, taken as fisheries bycatch (e.g., the 2009 "Year of the Skate"; CCAMLR, 2008: paragraph 4.55).

SPATIAL MANAGEMENT

General Management

Apart from SSMUs, CCAMLR is considering, or has initiated, a number of spatially bound measures to address the precautionary and ecosystem-directed elements

of Article II. One such measure (CM 26-01), applied to the entire CCAMLR area, aims to minimise the risks of alien-species contamination and marine pollution from fishing vessels. This measure has established specific controls on dumping, or discharge, and the translocation of poultry in the Convention area south of 60°S, where the effects of such events are likely to be most acutely felt. The measure has been recently modified to refine definitions of "offal," "discards," "releases," and "benthic" organisms (CCAMLR, 2009: paragraph 12.28).

Additional measures (e.g., CM 91-01) protect CEMP sites, and others set ice-strengthening requirements for fishing vessels at high latitude (Resolution 20/XXII), general vessel safety standards (Resolution 23/XXIII), and ballast-water exchange restrictions (Resolution 28/XXVII). Most recently, Resolution 29/XXVIII urges CCAMLR members to ratify the 1989 International Convention on Salvage, or any other measures deemed appropriate, to facilitate the recovery of reasonable expenses incurred by vessel operators assisting other vessels, or other property in danger, in the CCAMLR area (CCAMLR, 2009: paragraph 12.87). All such measures have drawn on advice from SC-CAMLR and the Committee in terms of mitigating potential dangers to the Antarctic marine environment.

Small-Scale Research Units

The CCAMLR has developed small-scale research units (SSRUs) to spread the risk of spatially concentrated fishing when scientific knowledge of the stock(s) concerned is limited (e.g., CM 41-09, paragraph 3). Such units were initially applied to experimental crab fisheries (CCAMLR: 1993, paragraph 8.36, CM 75/XII; Watters, 1997) but have since been expanded to various exploratory toothfish fisheries (CM 41-05, fig. 1; Figure 6). They not only impose a degree of precaution but also promote collection of essential operational data from the fishery, often a responsibility of the CCAMLR scientific observers aboard the vessels involved. In these terms, the use of SSRUs may be viewed as an inexpensive alternative to research vessel surveys as data may be consistently gathered from wide areas, with scientific observers providing the necessary scientific objectivity to render such data worthwhile.

Marine Protected Areas

Over the past decade, CCAMLR has considered implementing spatial management measures to facilitate biodiversity conservation consistent with targets set by the 2002 World Summit on Sustainable Development

FIGURE 6. Small-scale research units (SSRUs) in the CCAMLR area. From CCAMLR CM 41-01.

(WSSD). The CCAMLR and the Committee for Environmental Protection (CEP) have afforded high priority to the designation of Southern Ocean marine areas for biodiversity conservation (CCAMLR, 2004: paragraph 4.13; CEP, 2006: paragraphs 94–101).[11] In 2007 CCAMLR sponsored a workshop to develop benthic and pelagic bioregionalisations (CCAMLR, 2007: paragraphs 7.3–7.19) based on the results of a World Wildlife Fund–Peregrine Travel sponsored meeting of experts in 2006 (Grant et al., 2006).[12] These bioregionalisations are being used to design a representative network of CCAMLR marine protected areas (MPAs).

In 2007, CCAMLR also agreed to continue consolidating the scientific rationale for the above MPA network (CCAMLR, 2007: paragraph 7.18). It agreed that the network should focus on, but not be limited to, 11 priority areas identified by SC-CAMLR and the Committee (CCAMLR, 2008: paragraph 7.2(vi); SC-CAMLR, 2008: Annex 4, fig. 12; Figure 7a). Development of the network is ongoing and draws on a work plan outlined by SC-CAMLR (2008: paragraph 3.55). The network also is an important topic in the ongoing dialogue between SC-CAMLR and the Committee, and the CEP (CEP, 2009a; 2009b). Most significantly, the 2009 CCAMLR meeting adopted CM 91-03 (Figure 7b), which will contribute to

FIGURE 7a. The CCAMLR priority areas for identifying marine protected areas (MPAs) as part of a representative network of such sites (CCAMLR, 2008). Numbers refer to area and are not in priority order. 1, Western Antarctic Peninsula; 2, South Orkney Islands; 3, South Sandwich Islands; 4, South Georgia; 5, Maud Rise; 6, eastern Weddell Sea; 7, Prydz Bay; 8, Banzare Bank; 9, Kerguelen; 10, northern Ross Sea/East Antarctica; 11, Ross Sea Shelf. From SC-CAMLR (2008: Annex 4, fig. 12). **X**—South Orkney Islands MPA (see Figure 7b and text for details).

FIGURE 7b. The CCAMLR South Orkney Islands Southern Shelf Marine Protected Area. Depth contours are at 1000 m intervals (CCAMLR CM 91-03).

biodiversity conservation in Subarea 48.2 (South Orkney Islands), as well as to a network of protected areas across the CCAMLR area (SC-CAMLR, 2009: pars. 3.14–3.19; CCAMLR, 2009: paragraph 12.86). The biodiversity conservation area in Subarea 48.2 is one of the first of its kind to be adopted for the high seas and illustrates the value of science in the conservation of marine living resources. Conversely, some view CM 91-03 as little more than a compromise arrangement which required the originally proposed area to be reduced to avoid the inclusion of potential fishing grounds (CCAMLR, 2009: paragraph 7.17). Nevertheless, there is general agreement that the measure itself is an important milestone toward the achievement of

a representative system of MPAs within the Convention area by 2012 (CCAMLR, 2009: paragraph 7.19).

Vulnerable Marine Ecosystems

United Nations General Assembly (UNGA) Resolution 61/105 (UNGA, 2007) calls upon Regional Fisheries Management Organizations or Arrangements (RFMO/As) to close areas to bottom fishing until appropriate measures are in place to prevent significant adverse impacts on vulnerable marine ecosystems (VMEs). The resolution (UNGA, 2007: paragraph 83) urged RFMO/As to implement relevant VME measures by 31 December 2008. Despite a recent increase in research (Brandt et al., 2007), the data available for managing benthic fauna in the Southern Ocean remains sparse.

The CCAMLR responded to the UNGA resolution by formulating CMs 22-06 and 22-07. The CM 22-06 freezes the current bottom fishing footprint to areas approved for such fisheries in the 2006/2007 fishing season. The CM 22-07 provides a format for identifying VMEs encountered during scientific research cruises, defines a VME "encounter" during fishing operations, and describes the resulting action to be taken by a vessel. Two such notifications were made in 2008 (CCAMLR, 2008).

To determine when a VME has been encountered under CM 22-06, vessels are required to monitor the catch of agreed VME indicator organisms in an identified sampling segment. When 10 or more VME indicator units are recovered in one segment, the area is considered a "VME risk area," and vessels are required to complete hauling in the area and immediately communicate its location to CCAMLR and their flag state. On receiving this information, CCAMLR then notifies all fishing vessels in the fishery (and their flag states) that the area is closed to fishing.

Longline fishing targeting toothfish under CM 22-07 took place in seven CCAMLR subareas/divisions between December 2008 and February 2009. The highest fishing effort occurred in Subareas 88.1 and 88.2 in the Ross Sea, and seven VME risk areas (five in Subarea 88.1 and two in Subarea 88.2) were closed to fishing (Table 3). During the same period, eight notifications were received from a single "near-miss" area in Subarea 88.2.[13] In the five Subarea 88.1 VME risk areas, sponges (*Porifera*) were the dominant VME indicators, with lesser amounts of stony corals (*Scleractinia*) being present in three areas. In the two Subarea 88.2 VME risk areas, hydrocorals (*Anthoathecatae*) were the dominant VME indicator organisms, with sea fans/sea whips (*Gorgonacea*) also occurring.

At its 2009 meeting SC-CAMLR reviewed these data, as well as application of CM 22-07, to provide the Commission with relevant advice. It noted that CCAMLR scientific observers played a key role in implementing the CMs concerned. In addition to the information outlined in the previous paragraph, it was recognised that the CCAMLR Secretariat had received 30 VME indicator notifications, of which seven notifications consisted of at least 10 VME indicator units. This had resulted in seven risk areas being declared in Subareas 88.1 and 88.2 (SC-CAMLR, 2009: Annex 5, paragraph 10.29). In taking this information into account, CCAMLR urged the Scientific Committee and its working groups to carefully consider the practical aspects of implementing recommendations arising from its work (CCAMLR, 2009: paragraph 5.10). It therefore seems prudent to conclude that CCAMLR's approach to VME's remains under development and that care needs to

---

TABLE 3. CCAMLR vulnerable marine ecosystems (VME) risk areas for longline fisheries in 2008/2009.

Subarea/division	Date notified	Risk area midpoint		Number of VME indicator units	VME indicator taxa
		Latitude	Longitude		
88.1[a]	7 January 2009	75° 08.70′S	176° 04.98′W	60	*Porifera, Scleractinia*
	7 January 2009	75° 08.52′S	176° 07.14′W	69	*Porifera, Scleractinia*
	7 January 2009	75° 12.10′S	175° 55.10′W	25	*Porifera, Scleractinia, Actinaria*
	15 January 2009	71° 34.90′S	172° 11.40′E	11	*Porifera, Anthoathecatea, Gorgonacea*
	15 January 2009	71° 40.60′S	172° 15.40′E	13	*Porifera, Anthoathecatea*
88.2[b]	19 January 2009	69° 07.98′S	123° 41.34′W	10	*Anthoathecatea, Gorgonacea*
	19 January 2009	69° 08.04′S	123° 43.86′W	10	*Anthoathecatea, Gorgonacea*

[a] Longline fishing effort reflected as the number of hooks deployed = 5749982.
[b] Longline fishing effort reflected as the number of hooks deployed = 2751260.

be taken to ensure that that the current CMs (CMs 22-06 and 22-07) are not viewed as "having done the job." In these terms, CM 22-07 is truly an interim measure.

ECOSYSTEM STATUS

CEMP Indices

As indicated, ecosystem assessments of krill predators have been on CCAMLR's agenda since 1997. These entail examining trends in the predator parameters collected by CEMP and then applying various models to explain the trends. Key parameters are those that provide information on target species (i.e., notably krill), the physical environment (e.g., sea surface temperature and sea ice extent), and predators of the target species (i.e., CEMP-measured parameters).

While de la Mare and Constable (2000) have developed ways to summarise many CEMP parameters into a single metric, deciding what action to take in response to changes in parameter values or the single metric remains a challenge. For this purpose, the detection of extreme values in a naturally varying system is as important as detecting anomalous trends caused by fishing (Constable et al., 2000; Constable, 2001). The ongoing development of more-objective approaches to scaling CCAMLR management decisions thus remains under consideration. As Reid et al. (2008) have emphasised, some evaluation of risk in terms of identifying the consequence of type I and type II errors is essential, as illustrated by Field et al. (2004). Unfortunately, a clear strategy for applying such evaluations remains elusive in terms of selecting an appropriate level of statistical significance (α) and power to categorise any detected change in CEMP indices as a function of fishing.

Climate Change

The CCAMLR has recently tasked SC-CAMLR with addressing the issue of climate change in relation to conservation of Antarctic marine living resources (CCAMLR, 2007: paragraph 15.36). To that end, SC-CAMLR (SC-CAMLR, 2008: paragraph 7.13) has indicated that it should examine (1) the robustness of its advice and stock assessments, particularly with regard to predicting future population responses to climate change, (2) the need to improve current monitoring programs for harvested and other species to provide timely, robust indicators of climate change impacts, and (3) whether CCAMLR's management objectives and performance indicators should be modified to reflect the uncertainty regarding climate change

effects. The matter remains a high priority for CCAMLR, and Resolution 30/XXVIII, adopted in late 2009, urges consideration of climate change impacts in the Southern Ocean to better inform CCAMLR management decisions.

CONCLUSIONS

Within the ATS, science may be viewed as the observation, identification, description, experimental investigation, and theoretical explanation of phenomena. This paper illustrates the essential value of science to sustainable management, and the case studies provide a number of important lessons.

First, and in CCAMLR terms, "the best scientific evidence available" and "sustainable management" are essentially equivalent in that the latter will fail in the absence of the former. Second, at an organizational level CCAMLR has developed a way of doing business that not only promotes consensus but also serves to underpin its status as a successful "new generation" agreement (Miller et al., 2004). While its many advances owe their existence to the strong spirit of cooperation between the CCAMLR members, these advances have been hard-won and have required a coherent, adaptable, and decision-driven management approach over the years (Miller et al., 2004). The work of SC-CAMLR has had a major role to play in this regard.

Third, many of the Convention's objectives have been addressed and met, even when there is very little supporting information available and knowledge of ecosystem functioning is limited. Fourth, fisheries within the CCAMLR area can be managed using a precautionary, ecosystem-based approach, the krill fishery being the most notable example. Fifth, CCAMLR has been able to develop scientifically based management despite uncertainty about important parameters and ecosystem behaviour; the VME approach is a clear example of this.

Sixth, science provides an iterative and robust framework for developing and implementing rigorously defined, management action. As stipulated in Convention Article XV, SC-CAMLR constitutes "a forum for consultation and co-operation concerning the collection, study and exchange of information with respect to the marine living resources to which the Convention applies." The Committee has also encouraged and promoted scientific cooperation to expand knowledge about Antarctic marine living resources and the associated ecosystem.

However, there is still work to be done! Plausible models are needed to guide management procedures in the

face of the Antarctic marine ecosystem's "unknown and uncertain behaviors" (Constable et al., 2000). Expansion of the krill fishery is a very real possibility, and finalization of SSMUs has become a matter of growing urgency (Gascón and Werner, 2009). Equally, the majority of CCAMLR members have recognised the urgent need to subdivide krill areal catch limits within CCAMLR Statistical Area 48 (West Atlantic) to minimise risks associated with localised overfishing and associated ecosystem effects. Although this is a key concern, only an interim measure (CM 51-09) has been agreed by CCAMLR to date.

The CCAMLR further needs to articulate and set operational objectives for predators (Constable, 2002). This requires assessing the plausibility and furthering the development of ecosystem and food web models (Constable, 2005). Most importantly, the management procedures already in place must be evaluated prior to any appreciable increase in the krill fishery (Gascón and Werner, 2009). At the same time, decision rules associated with these and any new procedures should be tested and improved as needed. Such rules need to be robust to uncertainty and consistent, with objectively defined and clearly articulated operational criteria.

Despite the clear need for adaptability, CCAMLR has proven itself successful in addressing many of the ecological issues facing fisheries in other parts of the world's oceans. It has used science to overcome many challenges in ways consistent with the Antarctic Treaty's aspirations. As an innovative global leader in marine ecosystem management, CCAMLR warrants its status as an organization based on best practices in science and management (Lodge et al., 2007). The extensive research documented in the journal *CCAMLR Science* attests to the vast contribution that science has made to the formulation of the organization's conservation policies and management measures.[14] As De Cesari (1996:455) maintains, "The regulation of circumpolar waters falls under the legal ambit of the Antarctic Treaty System which aims to preserve and protect the right of Contracting Parties to conduct marine scientific research in the Southern Ocean".

The recently adopted CCAMLR Resolution 31/XXVIII (CCAMLR, 2009: pars. 12.90–12.93) highlights the role of science as fundamental to CCAMLR's work. This role is consistent with the vision espoused in Convention Article IX, which was renewed by the 1990 CCAMLR Working Group for the Development of Approaches to Conservation of Antarctic Marine Living Resources. In Resolution 31/XXVIII, formal recognition of the value of science in CCAMLR's day-to-day activities comes of age, as does its inclusion in the very fabric of the commission's

policy decisions. Coupled with CCAMLR's clearly stated policy to enhance cooperation with Non-Contracting Parties,[15] the recent innovative, and far-reaching, steps taken by the commission to build scientific capacity within the organization (CCAMLR, 2009: pars. 16.8–16.11) stand out as a clear indication of science's inestimable value to the organization's work.

NOTES

1. In this chapter the Southern Ocean is the area defined in CAMLR Convention Article I. The Convention also applies to the Antarctic Treaty area south of 60°S; see CCAMLR Web site, Basic Documents section, http://www.ccamlr.org/pu/e/e_pubs/bd/toc.htm (accessed 17 November 2010).

2. The Antarctic Treaty System comprises the international arrangements underpinning relations among states in the Antarctic.

3. Unless otherwise qualified, specific Articles of the Convention will be referred to by number as "Article [X]."

4. The Commission (CCAMLR) is established under Article VII of the CAMLR Convention. It is the Convention's executive arm (see note 5) and has legal personality under Article VIII. The Commission's functions and responsibilities are outlined in Article IX, with a key function being to promulgate conservation measures (CMs).

5. The CCAMLR CMs are outlined in Convention Article IX, paragraphs 1 and 2. Their adoption by consensus (Article XII) follows procedures in Convention Article IX, paragraph 3. They are found on the CCAMLR Web site, http://www.ccamlr.org/pu/e/e_pubs/cm/drt.htm (accessed 17 November 2010).

6. The CAMLR Scientific Committee (SC-CAMLR) was established under Article XIV of the Convention. It functions (Article XV) as a "forum for consultation and co-operation concerning the collection, study and exchange of information" on the resources to which the Convention applies.

7. "Ecosystem health" in CCAMLR is taken to be the provision of adequate safeguards for harvested species so that harvesting does not prejudice the long-term future of dependent species. An "ecosystem assessment" is necessary to ensure that all the management requirements of Convention Article II are met in an operational sense (Everson, 2002).

8. The CCAMLR CMs in force for any year may be found on the CCAMLR Web site, http://www.ccamlr.org/pu/e/e_pubs/cm/drt.htm (accessed 17 November 2010).

9. Small-scale management units (SSMUs) are defined in CCAMLR (2002: paragraph 4.5) using an agreed and scientifically objective approach (SC-CAMLR, 2002: Annex 4, Appendix D).

10. See CCAMLR, "Text of the CCAMLR Scheme of International Scientific Observation," http://www.ccamlr.org/pu/e/e_pubs/cm/08-09/obs.pdf (accessed 17 November 2010).

11. The CEP was set up under Article 11 of the 1991 Protocol on Environmental Protection to the Antarctic Treaty.

12. "Bioregionalisation" is an objective, usually scientific, process that identifies the spatial boundaries of bioregions on the basis of ecological attributes, such as geology, ocean currents, and biota (National Oceans Office, 2002).

13. A "near-miss" area is considered to be an area where five or more VME indicator units are recovered within one line segment, within a single fine-scale rectangle as per paragraphs 5 and 7 of CM 22-07.

14. Despite a specialised, CCAMLR-centric content, *CCAMLR Science* has an impact factor of 1.389. It is ranked 19th out of 40 fisheries journals in Thomson's Journal Citation Reports Science Edition. This ranking compares with the *ICES Journal of Marine Science*'s 10th ranking and impact factor of 1.661.

15. See CCAMLR, "Policy to Enhance Cooperation between CCAMLR and Non-Contracting Parties," http://www.ccamlr.org/pu/e/e_pubs/cm/09-10/coop.pdf (accessed 19 November 2010).

LITERATURE CITED

Agnew, D. J. 1997. Review: The CCAMLR Ecosystem Monitoring Programme. *Antarctic Science,* 9:235–242.

———. 1999. The Illegal and Unregulated Fishery for Toothfish in the Southern Ocean and the CCAMLR Catch Documentation Scheme. *Marine Policy*, 24:361–374.

Beddington, J. R., and J. G. Cooke. 1983. The Potential Yield of Fish Stocks. *FAO Fisheries Technical Paper* 242. Rome: Food and Agricultural Organisation.

Beddington, J. R., and R. M. May. 1980. Maximum Sustainable Yields in Systems Subject to Harvesting at More Than One Trophic Level. *Mathematical Biosciences*, 51:261–281.

Beverton, R. J. H., and S. J. Holt. 1957. On the Dynamics of Exploited Fish Stocks. *Fishery Investigation Series* 19. London: Ministry of Agriculture Fisheries and Food.

Brandt, A., A. J. Gooday, S. N. Brandão, S. Brix, W. Brökeland, T. Cedhagen, M. Choudhury, N. Cornelius, B. Danis, I. G. De Mesel, R. J. Diaz, D. C. Gillan, B. Ebbe, J. A. Howe, D. Janussen, S. Kaiser, K. Linse, M. Malyutina, J. Pawlowski, M. Raupach, and A. Vanreusel. 2007. First Insights into the Biodiversity and Biogeography of the Southern Ocean Deep Sea. *Nature,* 447(7142):307–311.

Brown, M., S. Kawaguchi, S. G. Candy, and P. Virtue. 2010. Temperature Effects on the Growth and Maturation of Antarctic Krill (*Euphausia superba*). *Deep Sea Research, Part II, Topical Studies in Oceanography,* 57(7–8):672–682.

Butterworth, D. S. 1986. Antarctic Ecosystem Management. *Polar Record,* 37–47.

Butterworth, D. S., G. R. Gluckman, R. B. Thomson, S. Chalis, K. Hiramatsu, and D. J. Agnew. 1994. Further Computations of the Consequences of Setting the Annual Krill Catch Limit to a Fixed Fraction of the Estimate of Krill Biomass from a Survey. *CCAMLR Science,* 1:81–106.

Butterworth, D. S., A. E. Punt, and M. Basson. 1991. A Simple Approach for Calculating the Potential Yield of Krill from Biomass Survey Results. *CCAMLR Selected Scientific Papers,* 8:207–217.

Butterworth, D. S., and R. B. Thomson. 1995. Possible Effects of Different Levels of Krill Fishing on Predators—Some Initial Modelling Attempts. *CCAMLR Science*, 2:79–97.

Candy, S. G., and A. J. Constable. 2008. An Integrated Stock Assessment for the Patagonian Toothfish (*Dissostichus eleginoides*) for Heard and McDonald Islands Using CASAL. *CCAMLR Science,* 15:1–34.

Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). 1990. Report of the Ninth Meeting of the Commission (CCAMLR-IX). Hobart, Australia.

———. 1993. Report of the Twelfth Meeting of the Commission (CCAMLR-XII). Hobart, Australia: CCAMLR.

———. 2002. Report of the Twenty-First Meeting of the Commission (CCAMLR-XXI). Hobart, Australia: CCAMLR.

———. 2004. Report of the Twenty-Third Meeting of the Commission (CCAMLR-XXIII). Hobart, Australia: CCAMLR.

———. 2005. Report of the Twenty-Fourth Meeting of the Commission (CCAMLR-XXIV). Hobart, Australia: CCAMLR.

———. 2007. Report of the Twenty-Sixth Meeting of the Commission (CCAMLR-XXVI). Hobart, Australia: CCAMLR.

———. 2008. Report of the Twenty-Seventh Meeting of the Commission (CCAMLR-XXVII). Hobart, Australia: CCAMLR.

———. 2009. Report of the Twenty-Eighth Meeting of the Commission (CCAMLR-XXVIII). Hobart, Australia: CCAMLR.

Committee for Environmental Protection (CEP). 2006. Report of the Committee for Environmental Protection CEP-IX. Buenos Aires, Argentina: Antarctic Treaty Secretariat. http://www.ats.aq/documents/cep/cep%20documents/atcm29_cepix_e.pdf, (accessed 17 November 2010).

———. 2009a. Report of the Committee for Environmental Protection CEP-XII–Section 7 (Paragraphs 159–170). Buenos Aires, Argentina: Antarctic Treaty Secretariat. http://www.ats.aq/documents/ATCM32/att/atcm32_att084_rev2_e.doc (accessed 17 November 2010).

———. 2009b. Towards a Representative System of Marine Spatial Protection for the Orkney Islands. ATCM-XXXIII Working Paper 29. Buenos Aires, Argentina: Antarctic Treaty Secretariat. http://www.ats.aq/documents/ATCM32/wp/ATCM32/wp/ATCM32_wp029_e.doc (accessed 17 November 2010).

Constable. A. J. 2001. The Ecosystem Approach to Managing Fisheries: Achieving Conservation Objectives for Predators of Fished Species. *CCAMLR Science,* 8:37–64.

———. 2002. CCAMLR Ecosystem Monitoring and Management: Future Work. *CCAMLR Science,* 9:233–253.

———. 2005. A Possible Framework in Which to Consider Plausible Models of the Antarctic Marine Ecosystem for Evaluating Krill Management Procedures. *CCAMLR Science,* 12:99–117.

Constable, A. J., and W. K. de la Mare. 1996. A Generalized Model for Evaluating Yield and the Long-Term Status of Fish Stocks under Conditions of Uncertainty. *CCAMLR Science,* 3:31–54.

Constable, A. J., W. K. de la Mare, D. J. Agnew, I. Everson, and D. G. M. Miller. 2000. Managing Fisheries to Conserve the Antarctic Marine Ecosystem: Practical Implementation of the Convention on the Conservation of Antarctic Marine Living Resources. *ICES Journal of Marine Science*, 57:778–791.

Constable, A. J., and S. Nicol. 2002. Defining Smaller-Scale Management Units to Further Develop the Ecosystem Approach in Managing Large-Scale Pelagic Krill Fisheries in Antarctica. *CCAMLR Science,* 9:117–131.

De Cesari, P. 1996. "Scientific Research in Antarctica: New Developments." In *International Law for Antarctica*, 2nd ed., ed.

F. Franconi and T. Scovazzi, pp. 413–455. The Hague: Kluwer International.

de la Mare, W. K. 1994a. Modelling Krill Recruitment. *CCAMLR Science,* 1:49–54.

———. 1994b, Estimating Krill Recruitment and Its Variability. *CCAMLR Science,* 1:55–69.

de la Mare, W. K., and A. J. Constable. 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.

Eddie, G. C. 1977. *The Harvesting of Krill.* Southern Ocean Fisheries Survey Programme GLO/SO/77/2. Rome: Food and Agricultural Organisation.

El-Sayed, S. Z. 1994. "History, Organization and Accomplishments of the BIOMASS Programme." In *Southern Ocean Ecology: The BIOMASS Perspective,* ed. S. Z. El-Sayed, pp. 1–8. Cambridge: Cambridge University Press.

Everson, I. 1977. *Antarctic Fisheries*. Southern Ocean Fisheries Survey Programme, GLO/SO/77/1. Rome: Food and Agricultural Organisation.

———. 2002. Consideration of Major Issues in Ecosystem Monitoring and Management. *CCAMLR Science,* 9:213–232.

Field, J., A. J. Tyre, N. Jonzen, J. R. Rhodes, and H. P. Possingham. 2004. Minimizing the Cost of Environmental Management Decisions by Optimizing Statistical Thresholds. *Ecology Letters,* 7:669–675.

Gascón, V. G., and R. K. Werner. 2009. Preserving the Antarctic Food Web: Achievements and Challenges in Antarctic Krill Fisheries Management. *Ocean Yearbook,* 23:279–307.

Grant, S., A. J. Constable, B. Raymond, and S. Doust. 2006. Bioregionalisation of the Southern Ocean: Report of Experts Workshop (Hobart, Australia, September 2006). Sydney: WWF-Australia. http://www.wwf.org.au/publications/bioregionalization-southern-ocean.pdf (accessed 17 November 2010).

Grantham, G. J. 1977. *The Utilization of Krill.* Southern Ocean Fisheries Survey Programme GLO/SO/77/3. Rome: Food and Agricultural Organisation.

Gulland, J. 1971. *The Fish Resources of the Ocean.* West Byfleet, UK: Fishing News (Books).

Hewitt, R. P., and E. H. Linen Low. 2000. The Fishery on Antarctic Krill: Defining an Ecosystem Approach to Management. *Reviews in Fisheries Science,* 8:235–298.

Hewitt, R. P., G. Watters, P. N. Trathan, J. P. Croxall, M. E. Goebel, D. Ramm, K. Reid, W. Z. Trivelpiece, and J. L. Watkins. 2004. Options for Allocating the Precautionary Catch Limit for Krill among Small-Scale Management Units in the Scotia Sea. *CCAMLR Science,* 11:81–97.

Hilborn, R., and C. J. Walters. 1992. *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty.* London: Chapman and Hall Inc.

Hillary, R. M., G. P. Kirkwod, and D. J. Agnew. 2006. An Assessment of Toothfish in Subarea 48.3 Using CASAL. *CCAMLR Science,* 13:65–96.

Hill, S. L, K. Reid, S. E. Thorpe, J. Hinke, and G. M. Watters. 2007. A Compilation of Parameters for Ecosystem Dynamics Models of the Scotia Sea—Antarctic Peninsula Region. *CCAMLR Science,* 14:1–25.

Kock, K.-H. 1992. *Antarctic Fish and Fisheries.* Cambridge: Cambridge University Press.

———, ed. 2000. *Understanding CCAMLR's Approach to Management.* Hobart, Australia: CCAMLR. http://www.ccamlr.org/pu/E/e_pubs/am/toc.htm (accessed 17 November 2010).

Lodge, M., D. Anderson, T. Løbach, G. Munro, K. Sainsbury, and A. Willock. 2007. *Recommended Best Practices for Regional Fisheries Management Organizations*. London: Chatham House. http://www.chathamhouse.org.uk/files/10301_rfmo0807.pdf (accessed 17 November 2010).

Mangel, M., and P. V. Switzer. 1998. A Model at the Level of the Foraging Trip for the Indirect Effects of Krill (*Euphausia superba*) Fisheries on Krill Predators. *Ecological Modelling,* 105:235–256.

Miller, D. G. M. 1991. Exploitation of Antarctic Marine Living Resources: A Brief History and a Possible Approach to Managing the Krill Fishery. *South African Journal of Marine Science,* 10:321–339.

———. 2000. The Southern Ocean: A Global View. *Ocean Yearbook,* 14:468–513.

———. 2002. Antarctic Krill and Ecosystem Management—From Seattle to Siena. *CCAMLR Science,* 9:175–212.

———. 2007. Managing Fishing in the Sub-Antarctic. *Papers and Proceedings of the Royal Society of Tasmania,* 141:121–140.

Miller, D. G. M., and D. J. Agnew. 2000. "Krill Fisheries in the Southern Ocean." In *Krill: Biology, Ecology and Fisheries*, ed. I. Everson, pp. 300–337. Fisheries and Aquatic Resources Series 6. Oxford: Blackwell Science.

Miller, D. G. M., and I. Hampton. 1988. Biology and Ecology of the Antarctic Krill (*Euphausia superba* Dana). *BIOMASS Scientific Series* 9. Cambridge: SCAR and SCOR.

Miller, D. G. M., E. N. Sabourenkov, and D. C. Ramm. 2004. Managing Antarctic Marine Living Resources: The CCAMLR Approach. *International Journal of Marine and Coastal Law,* 19:317–363.

Mitchell, B., and R. Sandbrook. 1980. *The Management of the Southern Ocean.* London: International Institute for Environmental Development.

Murphy, E. J. 1995. Spatial Structure of the Southern Ocean Ecosystem: Predator-Prey Linkages in Southern Ocean Food Webs. *Journal of Animal Ecology,* 64:333–347.

Murphy, E. J., D. J. Morris, J. L. Watkins, and J. Priddle. 1988. "Scales of Interaction between Antarctic Krill and the Environment." In *Antarctic Oceans and Resources Variability,* ed. D. Sahrhage, pp. 120–130. Berlin: Springer-Verlag.

National Oceans Office. 2002. Ecosystems: Nature's Diversity—The South-east Regional Marine Plan. Hobart, Australia. http://www.environment.gov.au/coasts/mbp/publications/south-east/pubs/natures-diversity.pdf (accessed 17 November 2010).

Reid, K., J. P. Croxall, and E. J. Murphy. 2008. The Power of Ecosystem Monitoring. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 17:S79–S92.

Sabourenkov, E. N., and D. G. M. Miller. 2004. "The Management of Transboundary Stocks of Toothfish, *Dissostichus* spp. under the Convention on the Conservation of Antarctic Marine Living Resources." In *Management of Shared Fish Stocks,* ed. A. I. L. Payne, C. M. O'Brien, and S. I. Rogers, pp. 68–94. Oxford: Blackwell.

Scientific Committee for the Conservation of Antarctic Marine Living Resources (SC-CAMLR). 1987. Report of the Sixth Meeting of the Scientific Committee (SC-CAMLR-VI). Hobart, Australia: CCAMLR.

———. 1990. Report of the Ninth Meeting of the Scientific Committee (SC-CAMLR-IX). Hobart, Australia: CCAMLR.

———. 1994. Report of the Thirteenth Meeting of the Scientific Committee (SC-CAMLR-XIII). Hobart, Australia: CCAMLR.

———. 1995. Report of the Fourteenth Meeting of the Scientific Committee (SC-CAMLR-XIV). Hobart, Australia: CCAMLR.

———. 2002. Report of the Twenty First Meeting of the Scientific Committee (SC-CAMLR-XXI). Hobart, Australia: CCAMLR.

———. 2008. Report of the Twenty-Seventh Meeting of the Scientific Committee (SC-CAMLR-XXVII). Hobart, Australia: CCAMLR.

———. 2009. Report of the Twenty-Eighth Meeting of the Scientific Committee (SC-CAMLR-XXVIII). Hobart, Australia: CCAMLR.

United Nations General Assembly (UNGA). 2007. *Sustainable Fisheries, Including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and Related Instruments.* Resolution A/Res/61/105. 61st sess. 6 March. http://daccess-dds-ny.un.org/doc/UNDOC/GEN/N06/500/73/PDF/N0650073.pdf?OpenElement (accessed 17 November 2010).

Virtue, P., S. Kawaguchi, J. McIvor, S. Nicol, S. Wotherspoon, M. Brown, R. Casper, S. Davenport, L. Finley, J. Foster, T. Yoshida, and T. Yoshiki. 2010. Krill Growth and Condition in Western Indian Ocean Sector of the Southern Ocean 30–80°E in Austral Summer 2006. *Deep Sea Research, Part II, Topical Studies in Oceanography,* 57(7–8):948–955.

Watters, G. 1997. Preliminary Analyses of Data Collected during Experimental Phases of the 1994/95 and 1995/96 Antarctic Crab Fishing Seasons. *CCAMLR Science,* 141–159.

Willock, A., and M. Lack. 2006. *Follow the Leader: Learning from Experience and Best Practice in Regional Fisheries Management Organizations.* London: WWF International and TRAFFIC International.

Zumberge, J. H., and L. A. Kimball. 1986. "Workshop on the Antarctic Treaty System: Overview." In *Antarctic Treaty System: An Assessment,* pp. 3–12. Washington, D.C.: National Academies Press.