SOME THOUGHTS ON PRECAUTIONARY MEASURES FOR THE KRILL FISHERY

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Abstract

The concept of precautionary measures for krill is discussed. A precautionary catch limit, based on the potential yield model developed by the CCAMLR Scientific Committee's Working Group on Krill (WG-Krill) is discussed and it is concluded that such a method is appropriate in setting an overall precautionary catch limit in large areas, such as Statistical Area 48, but the approach requires considerable refinement to provide a sufficient safeguard for land-based predators. A new approach is described which takes account of the requirements of land-based predators. Implementation of the approach is discussed and the question of how the method relates to the current CCAMLR Ecosystem Monitoring Program (CEMP) is considered.

Résumé

Dans cette communication, l'auteur examine le concept de mesures préventives concernant le krill et notamment la limite préventive de capture fondée sur le modèle de rendement potentiel développé par le groupe de travail sur le krill (WG-Krill), organe du Comité scientifique de la CCAMLR. Il parvient à la conclusion que ce type de méthode semble adapté à la mise en place de limites préventives générales de captures dans des régions étendues telles que la zone statistique 48 mais que, pour constituer une protection suffisante pour les prédateurs basés à terre, cette approche devrait être considérablement mise au point. L'auteur décrit également une nouvelle approche qui tient compte des besoins des prédateurs basés à terre. Il examine la mise en pratique de cette approche et recherche dans quelle mesure elle est pertinente au Programme de contrôle de l'écosystème de la CCAMLR (CEMP).

Резюме

Обсуждается концепция предохранительных мерах в случае промысла криля. Описывается предохранительное ограничение на вылов, основанное на разработанной Рабочей группой Научного комитета АНТКОМа по крилю (WG-Krill) модели потенциального вылова. Делается вывод, что такой метод является приемлемым в случае установления предохранительного ограничения на общий вылов в больших районах, однако для обеспечения благополучного выживания базирующихся на суше хищников потребуется значительная доработка имеющегося подхода к делу. Описывается новый поход, который учитывает потребности таких хищников. Обсуждается применение этого подхода, а также вопрос о том, каким образом данный метод связан с современной Программой АНТКОМа по мониторингу экосистемы (CEMP).

Resumen

Se considera el concepto de las medidas de precaución para el kril. Se examina un límite de captura precautorio basado en el modelo de rendimiento potencial diseñado por el Grupo de Trabajo del Kril (WG-Krill) del Comité Científico de la CCRVMA. Se concluye que, si bien este enfoque resulta apropiado para establecer un límite de captura precautorio global en áreas de gran extensión como es el Area estadística 48, necesita perfeccionarse mucho más a fin de brindar la protección suficiente a los depredadores terrestres. Se describe un nuevo enfoque que toma en cuenta las necesidades de los depredadores terrestres. Se ha examinado la implementación de este enfoque y la relación entre este método con el programa actual de seguimiento del ecosistema de la CCRVMA (CEMP).

Keywords: catch limit, CCAMLR, krill consumption, krill fishery, land-based predators, precautionary measures

THE CONCEPT OF PRECAUTIONARY MEASURES FOR KRILL

A fundamental aim of establishing conservation measures for a harvested resource is to ensure that harvesting is conducted at a level which can be sustained over the long term. Underpinning such measures is a series of ecological and population models which in turn are dependent on field information on the harvested resources and their role in the ecosystem. Clearly, therefore, the more complete this information and the more refined the models, the better will be the scientific advice on which to base management decisions.

One of the common ways of obtaining information about a harvested marine resource is to collect information from the fishery. However, a fishery could be allowed to exist only if there is enough information to ensure that the fishery does not expand beyond an unknown safe limit. Here we have a problem; without the fishery we may have insufficient data, and yet we do not know how large a fishery ought to be permitted. It is against this background of two conflicting requirements that the concept of precautionary measures was developed.

A precautionary measure is one that, on an intuitive and pragmatic level, appears 'safe' whilst permitting some harvesting to be undertaken from which more refined estimates can be made, leading to more precise conservation measures. Article II of the CCAMLR Convention requires that, firstly, harvesting is conducted on a sustainable basis, secondly, it does not adversely affect dependent species, and, thirdly, any harvesting-induced changes should be reversible over a period of two or three decades. Precautionary measures need to incorporate all three of these considerations.

RECENT PROGRESS TOWARDS A PRECAUTIONARY CATCH LIMIT FOR KRILL

In the context of CCAMLR considerable progress has been made in arriving at a precautionary catch limit for krill. The current approach is based on the use of a model that conceptually is relatively simple and is given by the formula:

$$C = \gamma B_0 \qquad (1)$$

In this equation B_0 is the estimated unexploited biomass and γ is the proportion of the estimate which can be taken as a constant catch. A set of sophisticated parameters has been incorporated into the estimation and application of γ, which take account of uncertainty in natural mortality, variability in recruitment and predator food demand (SC-CAMLR, 1994). In this form the model has been used to provide an estimate of potential yield for Area 48, the southwest Atlantic sector of the Southern Ocean. The important points about the model are that it not only addresses the problem of single-species harvesting, but also includes a factor to account for uncertainty and variability in the standing stock. The requirements of predators are considered on a macro-scale which is satisfactory in terms of their annual energy budgets.

The krill yield model in this form has been used to provide advice on the precautionary catch limit provided that the following criteria are satisfied:

- the probability of the spawning biomass dropping below 20% of its pre-exploitation median level over a 20-year harvesting period is 10%; and
- the median krill escapement[1] in the spawning biomass over a 20-year period is 75% of the pre-exploitation median level.

[1] In a fisheries management context, escapement is meant to refer to the average level of biomass of the exploited stock for a given level of fishing. Proportional escapement is the ratio of this exploited biomass to the average biomass of the stock before the start of the fishery (pristine biomass).

In an ecosystem context, these criteria are followed to ensure that there is not only a sustainable level of krill production, but also that the needs of all predators are safeguarded. In this context, 'predators' includes not just the land-based predators such as penguins, flying birds and fur seals, but all whales, seals, birds, fish and squid.

SUBDIVISION OF AREA ESTIMATES OF PRECAUTIONARY CATCH LIMITS

The fishery in Statistical Area 48 is not spread out over the whole region but is localised into relatively small areas on or close to the shelf (Everson and Goss, 1991). These same areas are those in which many land-based predators forage at the height of the breeding season. Concern has been expressed about the possibility that all the precautionary catch limit for Area 48 might be taken from the limited region close to predator colonies. Arising from this concern has been a quest for an equable way of dividing the precautionary catch limit for Area 48 among its subareas.

Knowledge of the water circulation patterns in Area 48 and the distribution and movements of krill indicates that the localised subareas, South Shetlands (Subarea 48.1), South Orkneys (Subarea 48.2), South Georgia (Subarea 48.3) and South Sandwich (Subarea 48.4), cannot be viewed independently. There is known to be interaction between these subareas, i.e. the krill flux, and this is a topic that forms the basis for continuing discussion and study within CCAMLR.

In order to implement a potential yield model on a subarea basis it would be necessary to undertake a standing stock survey prior to the start of harvesting to determine a catch limit that would be small enough to provide an acceptable impact on the land-based predators. A major difficulty with this approach is that CCAMLR subareas, such as 48.3, are known to be important but not necessarily the dominant components of a much larger system. Consequently, a single synoptic survey of krill will be affected by the distribution of krill over a much larger area; repeat surveys are likely to show widely differing results simply due to variation in water circulation in the region. We therefore consider alternative approaches, and, in developing them, we consider here major factors influencing the amount of krill likely to be present in a given region.

There is ample evidence to indicate that within Area 48 there is some form of linkage between all the subareas. The dominant cause of this linkage is through the Antarctic Circumpolar Current (ACC), although the rates of flow are influenced considerably by local patterns on the shelf and at the shelf-break. Within the ACC and the local circulation patterns there is sufficient krill to maintain the krill population and at the same time support large populations of dependent species. The FIBEX survey indicated the instantaneous standing stock during the survey to be 35.4 million tonnes (SC-CAMLR, 1994 - paragraph 5.31). This krill is moving through on the ACC; there is production due to growth and reproduction and also mortality due to predation, other natural causes and harvesting.

The FIBEX survey took place in the 1980/81 season, over a decade ago, which means that with a lifespan of five to seven years, at least two generations of krill have passed through the system since that time. The potential yield model assumes stochastic variation around the median level found during the survey. Over the surveyed area the krill distribution is known to be patchy (Miller and Hampton, 1989), varying both within and between seasons. This would indicate that it would be unrealistic to rely on the distribution observed during a single survey, such as FIBEX, to provide indications of the current distribution of krill concentrations. We conclude from this that there are reasonable indications of the size of the standing stock of krill, however we are limited in our understanding of where krill concentrations might predictably occur.

The ACC and the Weddell gyre vary both within and between seasons. The level of variation is affecting the distribution of krill and is a central factor in the study of krill fluxes in the region. Knowledge of the extent of the variation is improving, although we are currently unable to predict when and how circulation patterns will arise which contribute to specific phenomena associated with the observed krill distribution. Thus, in spite of the large body of information on water circulation, we are still unable reliably to predict where krill concentrations will occur.

For many years now the estimated rates of krill consumption by major predators have been used as an indication of krill production. These krill consumption rates have been derived from information on the standing stock (numbers and biomass), energy budgets and distribution of the major predators. Estimates of krill consumption on a Southern Ocean scale were summarised by Everson (1984) as follows:

	Estimated Consumption Per Annum (million tonnes)	Reference
Present whale stocks	43	Laws (1977)
Seals (1972)	64	Laws (1984)
Seals (1982)	128	Laws (1984)
Birds	33	Croxall (1984)
Squid	(100?)	Everson (1977)
Fish	?	

Taken together these figures indicate that a reasonable estimate of krill consumption might be between 100 and 200 million tonnes. Assuming a *pro rata* distribution of predation pressure this would indicate that in the area of the FIBEX survey, approximately one-sixth of the Southern Ocean, between 16 and 32 million tonnes of krill are taken by predators annually. These figures in turn are four to eight times the indicated precautionary catch limit for krill calculated using the potential yield model (SC-CAMLR, 1994).

CONSIDERATION OF CCAMLR SUBAREA 48.3 (SOUTH GEORGIA)

During the past decade there has been a large increase in the volume of published information on krill consumption by land-based predators. Much of this work has been undertaken at South Georgia, the major land mass within Subarea 48.3, and we take this as an example to develop ideas for incorporating the requirements of dependent species into the management regime for krill.

Impact of Predators

Recent estimates for annual krill consumption (million tonnes) at South Georgia are as follows:

Macaroni penguin	3.87	Croxall and Prince (1987)
Antarctic prion	1.35	Croxall and Prince (1987)
White-chinned petrel	0.21	Croxall and Prince (1987)
Diving petrel	0.18	Croxall and Prince (1987)
Other birds	0.10	Croxall and Prince (1987)
Fur seal	4.05*	Boyd (pers. comm.)
Total	9.76	

* assumes that 75% of the energy intake is derived from krill.

The following estimated maximum potential foraging ranges of these species when rearing offspring have been given by Croxall and Prince (1987):

Macaroni penguin	123 km
Antarctic prion	244 km
White-chinned petrel	1 218 km
Diving petrel	243 km
Fur seal	c. 150 km

Excluding the white-chinned petrel, which in any case only accounts for about 2% of the krill consumed, the potential foraging range of all these species is less than 250 km. Bearing in mind that 80% of the krill consumed is taken by macaroni penguins and fur seals the major impact is within a range of little more than 100 km.

If we now consider the origins of the data on which these estimates are based, we note that the breeding population size is derived from field counts which, since the locations of these sites are known, can be verified and analysed to determine trends. Foraging ranges have been determined by direct field observations and by means of micro-encapsulated instrument packages. The diet has also been determined from field observations either from stomach content or scat analysis, where energy budgets have either been determined empirically or derived from such data for closely related species. Thus, the data on which these estimates have been based all derive from rigorous field sampling programs.

Information on Krill Harvesting

Harvesting of krill is subject to monitoring by CCAMLR. Detailed information related to the catching process is required to be collected and submitted to CCAMLR in a summarised form. These data are available for analysis and are published in the *CCAMLR Statistical Bulletin* in a more summarised format. As a result of this monitoring we have a very good indication of how much krill is being taken from 'fine-scale rectangles', half a degree of latitude by a degree of longitude, per ten-day period.

Integration of Information into a Precautionary Management Plan

In terms of direct information on krill that is currently available and which might be incorporated into scientific advice on precautionary measures we have:

(i) a standing stock estimate from over a decade ago for Area 48;

(ii) imprecise estimates of pelagic predator consumption of krill on a Southern Ocean scale;

(iii) good estimates of land-based predator consumption of krill at some sites, such as South Georgia; and

(iv) fine-scale catch and effort data from the krill fishery.

In addition, there is oceanographic information to estimate rates of water movement over the deep ocean and programs are planned or in progress to estimate water movement on the shelf. Both estimations of water movement can be incorporated into models to estimate krill flux between areas and also the turnover rate of krill on the shelf.

Accepting that the potential yield model, based on the FIBEX survey, provides a reasonable indication of how much can be taken on an annual basis from Area 48 without having an adverse impact on krill or dependent species, we can turn our attention to consideration of what information obtained from those same dependent species can be utilised in framing subareal precautionary measures. At this stage, information from whales and phocid seals is of little help because the estimates refer to ill-defined areas, and the population sizes and energetic analyses are subject to considerable uncertainty. This leaves us with the land-based predators for whom, in the case of South Georgia, the indications are that on average about 10 million tonnes of krill are taken within a range of approximately 125 km from the island. The requirements of other predators and the krill flux to other areas 'downstream' mean that the total amount of krill passing through such a zone during the course of a year is unknown, but must be very much more than this figure. The estimated consumption of krill by land-based predators therefore represents the effective standing stock within the foraging range of those predators and a lower bound to the amount of krill present in the area during the course of a year. In order to incorporate this into equation (1), the level of annual predator consumption needs to be adjusted to take account of turnover rate and krill natural mortality according to the following relation (see the appendix for its derivation):

$$\hat{B} \approx \hat{P}\hat{T}\left(\frac{\hat{M}^2 + \mathrm{V}[\hat{M}]}{\hat{M}^3}\right) \qquad (2)$$

where $\hat{P}$ is the annual consumption of krill by land-based predators;

$\hat{M}$ is the annual rate of krill mortality;

$\hat{T}$ is the retention time; and

$\mathrm{V}[\hat{M}]$ is the variance of the estimate of $\hat{M}$ (see footnote[2]).

Applying the general yield model also requires an estimate of the variance of $\hat{B}_0$. This can be calculated from equations (10) and (11) given in the appendix.

For example, assuming a predator consumption level of 9.76 million tonnes (this paper), a natural mortality rate of 0.6 (Butterworth et al., 1992) with variance 0.1 and a turnover of twice each year (based on Everson, 1992), the instantaneous standing stock in the area would be 9.5 million tonnes. With a value of γ from the potential yield model of 0.116, this would provide for a potential yield of 1.1 million tonnes.

This approach presented in this basic form, if applied to, for example, Subarea 48.3, is still open to the criticism that all the catch could be taken from a key foraging site or else during the most sensitive period of the year. This criticism could be negated by restricting the catch to one-twelfth of the annual total during each of the months

[2] This differs from the form given in the report of the CCAMLR Scientific Committee's Working Group on Ecosystem Monitoring and Management (WG-EMM) (SC-CAMLR, 1995). In the notation of this paper, the WG-EMM formula has been transformed to:

$$B_0 = \frac{PT}{1 - e^{-M}}$$

The differences arise because the derivation at WG-EMM did not take into account the decline of krill abundance due to predation within the predator foraging region over the retention period *T*, nor the effects of growth, nor did it correct for the effects of sampling variability. Nonetheless, the two formulae give similar results. For the value of *M* likely for krill, equation (2) will give a result about 25% less than the formula derived at WG-EMM.

December, January and February, a period when land-based predators are likely to be most vulnerable. The only limit that would apply during the remaining months would be that the total annual catch could not exceed the local precautionary limit.

Applying this approach to each of the subareas within Area 48 will almost certainly give a total figure less than the 4.1 million tonnes presented in SC-CAMLR (1994), paragraph 5.31. There are two reasons for this difference. Firstly, they are derived from totally different datasets and, secondly, the subareal limits are based on the requirements of selected land-based predators and not on the requirements of all predators.

The difference mentioned above might be addressed by restricting krill harvesting to the levels outlined above within the potential foraging range of the breeding sites of the dominant land-based predators. The extent of such a zone relative to the predator breeding sites would be 125 km at South Georgia (Figure 1). Outside of these zones harvesting would be permitted provided that the total catch for Area 48 did not exceed 4.1 million tonnes. Within the zones, shaded in Figure 1, catch limits would be set based on input data for individual predators and month as described. While this refinement does permit utilisation of the full precautionary catch limit, it would require monitoring of the fishing fleet to ensure that there is no encroachment into the favoured coastal grounds when the limit there has been exhausted.

The approach described above could be used for other areas, however particular care would need to be exercised in applying it to regions where there are few or no breeding colonies of land-based predators. An absence of breeding penguins could indicate either that no suitable concentrations of krill occur on a regular basis, or that there are no suitable sites for breeding colonies. If krill concentrations rarely occur in an area then that area is unlikely to form the focus of concerted fishing effort. However, if concentrations do occur but there are no

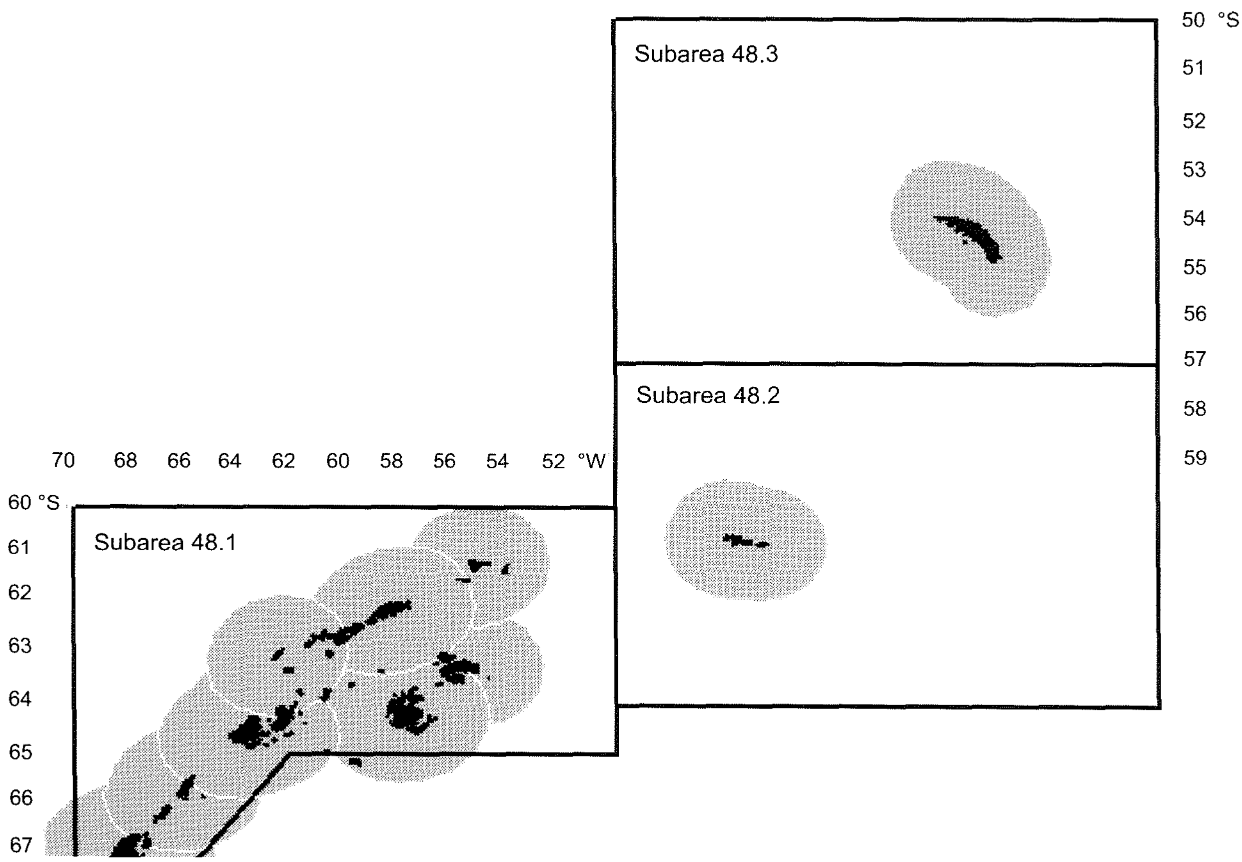

Figure 1: CCAMLR Statistical Subareas 48.1, 48.2 and 48.3. Shaded areas indicate the extent of 125-km conservation zones around the major land-based predator colonies.

land-based predator sites within range, then an alternative approach would be necessary to permit harvesting in that area.

Integrating CEMP into a Precautionary Management Plan

The approach outlined above makes direct use of some predator population census information although this is currently not one of the CEMP standard methods. The method A3 'Breeding Population Size' (SC-CAMLR, 1992) is aimed at investigating trends in population size within selected, clearly defined colonies. The precautionary management approach described in this paper ideally requires information from as many colonies as possible. The number of pairs within each colony would need to be estimated in accordance with method A3, although there would be no need to repeat this annually but rather on some longer time-scale, perhaps every five or ten years depending on the harvesting pressure in the region.

The second important component of the scheme is the development and refinement of energy budgets. This makes use of information derived from other CEMP monitoring parameters such as growth rates, foraging trip duration, meal size etc. Furthermore, the approach is likely to benefit from the planned research and development in monitoring at-sea behaviour of land-based predators. Increasing the database on all these parameters and developing a better understanding of the interactions will surely lead to refinements in models that should eventually produce advice for revised and more refined management measures.

Extension of the Approach

The initial aim behind the development of the approach presented in this paper was to indicate precautionary catch levels for areas in which land-based predators might be particularly vulnerable. However it need not be restricted to such a situation. On a Southern Ocean scale data on the annual consumption of krill by predators can be used to estimate instantaneous standing stock, and hence develop advice on precautionary catch limits, in the same way as has been done in this paper. Bearing in mind the high costs of obtaining direct estimates of standing stock from a synoptic survey over a large area (the largest to date has been FIBEX which covered less than a quarter of the Southern Ocean), refinements of estimates of predator demand may provide a cost-effective approach for Southern Ocean scale estimates.

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APPENDIX

CALCULATED ABUNDANCE ESTIMATES DERIVED FROM PREDATOR CONSUMPTION DATA

The aim is to arrive at a minimum estimate of krill biomass in a management area (A), in which the total consumption by krill predators is assumed to be known. This calculated biomass is then taken as the result which would have been obtained if a krill survey had been conducted in the same management area for the purpose of applying the general yield formula.

Assume that the predation occurs in area A, where the retention time for krill is T, and that there is a constant flux ϕ of krill (in numbers per year) entering A. Further assume that annual predation P in A (in terms of krill biomass) is the only source of natural mortality. The biomass of krill in A can be calculated given estimates of P, T and M (the annual rate of natural mortality). The derivation which follows is for the case where T is less than 1. If the annual rate of natural mortality is M, then the instantaneous rate of natural mortality for krill in A, designated M', must be greater than M. Consider a small volume of water V which enters A in the infinitesmal interval $\delta\tau$. The number of krill in V at the moment it enters A is:

$$n_0 = \phi \cdot \delta\tau$$

The number of krill surviving in V after a given time τ in A is given by the usual survivorship expression:

$$n_\tau = n_0 e^{-M'\tau} = \phi\, e^{-M'\tau} \cdot \delta\tau \qquad (1)$$

Therefore, the flux of krill leaving A is given by:

$$\phi' = \phi e^{-M'T}$$

However, the total number of krill leaving A in one year is also equal to ϕ'. If M is the rate of natural mortality which would result in the same total number of deaths, then:

$$\phi' = \phi e^{-M} \qquad (2)$$

and therefore:

$$M = M'T \qquad (3)$$

It follows from equation (1) that, as $\delta\tau \to 0$, the total number of krill in region A is given by:

$$N = \int_0^T \phi e^{-M'\tau} d\tau$$

that is:

$$N = \frac{\phi\left(1 - e^{-M'T}\right)}{M'}$$

Assume that due to growth, the average of the masses of the individual krill in the population varies with time according to some function such that:

$$\overline{w}_t = g(t)$$

The total biomass of krill in A at time t is therefore given by:

$$B_t = \overline{w}_t N = \frac{g(t)\phi\left(1-e^{-M'T}\right)}{M'} \qquad (4)$$

The instantaneous prey mass consumption rate at time t is given by:

$$\frac{dP}{dt} = B_t M'$$

and, therefore, the total prey consumed in one year is given by:

$$P = \phi\left(1-e^{-M'T}\right)\int_0^1 g(t)dt \qquad (5)$$

Thus:

$$\phi = \frac{P}{\left(1-e^{-M'T}\right)\int_0^1 g(t)dt} \qquad (6)$$

substituting equations (6) and (3) into (4) and simplifying gives:

$$B_t = \frac{PT \cdot g(t)}{M\int_0^1 g(t)dt} \qquad (7)$$

Thus, the biomass at time t is a function of t. However, a reasonable estimate of the biomass to be encountered during a survey at an arbitrary time would be the annual mean value of the biomass in A, which is given by:

$$\overline{B} = \frac{\int_0^1 B_t dt}{\int_0^1 dt}$$

Thus, from (7):

$$\overline{B} = \frac{PT\int_0^1 g(t)dt}{M\int_0^1 g(t)dt} = \frac{PT}{M} \qquad (8)$$

The mean value of the biomass in the region A is independent of the growth function for krill. This makes equation (8) a useful simplification for calculating the biomass of krill which would be expected to be encountered by a survey conducted in region A.

However, P, T and M are random variables because of the effects of sampling error. This means that equation (8) is a biased estimator of $\overline{B}$ when P, T and M are replaced with estimated values. The bias can be approximately corrected by using the delta method (Seber, 1982). Assuming that estimates of P, T and M are independent, an approximately unbiased estimate of $\overline{B}$ is given by:

$$\hat{B} \approx \hat{P}\hat{T}\left(\frac{\hat{M}^2 + \mathrm{V}\left[\hat{M}\right]}{\hat{M}^3}\right) \tag{9}$$

where $\hat{P}$, $\hat{T}$ and $\hat{M}$ denote the estimated values of *P*, *T* and *M* and V [.] denotes the variance of an estimate.

In applying the general yield formula we also need an estimate of the variance of $\hat{B}$. This can also be found from applying the delta method, which gives:

$$\mathrm{V}\left[\hat{B}\right] \approx \left(\frac{\hat{P}\hat{T}}{\hat{M}}\right)^2 \left(\frac{\mathrm{V}\left(\hat{P}\hat{T}\right)}{\left(\hat{P}\hat{T}\right)^2} + \frac{\mathrm{V}\left[\hat{M}\right]}{\hat{M}^2}\right) \tag{10}$$

where:

$$\mathrm{V}\left[\hat{P}\hat{T}\right] = \hat{P}^2\ \mathrm{V}\left[\hat{T}\right] + \hat{T}^2\ \mathrm{V}\left[\hat{P}\right] + \mathrm{V}\left[\hat{P}\right]\ \mathrm{V}\left[\hat{T}\right] \tag{11}$$