CCAMLR Science, Vol. 9 (2002): 233–253

CCAMLR ECOSYSTEM MONITORING AND MANAGEMENT: FUTURE WORK

A.J. Constable
Australian Antarctic Division
Channel Highway, Kingston 7050
Tasmania, Australia
Email – andrew.constable@antdiv.gov.au

Abstract

Harvesting of marine living resources in the Southern Ocean is managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). CCAMLR is widely known for its ecosystem approach to managing fisheries with the maintenance of ecological relationships included in the conservation objectives. In the late 1980s, CCAMLR's precautionary approach was developed, incorporating principles of how to use scientific evidence in the decision-making process. Even though this approach was based on the management of a single species (Antarctic krill, *Euphausia superba*), it takes account of the needs of predators in the assessment of catch limits. The success of this process is due to the formulation of a management procedure which includes decision rules that specify how harvest controls will be adjusted based on the scientific information available and the assessments that arise from such information. To assist the Commission in meeting its objectives, the CCAMLR Ecosystem Monitoring Program (CEMP) was set up to detect the effects of fishing on krill predators. CCAMLR needs to adopt a management procedure which has a good chance of maintaining ecological relationships and meeting the needs of predators, incorporating: (i) operational objectives that articulate the target conditions of relevant aspects of the system, (ii) methods for assessing the status of the system, (iii) decision rules on how to adjust harvest controls given the difference between the assessment and the agreed objectives, and (iv) methods for dealing with uncertainty. This paper reviews progress in developing ecosystem-based management procedures by summarising the gaps in the existing approach, the types of models developed for the Antarctic marine ecosystem, the implications of the large scale of the fishery for designing a monitoring program to detect the effects of fishing, and the types of procedures already proposed for management of the krill fishery. It highlights the need to focus future work in these areas, including the need to evaluate candidate management procedures in advance of the expansion of the krill fishery. Most importantly, operational objectives for dependent species and feasible management options need to be clearly articulated to guide this work.

Résumé

L'exploitation des ressources marines vivantes de l'océan Austral est gérée par la Commission pour la conservation de la faune et la flore marines de l'Antarctique (CCAMLR). La CCAMLR est réputée pour tenir compte de l'écosystème dans la gestion des pêcheries : le maintien des rapports écologiques fait partie intégrante de ses objectifs de conservation. Vers la fin des années 80, la CCAMLR a élaboré une approche de précaution qui englobe le principe de l'utilisation de preuves scientifiques dans le processus de prise de décision. Bien que cette approche repose sur la gestion d'une espèce unique (le krill antarctique, *Euphausia superba*), elle tient compte des besoins des prédateurs dans l'évaluation des limites de capture. Le succès de ce processus est dû à la formulation d'une procédure de gestion qui comporte des règles de décision spécifiant comment les contrôles de l'exploitation seront ajustés en fonction des informations scientifiques disponibles et des évaluations dérivées de ces informations. Pour aider la Commission à atteindre ses objectifs, le Programme de contrôle de l'écosystème de la CCAMLR (CEMP) a été créé pour détecter les effets de la pêche sur les prédateurs de krill. La CCAMLR doit adopter une procédure de gestion qui soit susceptible de maintenir l'équilibre écologique et de satisfaire les besoins des prédateurs. Celle-ci doit donc comporter : i) des objectifs opérationnels formulant les conditions visées des aspects pertinents du système, ii) des méthodes d'évaluation du statut du système, iii) des règles de décision sur la manière d'ajuster les contrôles de l'exploitation compte tenu de la différence entre l'évaluation et objectifs convenus, et iv) des méthodes pour gérer l'incertitude. Le présent document examine l'évolution des procédures de gestion reposant sur l'écosystème en récapitulant les lacunes de l'approche existante, les divers types de modèles développés pour l'écosystème marin de l'Antarctique, les conséquences de l'ampleur de la pêcherie dans la conception d'un programme de contrôle visant à déceler les effets de la pêche, ainsi que les diverses procédures déjà proposées pour la gestion de la pêche de krill. Il met en relief la nécessité de diriger les prochains travaux sur ces domaines, en évaluant notamment les procédures de gestion possibles avant l'expansion de la pêche de krill. Mais il est primordial, pour guider ces travaux, de formuler clairement des objectifs opérationnels relativement aux espèces dépendantes et des solutions de gestion qui soient faisables.

Резюме

Управление морскими живыми ресурсами в Южном океане осуществляется Комиссией по сохранению морских живых ресурсов Антарктики (АНТКОМ). АНТКОМ широко известен своим экосистемным подходом к управлению промыслами, где поддержание экологических связей является одной из целей сохранения. В конце 1980-х гг. получил развитие предохранительный подход АНТКОМа, учитывающий принципы использования научных данных в процессе принятия решений. Несмотря на то, что этот подход основывался на управлении только одним видом (антарктическим крилем *Euphausia superba*), он учитывал потребности хищников в оценке ограничений на объем вылова. Успех этого способа объясняется созданием такого метода управления, который включает в себя правила принятия решений, определяющие, как регулировать вылов на основе доступной научной информации и вытекающих из нее оценок. С целью помочь Комиссии в выполнении ее задач была создана программа АНТКОМа по мониторингу экосистемы (СЕМР), направленная на выявление влияния промысла на питающихся крилем хищников. АНТКОМу необходимо принять метод управления, имеющий хорошие перспективы для поддержания экологических связей и удовлетворения потребностей хищников и включающий в себя: (i) оперативные цели, четко определяющие конечные условия соответствующих аспектов данной системы; (ii) способы оценки состояния системы; (iii) правила принятия решений, определяющие, как регулировать вылов с учетом разницы между оценкой и установленными задачами; (iv) методы преодоления неопределенности. В данной работе описывается ход развития методов управления на экосистемной основе путем рассмотрения недостатков в существующем подходе, видов моделей, разработанных для морской экосистемы Антарктики, значения крупномасштабного промысла для выработки программы мониторинга с целью определения последствий промысла, а также уже предложенных для управления промыслом криля методов управления. Подчеркивается необходимость сосредоточить работу в будущем на этих направлениях, включая необходимость оценки предлагаемых методов управления до расширения промысла криля. И что самое важное, при проведении этой работы должны быть четко определены оперативные цели для зависимых видов и подходящие варианты управления.

Resumen

La Comisión para la Conservación de los Recursos Vivos Marinos Antárticos (CCRVMA) administra la explotación de los recursos vivos marinos del Océano Austral. La CCRVMA goza de amplio reconocimiento por su sistema de ordenación de pesquerías basado en la conservación, e incluye el mantenimiento de las interacciones ecológicas del ecosistema como uno de sus objetivos de conservación. A fines de la década de los 80 la CCRVMA elaboró un enfoque precautorio que incluye disposiciones para el uso de la información científica en el proceso de toma de decisiones. Si bien este enfoque se basa en la ordenación de una especie (kril antártico, *Euphausia superba*), la evaluación de los límites de captura toma en cuenta las necesidades de los depredadores. El éxito de este proceso radica en la formulación de un método de ordenación que incluye criterios de decisión para controlar la explotación sobre la base de la información científica disponible, y de las evaluaciones derivadas de dicha información. El programa de la CCRVMA de seguimiento del ecosistema (CEMP) fue establecido para ayudar a la Comisión en el cumplimiento de sus objetivos mediante el estudio de los efectos de la pesca en los depredadores del kril. La CCRVMA debe adoptar un método de ordenación que pueda asegurar que la preservación de las relaciones ecológicas se van a mantener y las necesidades de los depredadores van a ser satisfechas, incorporando: (i) objetivos operacionales que expresen las condiciones deseadas en distintos aspectos del ecosistema, (ii) métodos para evaluar el estado del sistema, (iii) criterios de decisión que disponen el control de la explotación habida cuenta de las discrepancias entre la evaluación y los objetivos acordados, y (iv) métodos para considerar la incertidumbre. Este trabajo examina el avance logrado en el desarrollo de los métodos de ordenación basados en el ecosistema, presentando un resumen de las incertidumbres en el enfoque actual, los distintos modelos elaborados para el ecosistema marino antártico, las consecuencias de la pesca a gran escala en el diseño de un programa de seguimiento para determinar los efectos de la pesca y los distintos métodos que ya han sido propuestos para la ordenación de la pesquería de kril. Se destaca la necesidad de enfocar la futura labor en estas áreas, incluida la necesidad de evaluar los posibles métodos de ordenación antes de la expansión de la pesquería de kril. Por sobre todo, los objetivos operacionales para las especies dependientes y los posibles métodos de ordenación deben determinarse claramente para guiar la dirección de esta labor.

Keywords: ecosystem-based management, management procedures, fisheries conservation, CCAMLR

INTRODUCTION

The harvesting of marine living resources in the Southern Ocean has been managed by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) since 1982. Article IX of the Convention on the Conservation of Antarctic Marine Living Resources (the Convention) indicates that the Commission must use the best scientific evidence available for determining appropriate harvest controls. There was no clear process for assessing such evidence during the formative years of CCAMLR. Decisions were made only in reaction to overwhelming evidence for the need to take action (reactive management) (Constable et al., 2000). A process was needed to satisfactorily account for scientific uncertainty, such as poor precision in parameter estimates used in yield assessments as well as the potential for divergent conclusions as to which factors were important to the ecology of the stocks. Without such a process, scientific advice was marginalised when it was not unanimously supported by the Scientific Committee of CCAMLR.

Since the late 1980s, CCAMLR has developed the precautionary approach, which incorporated the principles of how scientific evidence could be used in the decision-making process (Constable et al., 2000; CCAMLR, 2000). This approach is based on the management of a single species (Antarctic krill, *Euphausia superba*) but does take account of the needs of predators in determining catch limits. Its application is based on a management procedure with pre-agreed decision rules that specify how harvest controls (catch limits) will be adjusted given the scientific assessments available (de la Mare, 1996, 1998).

Amongst other achievements, CCAMLR is widely known for its ecosystem approach to managing fisheries. Article II of the Convention specifies that the conservation objectives include the maintenance of ecological relationships between species. In addition to the precautionary approach, CCAMLR needs to determine what else may be required to ensure that the application of these precautionary catch limits meet the objectives of the Convention. It would be contrary to the precautionary approach to wait until there was overwhelming evidence of indirect impacts of fishing on predators before further harvesting controls are applied.

CCAMLR needs to adopt a management procedure which has a great chance of maintaining ecological relationships and meeting the needs of predators (see Figure 1). Such a management procedure would incorporate: (i) operational objectives that articulate the target status of relevant aspects of the system, (ii) methods of assessing the status of the system, (iii) decision rules governing how harvest controls should be adjusted given the difference between the assessment and the agreed objectives, and (iv) methods for dealing with uncertainty, including uncertainty in ecosystem (‘physical world’) function, and achieving scientific consensus.

The management procedure should be able to work effectively despite uncertainty so that correct decisions (by consensus in CCAMLR) are most likely to be made in sufficient time by the Commission to conserve the Antarctic marine ecosystem and to enable rational use of the marine living resources.

The development of an ecosystem-based management procedure is the primary task of the CCAMLR Working Group on Ecosystem Monitoring and Management (WG-EMM), which is a subsidiary body of the Scientific Committee. The evolution of the work of this working group is presented by Drs I. Everson and D. Miller in this volume. This paper discusses the future steps which need to be addressed in the development of such a management procedure, drawing on the existing work where possible to provide illustrative examples. First, the paper examines the gaps in the existing approach to achieving the conservation objectives for predators. Second, a background summary is given on current approaches to modelling

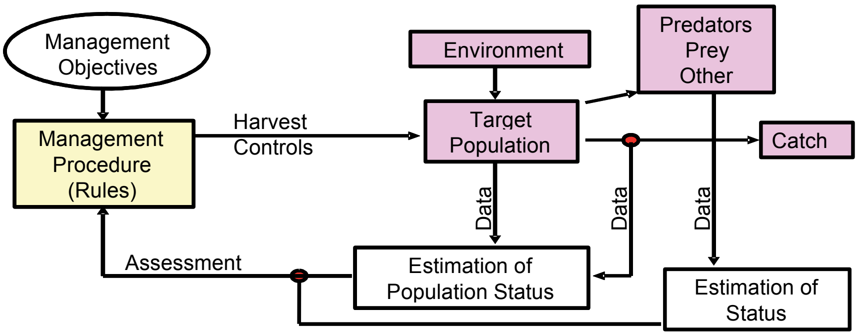

Figure 1: An illustration of the ecosystem-based approach to managing the effects of fishing on dependent and related species (after de la Mare, 1996). The management procedure is a set of decision rules used to adjust harvest controls in response to assessments such that the operational objectives will be highly likely to be met. The physical world (shaded boxes) represents the actual state of the system which is observed through the monitoring program. Assessments take account of uncertainty as to how the physical world functions and the relationship between the monitoring program and the physical world.

the Antarctic marine ecosystem. Third, a general framework is presented on how the ecosystem could be monitored in support of a management procedure, particularly as it relates to the scale of the krill fishery. Fourth, example management procedures for krill fisheries are discussed in light of approaches presented, mostly tacitly, in the literature. In conclusion, a work plan for the development of an ecosystem-based management procedure is presented.

Gaps in the Existing Approach

Currently, the Krill Yield Model (Butterworth et al., 1994 derived from the approach of Beddington and Cooke, 1983) is used to determine the long-term sustainable yield (catch limit) for krill fisheries following a fishery-independent survey of krill biomass. The decision rule specifying how the biomass is translated into a precautionary yield includes a predator criterion and a recruitment criterion (de la Mare, 1996). The predator criterion endeavours to account for the needs of predators by aiming to ensure that 75% of krill escapes the fishery. This differs from the usual single-species approach, which would aim to ensure that approximately 50% of krill would escape the fishery in order to sustain the productivity of the stock.

These catch limits are set over large areas (harvesting units) of the Southern Ocean, e.g. the South Atlantic (Statistical Area 48). Such limits need to be subdivided into small-scale management units (predator units) in order to avoid substantial local effects of fishing that may arise if all of the catch was taken from only a small area (SC-CAMLR, 2000). This issue is currently being addressed by WG-EMM.

The catch limits are recommended with the expectation (prediction) that such harvest controls will not affect predators in an unacceptable way. A monitoring program is needed to provide some checks on whether the predictions could be incorrect, in the manner of feedbacks to management (Holling, 1978). The monitoring program would be expected to have high power for achieving this. A 'rule of thumb' is for power to be greater than or equal to 0.8 (see Peterman, 1990 for discussion).

The CCAMLR Ecosystem Monitoring Program (CEMP) was established to provide a foundation for distinguishing the effects of fishing from the effects of environmental variability and change (see Agnew, 1997 for a full description). An early review of the program indicated that the results would vary in their value to management but some general procedures could be applied to give general background indicators of the status of the system (Croxall, 1989). Recent work indicates that more quantitative integrated assessments may be possible but the types of data to be included in the assessments remain to be determined (de la Mare and Constable, 2000, see below).

Importantly, the objectives in Article II of the Convention also indicate that if harvesting alters the ecosystem it must then be able to recover in two to three decades. Thus, having a change in the ecosystem attributed to harvesting is insufficient to satisfy the objectives of the convention. Any such effects need to be identified in sufficient time for harvesting activities to be modified before the change is unable to be reversed in the stipulated time of two to three decades.

CCAMLR's precautionary approach can still be improved by refining assessments of krill yield based on new estimates of krill demographic parameters as well as by subdividing the precautionary yield into small-scale management units. This remains a predictive approach to managing krill fisheries. CEMP will need to signal when harvesting should be modified to avoid irreversible changes to the ecosystem. It should be able to achieve this within a spatial context, such that management actions are appropriately scaled (Murphy et al., 1988).

Importantly, the ecosystem-based approach requires operational objectives for non-harvested species (Beddington and de la Mare, 1985; Butterworth, 1986; de la Mare, 1986a). In that respect, these objectives will need to account for uncertainties, including those in relation to understanding of ecosystem function and the dynamic relationships amongst predators, and between predators and their prey.

Current Theoretical Models of the Antarctic Marine Ecosystem

Models of the Antarctic marine ecosystem mostly comprise: (i) statistical models of the distribution and abundance of marine species, particularly as they relate to krill (see Constable et al., in press for review); (ii) population models of krill (e.g. Constable et al., in press); and (iii) estimates of consumption of krill by predators (e.g. Croll and Tershy, 1998; Croxall et al., 1990). Few models take account of the spatial and temporal dynamics of the system (but see Croxall et al., 1985, for a spatial and seasonal analysis of krill consumption by seals and seabirds, and Mangel and Switzer, 1998, for spatial and temporal variation in the foraging success of Adélie penguins) or the uncertainties surrounding the structure of the models or the estimates of parameters.

For the purposes of developing an ecosystem-based management procedure, plausible models that capture the dynamics of the major species are needed (Beddington and de la Mare, 1985; Butterworth, 1986; de la Mare, 1986a). These models are not necessarily used for predicting what will happen to the ecosystem in the event of an expanded krill fishery but are used to test the robustness of management procedures to uncertainties in: (i) model structure and function, (ii) trends over time, such as climate change, (iii) estimates of parameters used in assessments, (iv) explanation of cause and effect, and (v) the predictions of the types and magnitudes of effects of fishing arising from the models and/or assessments (Butterworth and Punt, 1999).

An early attempt at dynamic modelling for the Southern Ocean marine ecosystem was provided by Green (1977). Theoretical approaches to the effects of exploitation in the region were explored by May et al. (1979) and Beddington and May (1982).

Models designed to directly explore the effects of krill harvesting on predators while taking account of uncertainties did not appear until the late 1980s and early 1990s. Three published modelling approaches have been presented to CCAMLR – Butterworth and Thomson (1995, extended in Thomson et al., 2000), Mangel and Switzer (1998) and Constable (2001) – although such modelling was also undertaken for the CCAMLR Working Group on Developing Approaches to Conservation (WG-DAC) in the 1980s by de la Mare (1988). The characteristics of the models are summarised in Table 1.

To date, the de la Mare model is the only one to have a closed predator–prey system; it is modelled with a single predator and single prey. All four models have been used to explore the consequences of different harvesting strategies on predators.

For the purposes of developing a management procedure, it will not be sufficient to develop only a single 'best' view of the marine ecosystem. Modelling will help test the plausibility of different hypotheses about how the system functions. However, some structural uncertainties may be difficult to resolve. For example, krill are known to move from west to east in the Scotia Sea (Hofmann et al., 1998). However, the degree to which krill are retained in different locations is largely unknown but could have consequences for the dynamics of local populations (Constable et al., in press). A management procedure will need to account for these types of uncertainties. For example, until better knowledge is available, the harvest strategy may need to be one that does not fish for krill upstream from predator colonies in summer.

The important task will be to develop models with sufficient structural complexity to capture the dynamics of the major species and how they might respond to changes in the ecosystem, noting that

Table 1: Characteristics of the four principal approaches to modelling the Antarctic marine ecosystem.

	de la Mare (1988)	Butterworth and Thomson (1995); Thomson et al. (2000)	Mangel and Switzer (1998)	Constable (2001)
Effect direction	Closed food-web model with effects of changes in prey on predators and the converse	Effect of changes in prey on predator (potential to examine effect of change in predators on prey)	Effect of changes in prey on predator	Effect of changes in prey on predator (potential to examine effect of change in predators on prey)
Prey	Single short-lived prey (potential for many)	Krill	Krill	Potential for many
Predators	Single long-lived predator (potential for many)	Many individual predators not interacting	Adélie penguin	Potential for many predators with competition and complex trophic structure
Predator dynamics	Biomass	Age-structured population	Autecological energetic model	Age-structured population
Prey dynamics	Biomass with stochastic recruitment	Age-structured population with stochastic recruitment	Biomass	Biomass Physical forcing of prey dynamics
Data used	Estimated parameters can be used	Some fitting of models to estimated parameters	Estimated parameters	Estimated parameters can be used
Spatial scale	None	None	Colony	None
Temporal scale	Years	Years	Seasons	Years
Predator limits	K	K	Food density	K
Prey limits	K	Population stochastic model	Maximum density	K
Effects on predators	K, B, M, R	N	M, R	P, B, N, R

K = carrying capacity; N = population numbers; M = mortality; R = reproduction; P = productivity; B = biomass these models will not incorporate all interactions amongst all species and the physical dynamics of the system (Butterworth, 1986; de la Mare, 1998). The aim will be to develop these kinds of models, taking care to adequately encapsulate important indirect effects on the major species (see Yodzis, 2001 for review).

Scales of Monitoring and Management for a Krill Fishery

The issue of scales of interactions of different species with each other, with the environment and with fisheries has long been discussed in relation to the Southern Ocean (e.g. Murphy et al., 1988). For managing fisheries, predators are monitored to determine whether krill harvesting is affecting their populations and to signal when harvest controls (CCAMLR conservation measures) need to be modified to achieve conservation objectives for predators. Such monitoring should take account of: (i) the spatial and temporal relationships between predators and krill, and (ii) the metapopulation structure and dynamics of the predators. The first part will indicate how local consumption of krill in foraging grounds might be affected by krill harvesting. The second part will dictate how any effect at the local scale might be manifested in the whole predator metapopulation, depending on the linkages between the local populations of that predator. In other words, how does a change in local krill consumption translate to a change in one or more characteristics of the local population of predators (e.g. a land-based colony) at that time, and then how might such local effects be translated over time to impact on the whole population? For some species, the effects may be contained within the local population due to a high degree of site fidelity from one year to the next. For more mobile species, the effects may be promulgated through the whole population over a small number of years. Importantly, what can be used to signal when, and by how much, population-wide and regional effects are likely to occur?

The most accessible predators for monitoring are those which are on land ('land-based') during their breeding season. Predators that do not spend time on land are difficult to monitor. An important question is whether these accessible colonies are representative of the region. Does a change in one predator species at a given location at a given time represent the changes experienced by all species of predators at that time, and is that change representative or indicative of the overall impact of the fishery over time on the populations of predators?

For the Antarctic marine ecosystem, both the fishery and CEMP are in early stages of their development, even though both have been under way for significant periods. The krill catch is less than 5% of the precautionary catch limits set by CCAMLR. CEMP is well developed in only a few locations and only for a subset of land-based predators (Agnew, 1997). It is unlikely that CEMP will be able to expand in a meaningful way in the near future to include predators found solely offshore, such as whales and crabeater seals. Monitoring of other seals, penguins and seabirds would be possible at more sites but would require a substantial increase in field operations.

The principles for designing a monitoring program to adequately test for the effects of an environmental perturbation, such as fishing, are well described in the literature (e.g. Downes et al., 2002; Mangel et al., 1996; Peterson, 1993; Stewart-Oaten et al., 1992; Underwood, 1989, 1990, 1994). It is now commonly considered that fishing is a large-scale experiment (Beddington and de la Mare, 1985; Ludwig et al., 1993; Mangel et al., 1996; Walters, 1986). In order to test for the effects of fishing, there are two parts of the system that can be manipulated – the first is the location and timing of harvesting activities while the second is the location and timing of monitoring. If the location and timing of fishing cannot be controlled then the monitoring program needs to have appropriate coverage across the whole of the harvesting unit and across all times. In this case, the monitoring effort will need to provide representative information on the effects of fishing. If the monitoring program cannot provide this coverage then the effects of fishing may remain undetected unless the harvesting activities can be limited to the areas and times for which effects can be monitored.

Ultimately the power of the program for management purposes will be dictated by the spatial and temporal relationships between predator populations, the krill population, harvesting activities and monitoring activities as well as the procedures that have been put in place to translate the observed changes into management action.

Spatial Configuration of Monitoring

Hypothetically, the simplest case to consider as regards monitoring is when harvesting is occurring at random throughout the range of the harvested population (such as krill) and when the abundance of predators and krill can be easily estimated. In this case, the effects of fishing on predators could be assessed relatively easily. In reality, the krill distribution is patchy, the fishery targets these patches and may be selective as to which locations are favoured and predator foraging also reflects that patchiness. Also, krill potentially move over large distances.

These non-random distributions are difficult to assess over large scales. Regular monitoring of krill is primarily at local scales (foraging areas) rather than over the range of the krill population and, at best, only annually. Similarly, regular monitoring of predators is primarily limited to the age groups of populations found breeding on land, and monitoring is restricted to the breeding period.

Local availability of krill will be influenced by the population abundance of krill combined with the factors that influence the spatial patchiness of the population (Hofmann et al., 1998; Murphy et al., 1988; Miller and Hampton, 1989). As a result, the density of krill in a specified foraging area of predators may or may not be directly correlated to the population abundance.

For predators, each colony is a single sampling replicate influenced by the local abundance of krill. Ideally, many replicate colonies randomly distributed throughout the range of the krill population will be needed to provide representative estimates of the overall status of predators relative to the overall status of prey. The number of colonies needed will be dictated by the degree of homogeneity of the krill density throughout the population combined with the variability expressed in measurable parameters. Ideally, the sources of variation need to be evaluated prior to the full implementation of the monitoring program so that the number of sites chosen to be used is sufficient for management purposes.

Given the expense and difficulty of repeated sampling of the whole krill population as well as the sampling of many colonies, it may not be possible to satisfy the usual demands for representative sampling. Consequently, the loss of power in the spatial design will need to be compensated for in how the information is used in assessments encapsulated within a management procedure (e.g. Mapstone, 1995).

Monitoring over Time

The timing of sampling within a year in order to determine the relationship between krill and predators for that year is dependent on the objectives being addressed (discussed below). The main issue to be taken into account when designing a time series of sampling events is the magnitude of interannual variation that might arise (see Murphy et al., 1988 for review), including variation in abundance and/or productivity of krill, the availability of krill in foraging grounds, feeding behaviour of the predators, including prey switching (e.g. fur seals – Agnew et al., 1998), and predator productivity (Constable, 2001). In addition, variation in the fishery might arise through varying dependence on particular fishing grounds coupled with varying relationships between fishing grounds and foraging areas.

Consequently, changes in predator performance from one year to the next may simply be due to this natural variation. It is important that a baseline period be established prior to, or at least in the early phase of, fishery development (de la Mare and Constable, 2000). Changes in predator performance can be compared relative to this baseline as the fishery develops in order to determine whether fishing might be affecting predators. It will be necessary to determine what magnitude of change in predator performance will trigger modification to the harvest controls.

Some careful attention may also need to be given to monitoring for trends in abundance of krill, such as long-term trends or cycles in abundance (Brierley et al., 1999).

Monitoring to Detect Effects of Fishing

Given the complexity in the spatial and temporal structure of the Antarctic marine ecosystem, how could a monitoring program be designed to detect the effects of fishing?

Table 2 summarises the major categories of factors that might influence replicate observations of a predator parameter (indicator) at a given location. The table can be interpreted in the following way. For the purposes of detecting the effects of fishing, the value of the indicator is expected to correspond directly to the amount of the harvest species (krill) consumed. This value will be influenced by the degree to which the indicator is affected by such consumption (correlation with amount consumed) and the precision of the field method used to estimate the parameter. This correlation may also be dependent on the total quantity of food consumed and the composition of the diet, i.e. how much of other prey are eaten?

The amount consumed will be affected by the amount of krill available and the functional feeding relationship between the predator and krill

Table 2: General factors that potentially influence the characteristics of the population of harvest/prey species, the consumption of those species by predators and the consequent values of predator parameters (indicators) being monitored. The factors influencing these characteristics are combined into functions at the bottom of the table.

Category	Factor	Symbol
Large-scale prey population	Abundance of target species	A_L
	Large-scale dynamics (production, mortality)	D
	Spatial patchiness (affected by behaviour, oceanography, ice, mortality, production)	S
Predator foraging grounds	Abundance of target species	A_f
	Local population dynamics (immigration, emigration, production, mortality)	L_d
	Effect of ice, oceanography and other physical factors on availability	L_p
	Functional feeding relationship	f
Harvesting	Large-scale effects on abundance in a given year	E_a
	Small-scale effects on availability in a given year	E_f
Interannual variation	Large-scale dynamics in abundance	T_a
	Small-scale availability	T_L
	Trends in productivity	T_P
	Trends in natural mortality	T_M
	Changes in behaviour of fishery	T_h
	Trends in fish catch	T_F
Indicator	Consumption of target species	C
	Correlation between indicator and consumption of target prey species	c
	Bias	B
	Measurement precision	$\mathcal{E}$

Characteristic	Function
Observation of a predator parameter (indicator)	$I(C,c,B,\mathcal{E})$
Consumption of prey by predator	$C[f(A_f,E_f),L_d, L_p]$
Local abundance of prey	$A_f[A_L,S,T_L,T_h]$,
Total abundance of prey	$A_L[D,E_a,T_a,T_P,T_M,T_F]$

availability. It will also be influenced by physical factors that might restrict foraging activities, such as the presence of sea-ice.

The local availability of krill in a foraging area will be influenced by its regional abundance and by the factors that determine its patchiness, dynamics and productivity, particularly in relation to the foraging area of interest.

The regional abundance of krill will be influenced by the general dynamics of the population and the influence of interannual variation in the physical environment, productivity and natural mortality.

Fishing can affect a monitored predator in two ways. First, it may not overlap directly with the foraging area. In this case, it will affect the regional abundance of krill (Figure 2a), which is the type of effect examined by Butterworth and Thomson (1995) and Thomson et al. (2000). This population-wide or 'global' effect could be considered as a proportional change in overall density (E_a in Table 2). Second, fishing might occur in the foraging ground of the monitored predator and is likely to cause a reduction in the availability of krill to the predator (Figure 2b). This local effect in foraging grounds would also be a proportional change in density (E_f in Table 2). This latter reduction would be expected to result in an observed change in the indicator in that season compared to changes arising from the more distant large-scale effects on the whole krill population which may not become manifest in the foraging area until some time later.

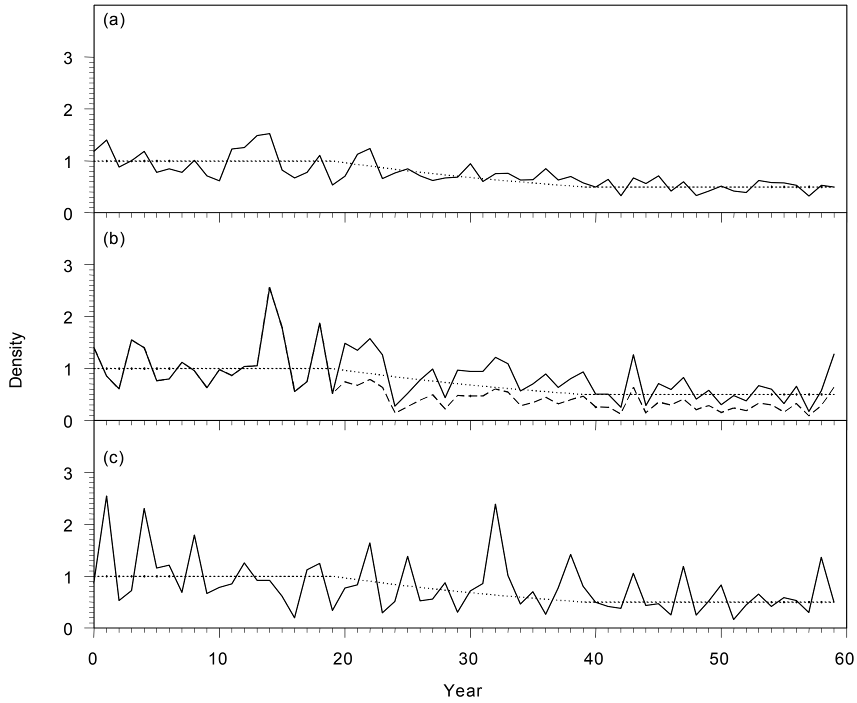

Figure 2: Potential effects of fishing on krill density. The dotted lines in each panel show a reduction in the median abundance of krill to 0.5 of the pre-exploitation level over the period between years 21 and 40, sustained thereafter by fishing: (a) population-wide interannual variation in krill density (solid line); (b) a consequent time series of density in a local area (solid line), with abundance in the local area being influenced by the global population density but showing interannual variation in the relationship between global and local density. The dashed line indicates that the local density after fishing has taken 0.5 of the available abundance; (c) time series of density in a second local area, as in (b), but with no correlation between the two local areas in terms of how interannual variation in the physical environment affects the relationship between global and local densities.

These two types of effects, as proportional reductions in krill density (E_a and E_f), will potentially result in different signals in the monitoring program. If the fishery is random throughout the range of krill population then there would be little or no difference between E_a and E_f and any predator colony could be monitored. However, if harvesting is non-random then, clearly, E_f in areas being harvested will be greater than other areas that only experience the global effect of E_a (Figure 2c). If this is the case then it would be better to monitor predators in the areas in which fishing is occurring because the effects in harvested areas will potentially be greater than in non-harvested areas and more easily detected (see Figure 2).

Non-random harvesting is likely to provide more opportunities for discriminating between the effects of fishing and the effects of changes in other factors in the environment. This is because krill metapopulations cover large geographic areas in the Antarctic. Each metapopulation is likely to experience great differences in oceanography, ice and climate and, as such, the effects of fishing are unlikely to be comparable between different metapopulations (Nicol et al., 2000). Thus, a randomly distributed fishery throughout the range of a krill population will mean that all predator monitoring sites will be affected equally by the fishery and there will be no capacity to understand the relative effects of fishing and the environment.

This framework for local and population-wide effects provides a foundation for designing a monitoring program. If no areas or predators are to be disproportionately affected by fishing once the fishery is fully established, then E_a and E_f should be equal in the fully developed fishery or, at least, E_f for an area or predator should never exceed E_a.

In the absence of information about appropriate levels of the effects of fishing (E_a and/or E_f) it is important to determine such levels at the local scale during the early stages of the fishery and to then use the indicators of these effects in a wider monitoring program as the fishery develops. It is important to do this early because of the need to ensure that E_f does not exceed the magnitude of E_a that will arise in the fully developed fishery. This approach will require cooperation of the fishery to concentrate its effort in only a few areas to establish the nature of the effects of fishing and how these can best be managed.

The ability to differentiate between environmental variation and the effects of fishing can only be attained by contrasting monitoring results from fished areas with nearby reference locations, which have monitoring but no fishing. Such differentiation will only be available in the early phases of the fishery while E_a is substantially less than E_f. If there is no requirement to make such differentiation then such reference locations may not be required.

de la Mare and Constable (2000) indicate the work required to design a robust monitoring and assessment method for a monitoring program. Ultimately, the configuration of the monitoring program, including the number of sites, foraging areas, number of years and the predators and krill surveys required, will be determined by the way in which the information will be incorporated into a management procedure. Some consideration will need to be given to the different scales of interaction for different predators, such as between seals, penguins, seabirds, whales, fish and squid.

Examples of Proposed Management Procedures for Krill Fisheries

A management procedure is primarily a set of agreed decision rules that are used to adjust harvest controls based on information emanating from a monitoring program. The development of an effective management procedure requires: (i) **operational objectives** for the ecosystem, (ii) methods for **assessing** the status of the system following the monitoring of **indicators,** and (iii) the **decision rules** for setting harvest controls based on the relative difference between the assessment and the objectives (see Figure 1; de la Mare, 1986a, 1986b, 1996). The decision rules also provide a means of accounting for uncertainties. The development of a management procedure within CCAMLR is best illustrated by the precautionary approach for estimating long-term annual yields of krill, including the work of WG-DAC (e.g. Butterworth, 1986; de la Mare, 1986a, 1988; see Constable et al., 2000 for background), and methods used in the International Whaling Commission (see de la Mare, 1986b, 1996; Butterworth and Punt, 1999; Cooke, 1999 for review). In the case of the precautionary approach for krill, the objectives are couched in terms of target and critical limit **reference levels** known respectively as the predator criterion (target median status of the spawning stock is 0.75 of the pre-exploitation median status) and the recruitment criterion (lower acceptable limit of abundance for spawning stock is 0.2 of pre-exploitation median) (see CCAMLR, 2000 for a full description). This management procedure is described in more detail below and in Miller (2002 – this volume).

This section reviews existing examples of ecosystem-based management procedures that have been proposed (usually implicitly) from time to time in CCAMLR and how they will assist CCAMLR in achieving objectives as regards predators.

It is important to note that indicators may not necessarily be directly related to the measurable quantities specified in the operational objective, such as critical predator abundance. The assessment is the tool by which the indicator can be related to the status of those quantities. For example, the precautionary approach for krill has objectives couched in terms of the median spawning stock biomass, but no field estimation of this is necessary for the decision rule to be applied (see Miller, 2002 – this volume, for a presentation of the decision rule described above).

For each example, a summary of the main structural features of each management procedure are given, followed by a brief discussion on important issues that need to be addressed during their evaluation and prior to implementation.

Example 1: Precautionary catch limits for target species

- *Objective*: the median escapement from the fishery of the krill spawning stock should be 75% (current CCAMLR precautionary approach for krill).
- *Decision rule*: find the long-term annual yield as a proportion, γ, of a biomass estimate prior to exploitation, B_0, that is highly likely to ensure the level of escapement is achieved and for which there is only a low probability of stock depletion (based on Beddington and Cooke, 1983).
- *Indicator*: biomass of krill population.
- *Monitoring*: single estimate of krill biomass, krill demography.

- *Assessment method*: age-structured krill population projection model with Monte Carlo simulations to account for uncertainty (Butterworth et al., 1994).

This management procedure is recognised as being the first step to establishing an ecosystem-based management procedure for the krill fishery by taking account of predators in the assessment process. It is also recognised that the requirements of predators remained unknown in this process and that the level of escapement will need to be refined as these requirements become better understood. This approach provides an assessment of the long-term constant annual yield of krill and, as a result, provides long-term security of catches for the fishery. It is a predictive approach. The link between a single estimate of biomass and the median status of the spawning stock is through the development of the population projection model based on estimates of krill demographic parameters and recruitment variability (Butterworth et al., 1994). Currently, there are no mechanisms in place within this management procedure to (i) check whether the escapement is sufficient for predators, (ii) judge whether the effect on predators is within acceptable bounds, i.e. there is no agreement on the objectives for predators, and (iii) whether the median abundance of the spawning stock remains at or above 75% of the pre-exploitation median.

Example 2: Target population size for predators

- *Objective*: abundance of predator populations should not fall below 50% of that prior to harvesting of the prey species (Butterworth and Thomson, 1995; Thomson et al., 2000).

- *Decision rule*: find the long-term annual yield as a proportion, γ, of a krill biomass estimate prior to exploitation, B_0, that will result in specified predator populations being retained at 50% or more of their abundance prior to krill exploitation.

- *Indicator*: biomass of krill population.

- *Monitoring*: single estimate of krill biomass; krill and predator demography and functional feeding relationship between predators and krill.

- *Assessment method*: age-structured krill population model with additional models of predator–prey system to assess changes in abundance of predators, with Monte Carlo simulations to account for uncertainty (see Thomson et al., 2000 for full details).

As for Example 1, this uses a population projection model to assess the appropriate catch limit to meet the objectives based on an estimate of krill biomass. In addition, it has the added complexity of the predator–prey system incorporated into the assessment. Thomson et al. (2000) indicate that there are uncertainties in the model structure that need to be accounted for before this approach would be ready for use. This procedure explicitly states the objectives for predators but will need a monitoring program to check whether the abundances of the selected predators are kept at or above their target levels. A survey of key predators would be required to establish the status of the predator populations prior to the development of the fishery.

Example 3: Average fitness of predators not reduced

- *Objective*: predator fitness remains unaffected by fishing (Boyd, 2002).

- *Decision rule*: if local krill density falls below critical level then fishery will be closed.

- *Indicator*: krill density.

- *Monitoring*: annual krill density in the foraging grounds of predators; relationship between predator fitness and krill density in foraging grounds prior to harvesting.

- *Assessment method*: statistical model relating predator fitness and the density of krill in the nearby foraging grounds; a model that predicts the availability of krill in the forthcoming fishing season.

This example relies on the development of an assessment model relating predator fitness and krill availability. Boyd and Murray (2001) showed that a combined index of summer land-based predator parameters (de la Mare and Constable, 2000; Boyd and Murray, 2001 – termed 'composite standardised indices') at South Georgia can be related to estimates of krill density from the local area using an asymptotic function (Figure 3). Boyd (2002) argued that the index was related to the fitness of those predators. He proposed that predator fitness could be retained at approximately existing levels if the fishery only had access to the foraging grounds when krill was at such a density that the fishery would cause little change to fitness. Thus, it was proposed to identify the critical density of krill below which substantial reduction in fitness might arise. If the krill density is below this level then the fishery was to be closed.

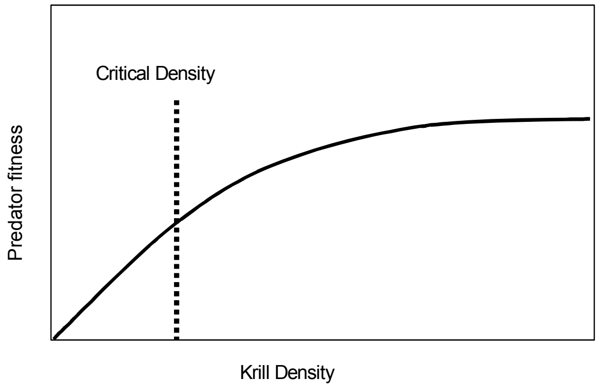

Figure 3: A functional relationship between predator fitness and local krill density in the local foraging area, used to establish a critical density such that krill fishing in the foraging area would be closed if the density of krill was less than the critical level (after Boyd, 2002).

The application of composite standardised indices in this way provides an appealing alternative to applications considered in the past. Nevertheless, the appropriateness of predator parameters for inclusion in the index as representative measures of fitness (lifetime reproductive success) and the application of the index in this way will need to be carefully considered in the formulation of the relationship between the index and krill density and for its use in a management procedure (see de la Mare and Constable 2000, for further discussion on the development of these indices). Of importance here is whether this approach will provide the protection to lifetime reproductive output as expected.

The other aspect to this approach is the need for a method of assessing when the krill density is below the critical level in a given season. The usual method for such an approach would be to conduct regular krill surveys in the seasons prior to fishing and use a predictive model to estimate abundance in the following season. Such a model has been developed for krill at South Georgia (Brierley et al., 1999) but its efficacy has not yet been tested.

Some thought will need to be given as to how predators could be safeguarded from errors in the assessment framework. For example, a number of predator parameters, such as reproductive success, are density dependent (Constable, 2001). The relationship in Figure 3 is likely to alter if predator abundances change because the consumption requirements will change. The monitoring program could be used to determine whether the relationship between predator performance and krill density alters over time. However, if such a change occurs, what adjustments could/would be made to the fishery? Would action be taken in sufficient time to prevent irreversible change?

This approach could not be readily applied to other areas unless a long-term monitoring program already existed to generate the relationship developed by Boyd and Murray (2001). The relationship is also dependent on the consumption requirements of predators in the foraging area of interest. A first approximation of the critical krill density in the new area could be to simply prorate this density by the relative total consumption per area. Such an approximation may fail if there are different feeding behaviours in these new areas, such as prey switching or movement to other areas when krill is not very abundant.

A further consideration will be to how to allow for recovering species. In this case, it may be important to have higher critical krill densities.

One aspect of this approach to be considered is the potential cost to the fishery. It differs from the existing approach to the krill fishery (Example 1), which provides for a long-term constant annual yield, in that it would require that the annual fishery be closed, substantially reduced, or constrained when krill density is below the critical level.

Example 4: Median predator productivity arising from harvested species should not fall below 80% of the pre-exploitation level

- *Objective*: median predator productivity attributed to the consumption of harvested species to be maintained at or above 80% of its level prior to harvesting (Constable, 2001).

- *Decision rule*: krill catch adjusted after comparison of predator productivity with baseline and expected outcomes.
- *Indicator*: index of predator productivity.
- *Monitoring*: parameters necessary for estimating predator productivity attributed to the consumption of harvested species (e.g. predator abundance, weight, diet).
- *Assessment method*: initial examination of the properties of productivity indicators; statistical assessment of predator productivity following a baseline time series being established.

This proposal is based on the assumption that catches will reduce the total production of predators arising from those harvested species. How much the predators are affected will depend upon the surplus production of the harvested species that could be taken by the fishery without competing with the predators; some will be affected more than others, according to their dependence on the harvested species. This approach does not try to set targets for individual predator species, whose populations may not be stable, but endeavours to ensure that the overall production of predators is not substantially reduced.

Constable (2001) outlines a rationale and method for using this approach in a management procedure, in which estimates of predator production attributed to the consumption of harvested species, *W*, is estimated at regular intervals. It is proposed that the catch is adjusted upwards or downwards depending on the frequency of *W* being greater or lower than the range limits set according to a baseline time series (Figure 4).

Currently, this proposal has only been developed in theoretical terms. The approach needs to be developed further, particularly in relation to the decision rules and an efficient monitoring program to support the procedure.

Constable (2001) noted that the utility of decision rules based on *W* for use in a management procedure should be evaluated to determine whether they are robust against uncertainties arising from errors in the estimates of parameters or *W* and for the likely case of sampling being limited to only a subset of predators of harvested species.

Example 5: No interference by fisheries near colonies with land-based predators

- *Objective*: to eliminate the potential for interference with foraging of land-based predators by fisheries.
- *Decision rule*: exclude fishery from critical foraging locations and seasons.
- *Indicator*: foraging activity.
- *Monitoring*: predator abundance and foraging locations.
- *Assessment method*: evaluation of foraging density to define the limits of critical foraging locations.

One way of eliminating direct competition between fisheries and land-based predators would be to close important foraging areas for these predators so that fisheries would not directly reduce the availability of food. Such an approach could be applied by continually monitoring the foraging activities of predators and adjusting the boundaries of the areas as the foraging changes.

While this approach may be appealing, it will not remove the need for a monitoring program to check that predators are not adversely affected by krill harvesting in areas distant from the foraging grounds (see monitoring above). For example, a reduction in the regional abundance of krill may result in more widespread winter foraging by predators based on land in summer, potentially being inadvertently affected through this approach. Also, the fishery may become concentrated in areas nearby that could affect sea-based predators, which cannot be monitored in a manner which would allow detection of the effects of fishing on those predators before irreversible changes arise (Beddington and de la Mare, 1985).

This approach would need careful implementation to ensure that, at the very least, sea-based predators are not disproportionately affected by fisheries.

Developing an Ecosystem-based Management Procedure

The existing examples of management procedures described above have varying levels of appeal. However, they each have their attendant uncertainties as regards how well they might perform in practice. Most importantly, the operational

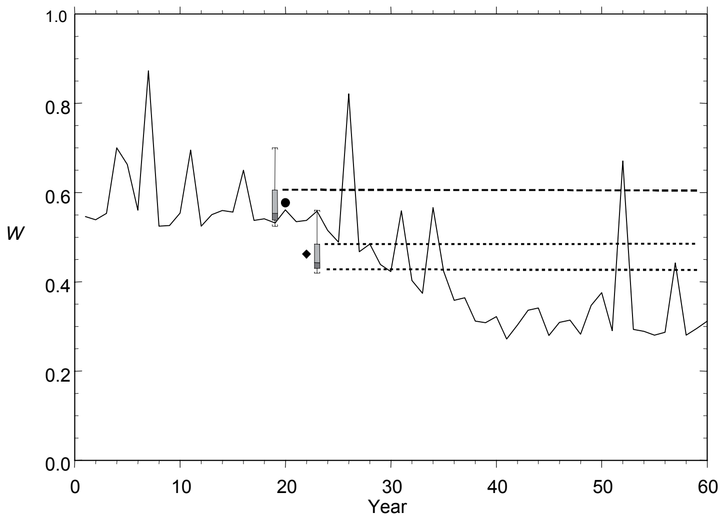

Figure 4: Hypothetical time series for the productivity indicator, *W*, over 60 years. No fishing occurred in the first 20 years, over which time a baseline *W* series was used to estimate the reference mean level (solid circle). The target mean level for *W* is shown as a solid diamond. The box and whisker plots show the frequency distribution of *W* during that baseline period. The dotted horizontal lines are critical range lines between which *W* is generally expected to remain after fishing has become established. The dashed line refers to an interim upper range limit during the period when the system is adjusting to the fishing activity. In this example, the trend for *W* to remain below the lower range limit after 16 years of fishing would signal that a reduction in fishing was required. If values of *W* were frequently greater than the upper range limits, fishing could conceivably be increased (see Constable, 2001 for details).

objectives for predators remain to be articulated and agreed by CCAMLR, despite the fact that this need was expressed at an early stage (e.g. Beddington and de la Mare, 1985; Butterworth, 1986).

The example procedures presented here include various objectives: managing predators as if they are harvested species (Example 2), recognising that fishing will reduce the amount of productivity able to be utilised by predators (Example 4), and endeavouring to have a negligible effect on the current status of predators by minimising the impacts on the fitness of species (Example 3). The above discussion on monitoring indicates that the presence of a fishery at the levels established using the precautionary approach is likely to have some consequences for predators, despite the location of harvesting. The degree to which a fishery will affect predators will be dependent, in part, on how much and how often there will be surplus krill available to all predators and the fishery.

As indicated above, it is during the early phases of the fishery that most information on the potential for effects can be learnt, particularly if an experimental approach can be taken (Beddington and de la Mare, 1985; Butterworth, 1986). It is also during the early phases of the fishery that a management procedure needs to be adopted to put in place agreed ways of managing the fishery, based on the information available combined with an effective monitoring program to ensure the objectives can be met in the longer term.

This review outlines the existing proposals for management procedures, each of which need further evaluation, along with the existing models of how the Antarctic ecosystem functions as well as approaches for constructing ecosystem-based simulation models. The next stage in the program of work for WG-EMM is to assess the plausibility of the ecosystem and food-web models, provide input to the further development of such models and, most importantly, to evaluate these and other management procedures prior to the expansion of the krill fishery.

The evaluation of potential management procedures in advance of the full development of a fishery involves building simulation models of the system as shown in Figure 1, to test how well the operational objectives for the ecosystem can be met given a combination of decision rules, monitoring programs and assessment methods. This process has been well described in the literature (e.g. Cooke, 1999; de la Mare, 1986a, 1988, 1996, 1998; Mangel, 2000; Smith, 1993). It should enable a number of questions to be addressed.

First, what combinations of monitoring, assessments and decision rules meet the required performance standards for different plausible formulations of the Antarctic ecosystem? Here, performance is judged by how well the objectives are met in the model ecosystem. It is important to identify early whether a monitoring program and the assessment methods are able to provide solid foundations for the management procedure. Importantly, the governing feature of the management procedure is not the precision with which an indicator can be measured but how well the indicator can be used to make robust decisions on harvest controls (de la Mare, 1996).

Second, could the different parts of the management system be made simpler and work just as effectively? A simpler monitoring program at specific locations in the Antarctic could save considerable expense and facilitate better areal coverage.

Third, how could the performance of the management system be improved by altering its decision rules?

The advantage of such evaluations is that the initial management system can be built on the simplest of decision rules and then progressively modified to improve performance according to the performance criteria. In some instances, the decision rules may not be based directly on the performance criteria in order to be potentially able to achieve the desired effects. Importantly, management procedures must be robust against all the uncertainties in our understanding of food-web structure and other elements in the assessment and decision-making process.

CONCLUDING REMARKS

This review has highlighted the need to structure the future work on developing ecosystem-based management procedures into three parts: (i) to further develop plausible models of the ecosystem; (ii) to refine and, where possible, extend the CEMP and other field work to provide assessments on which robust management decisions can be based; and (iii) prior to the expansion of the krill fishery, to evaluate proposed management procedures aimed at achieving the ecosystem objectives set out in Article II of CCAMLR. Most importantly, operational objectives for dependent species and feasible management options need to be clearly articulated to guide this work, e.g. to what extent should parts or all of the marine ecosystem be affected by fishing for krill?

CCAMLR and its Members are to be congratulated for giving considerable attention to field programs on krill and some of the dominant land-based predators. The next step is to extend this work into the decision-making arena, which will require equivalent attention to be given to the development of models and approaches as reviewed here. There is a pressing need to determine how best to utilise the expensive research programs in the Antarctic to help meet these goals. Further development of coordinated programs, similar to the CCAMLR 2000 Krill Synoptic Survey of Area 48, is urgently needed to provide the broad spatial and temporal coverage in areas close to and at a distance from krill harvesting. Lastly, special consideration will need to be given to how to ensure that harvesting will not affect predators in unforeseen ways, particularly those unable to be effectively monitored, such as whales, pack-ice seals, many seabirds, fish and squid.

ACKNOWLEDGEMENTS

Many thanks to Bill de la Mare, Steve Nicol, Ian Ball, Campbell Davies, Inigo Everson, David Agnew, Graeme Parkes, Ian Boyd, Denzil Miller and John Croxall for many stimulating and challenging discussions over the years about ecosystem-based management. Also, thanks to Steve, Nick Gales, Denzil, John and Gillian von Bertouch for providing very constructive comments and suggestions on the manuscript and to Angela Williamson for her great assistance in the preparation of the materials presented here. Thanks also to Roger Hewitt for inviting me to prepare this review to present to WG-EMM at a workshop during its annual meeting in 2001. Lastly, I would like to thank my colleagues in the working group and at the Australian Antarctic Division for the many conversations and meetings that contributed to the substance of this manuscript.

REFERENCES

Agnew, D. 1997. Review: the CCAMLR Ecosystem Monitoring Program. *Ant. Sci.*, 9 (3): 235–242.

Beddington, J.R. and R.M. May. 1982. The harvesting of interacting species in a natural ecosystem. *Sci. Am.*, 247: 42–49.

Beddington, J.R. and J.G. Cooke. 1983. The potential yield of fish stocks. *FAO Fish. Tech. Pap.*, 242: 47 pp.

Beddington, J. and W.K. de la Mare. 1985. Marine mammal–fishery interactions: modelling and the Southern Ocean. In: Beddington, J.R., R.J.H. Beverton and D.M. Lavigne (Eds). *Marine Mammals and Fisheries*. Allen and Unwin, London: 94–105.

Boyd, I.L. 2002. Integrated environment–prey interactions off South Georgia: implications for management of fisheries. *Aquatic Conservation*, 12**:** 119–126.

Boyd, I.L. and A.W.A. Murray. 2001. Monitoring a marine ecosystem using responses of upper trophic level predators. *J. Anim. Ecol.*, 70: 747–760.

Brierley, A.S., D.A. Demer, J.L. Watkins and R.P. Hewitt. 1999. Concordance of interannual fluctuations in acoustically estimated densities of Antarctic krill around South Georgia and Elephant Island: biological evidence of same-year teleconnections across the Scotia Sea. *Mar. Biol.*, 227.

Butterworth, D.S. 1986. Antarctic marine ecosystem management. *Polar Rec.*, 23: 37–47.

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.

Butterworth, D.S. and A.E. Punt. 1999. Experiences in the evaluation and implementation of management procedures. *ICES J. Mar. Sci.*, 56: 985–998.

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.

CCAMLR. 2000. *Understanding CCAMLR's Approach to Management*. CCAMLR website: www.ccamlr.org.

Constable, A.J. 2001. The ecosystem approach to managing fisheries: achieving conservation objectives for predators of fished species. *CCAMLR Science*, 8: 37–64.

Constable, A.J., W.K. de la Mare, D.J. Agnew, I. Everson and D. Miller. 2000. Managing fisheries to conserve the Antarctic marine ecosystem: practical implementation of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR). *ICES J. Mar. Sci.*, 57 (3): 778–791.

Constable, A.J., S. Nicol and P. Strutton. In press. Southern Ocean productivity in relation to spatial and temporal variation in the physical environment. *J. Geophys. Res. – Oceans*.

Cooke, J.G. 1999. Improvement of fishery-management advice through simulation testing of harvest algorithms. *ICES J. Mar. Sci.*, 56: 797–810.

Croll, D.A. and B.R. Tershy. 1998. Penguins, fur seals, and fishing: prey requirements and potential competition in the South Shetland Islands, Antarctica. *Polar Biol.*, 19: 365–374.

Croxall, J.P. 1989. Use of indices of predator status and performance in CCAMLR fishery management. In: *Selected Scientific Papers, 1989 (SC-CAMLR-SSP/6)*. CCAMLR, Hobart, Australia: 353–365.

Croxall, J.P., P.A. Prince and C. Ricketts. 1985. Relationships between prey life-cycles and the extent, nature and timing of seal and seabird predation in the Scotia Sea. In: Siegfried, W.R., P.R. Condy and R.M. Laws (Eds). *Antarctic Nurtient Cycles and Food Webs.* Springer-Verlag, Berlin Heidelberg: 487–492.

Croxall, J.P., C. Ricketts and A.G. Wood. 1990. Food consumption by predators in a CCAMLR Integrated Study Region. In: *Selected Scientific Papers, 1990 (SC-CAMLR-SSP/7)*. CCAMLR, Hobart, Australia: 489–519.

de la Mare, W.K. 1986a. Some principles for fisheries regulation from an ecosystem perspective. In: *Selected Scientific Papers, 1986 (SC-CAMLR-SSP/3)*. CCAMLR, Hobart, Australia: 323–339.

de la Mare, W.K. 1986b. Simulation studies on management procedures. *Rep. Int. Whal. Commn.*, 36: 429–450.

de la Mare, W.K. 1988. Preliminary consideration of performance criteria for the evaluation of conservation strategies. Document *WG-CSD-88/8*. CCAMLR, Hobart, Australia: 17 pp.

de la Mare, W.K. 1996. Some recent developments in the management of marine living resources. In: Floyd, R.B., A.W. Sheppard and P.J.D. Barro (Eds). *Frontiers of Ecology*. CSIRO Publishing, Melbourne: 599–616.

de la Mare, W.K. 1998. Tidier fisheries management requires a new MOP (management-oriented paradigm). *Rev. Fish Biol. Fish.,* 8: 349–356.

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 Program. *CCAMLR Science*, 7: 101–117.

Downes, B.J., L.A. Barmuta, P.G. Fairweather, D.P. Faith, M.J. Keough, P.S. Lake, B.D. Mapstone and G.P. Quinn. 2002. *Monitoring Ecological Impacts: Concepts and Practice in Flowing Waters*. Cambridge University Press, Cambridge: 434 pp.

Everson, I. and W.K. de la Mare. 1996. Some thoughts on precautionary measures for the krill fishery. *CCAMLR Science*, 3: 1–11.

Green, K.A. 1977. Antarctic marine ecosystem modelling: revised Ross Sea model, general Southern Ocean budget and seal model. Marine Mammal Commission, Washington, D.C.

Hofmann, E.E., J.M. Klinck, R.A. Locarnini, B. Fach and E.J. Murphy. 1998. Krill transport in the Scotia Sea and environs. *Ant. Sci.*, 10 (4): 406–415.

Holling, C.S. (Ed.). 1978. *Adaptive Environmental Assessment and Management*. Wiley, New York. 363 pp.

Ludwig, D., R. Hilborn C. and Walters. 1993. Uncertainty, resource exploitation, and conservation: lessons from history. *Science*, 260: 17, 36.

Mangel, M. 2000. Irreducible uncertainties, sustainable fisheries and marine reserves. *Evolutionary Ecology Research*, 2: 547–557.

Mangel, M. and P.V. Switzer. 1998. A model at the level of the foraging trip for the indirect effects of krill (*Euphausia superba*) on krill predators. *Ecol. Modelling*, 105 (2–3): 235–256.

Mangel, M., L.M. Talbot, G.K. Meffe, M.T. Agardy, D.L. Alverson, J. Barlow, D.B. Botkin, G. Budowski, T. Clark, J. Cooke, R.H. Crozier, P.K. Dayton, D.L. Elder, C.W. Foweler, S. Funtowicz, J. Giske, R.J. Hofman, S.J. Holt, S.R. Kellert, L.A. Kimball, D. Ludwig, K. Magnusson, B.S. Malayang III, C. Mann, E.A. Norse, S.P. Northridge, W.F. Perrin, C. Perrings, R.M. Peterman, G.B. Rabb, H.A. Regier, J.E. Reynolds III, K. Sherman, M.P. Sissenwine, T.D. Smith, A. Starfield, R.J. Taylor, M.F. Tillman, C. Toft, J.R. Twiss Jr., J. Wilen and T.P. Young. 1996. Principles for the conservation of wild living resources. *Ecol. Appl.*, 6: 338–362.

Mapstone, B.D. 1995. Scalable decision criteria for environmental impact assessment. In: Schmitt, R.J. and C.W. Osenberg (Eds). *Detecting Ecological Impacts: Concepts and Applications in Coastal Habitats*. Academic Press, San Diego.

May, R.M., J.R. Beddington, C.W. Clark, S.J. Holt and R.M. Laws. 1979. Management of multispecies fisheries. *Science*, 205: 267–277.

Miller, D.G.M. 2002. Antarctic krill and ecosystem management – from Seattle to Siena. *CCAMLR Science*, 9: 175–212 (this volume).

Miller, D.G.M. and I. Hampton. 1989. Biology and ecology of the Antarctic krill (*Euphausia superba* Dana): a review. *BIOMASS Sci. Ser.*, 9: 166 pp.

Murphy, E.J., D.J. Morris, J.L. Watkins and J. Priddle. 1988. Scales of interaction between Antarctic krill and the environment. In: Sahrhage, D. (Ed.). *Antarctic Ocean and Resources Variability*. Springer-Verlag, Berlin Heidelberg: 120–130.

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

Peterman, R.M. 1990. Statistical power analysis can improve fisheries research and management. *Can. J. Fish. Aquat. Sci.*, 47: 2–15.

Peterson, C.H. 1993. Improvement of environmental impact analysis by application of principles derived from manipulative ecology: lessons from coastal marine case histories. *Aust. J. Ecol.*, 18: 21–52.

SC-CAMLR. 2000. *Report of the Nineteenth Meeting of the Scientific Committee (SC-CAMLR-XIX)*. CCAMLR, Hobart, Australia: 518 pp.

Smith, A.D.M. 1993. Risks of over- and under-fishing new resources. In: Smith, S.J., J.J. Hunt and D. Rivard (Eds). *Risk Evaluation and Biological Reference Points for Fisheries Management*. National Research Council for Canada, Ottawa: 261–267.

Stewart-Oaten, A., J.R. Bence and C.W. Osenberg. 1992. Assessing effects of unreplicated perturbations: no simple solutions. *Ecology*, 73: 1396–1404.

Thomson, R.B., D.S. Butterworth, I.L. Boyd and J.P. Croxall. 2000. Modelling the consequences of Antarctic krill harvesting on Antarctic fur seals. *Ecol. Appl.*, 10 (6): 1806–1819.

Underwood, A.J. 1989. The analysis of stress in natural populations. *Biol. J. Linn. Soc.*, 37: 51–78.

Underwood, A.J. 1990. Experiments in ecology and management: their logics, functions and interpretations. *Aust. J. Ecol.*, 15: 365–89.

Underwood, A.J. 1994. On beyond BACI: sampling designs that might reliably detect environmental disturbances. *Ecol. Appl.*, 4: 3–15.

Walters, C.J. 1986. *Adaptive Management of Renewable Resources*. MacMillan Publishing Co., New York: 374 pp.

Yodzis, P. 2001. Must top predators be culled for the sake of fisheries? *TREE*, 16: 78–84.

Liste des tableaux

Tableau 1 Caractéristiques des quatre principales approches de la modélisation de l'écosystème marin de l'Antarctique.

Tableau 2: Facteurs généraux susceptibles d'influencer les caractéristiques de la population de l'espèce visée ou des espèces proies, la consommation de ces espèces par les prédateurs et les valeurs résultantes des paramètres des prédateurs (indicateurs) contrôlés. Les facteurs influençant ces caractéristiques sont combinés en fonctions au bas du tableau.

Liste des figures

Figure 1: Illustration de l'approche fondée sur l'écosystème de la gestion des effets de la pêche sur les espèces dépendantes et voisines (d'après de la Mare, 1996). La procédure de gestion consiste en un jeu de règles de décision servant à ajuster le contrôle de l'exploitation en réponse aux évaluations afin de rendre tout à fait probable la réalisation des objectifs opérationnels. Le milieu physique (cadres gris) représente l'état actuel du système tel qu'il est observé par le biais du programme de contrôle. Les évaluations tiennent compte de l'incertitude entourant le fonctionnement du milieu physique et la relation entre le programme de contrôle et ce milieu.

Figure 2: Effets potentiels de la pêche sur la densité du krill. Dans chaque cadre, la ligne pointillée montre la réduction de l'abondance médiane du krill à 0,5 du niveau de pré-exploitation sur la période comprise entre les années 21 et 40, perpétré par la pêche : a) variation interannuelle de la densité du krill sur l'ensemble de la population (trait plein), b) une série chronologique ultérieure de la densité dans une région localisée (trait plein), l'abondance dans la région étant influencée par la densité de la population globale, avec une indication de la variation interannuelle dans la relation entre la densité globale et la densité locale. La ligne en tirets indique la densité locale quand la pêche a réduit l'abondance disponible à 0,5 de son niveau de pré-exploitation, c) série chronologique de la densité dans une deuxième région localisée, comme dans b), mais sans corrélation entre les deux régions en ce qui concerne la manière dont la variation interannuelle dans l'environnement physique affecte la relation entre la densité globale et la densité locale.

Figure 3: Relation fonctionnelle entre la condition des prédateurs et la densité locale du krill dans le secteur local d'alimentation; cette relation sert à établir une densité critique permettant de fermer la pêche au krill dans le secteur d'alimentation si la densité du krill tombe en dessous du seuil critique (d'après Boyd, 2002).

Figure 4: Série chronologique hypothétique de l'indicateur de productivité , *W*, sur 60 ans. Aucune pêche n'aurait eu lieu les 20 premières années, pour lesquelles une série de base *W* aurait servi à estimer le niveau moyen de référence (cercle). Le niveau moyen visé pour *W* serait indiqué par un losange. Les boîtes à moustaches indiquent la distribution des fréquences de *W* pendant la période de base. Les lignes horizontales en pointillés sont les limites critiques de l'intervalle dans lequel, en général, *W* est censé rester une fois la pêche établie. La ligne en tirets se réfère à la limite supérieure provisoire de la période d'ajustement du système aux activités de pêche. Dans cet exemple, la tendance de *W* à rester en dessous de la limite inférieure de l'intervalle après 16 ans de pêche signalerait qu'il conviendrait de réduire la pêche. Sil les valeurs de *W* étaient fréquemment supérieures aux limites supérieures de l'intervalle, une augmentation de la pêche serait envisageable (voir Constable, 2001 pour plus de détails).

Список таблиц

Список рисунков

Lista de las tablas

Lista de las figuras