CCAMLR Science, Vol. 3 (1996): 31-54

A GENERALISED MODEL FOR EVALUATING YIELD AND THE LONG-TERM STATUS OF FISH STOCKS UNDER CONDITIONS OF UNCERTAINTY

A.J. Constable
School of Aquatic Science and Natural Resources Management
Deakin University
P.O. Box 423, Warrnambool 3280
Victoria, Australia

W.K. de la Mare
Australian Antarctic Division
Channel Highway, Kingston 7050
Tasmania, Australia

Abstract

This paper presents a general fish stock projection model for assessing the long-term annual yield which satisfies objectives for the maintenance of the spawning stock biomass in accordance with CCAMLR criteria. These specify a bound on the probability that the spawning biomass will become depleted to below some specified level over a specified period and set a further constraint on the long-term status of the stock relative to the pre-exploitation biomass. The model provides a flexible method for assessing the influence of different patterns of growth, natural mortality, spawning and fishing on estimates of yield and yield per recruit. It can also be used to evaluate stochastic stock trajectories under a specified catch regime. The model uses an adaptive Runge-Kutta algorithm to calculate stock trajectories and catch rates over a specified simulation period. The procedure numerically integrates a set of differential equations which incorporate functions that specify growth, mortality, age-dependent selectivity and seasonal patterns in fishing mortality. Results from the model are compared with existing analyses from the krill yield model. The model can include a known catch history and thus allow assessments of yield to be made for existing fisheries. An example is presented for the Patagonian toothfish, *Dissostichus eleginoides*, around South Georgia Island.

Résumé

Ce document porte sur un modèle général de projection des stocks de poissons destiné à l'évaluation du rendement annuel à long terme qui satisfait aux objectifs de conservation de la biomasse reproductrice des stocks conformément aux critères de la CCAMLR. Ces critères spécifient une limite relative à la probabilité que la biomasse du stock reproducteur soit épuisée au-delà d'un niveau donné sur une période donnée. De plus, ils établissent d'autres restrictions sur le statut à long terme du stock relativement à la biomasse de pré-exploitation. Ce modèle fournit une méthode souple d'évaluation de l'influence des diverses tendances de croissance, de mortalité naturelle, de frai et de pêche sur le rendement estimé et le rendement par recrue. Il peut également servir à évaluer les trajectoires stochastiques des stocks sous un régime de capture donné. C'est au moyen d'un algorithme adaptatif Runge-Kutta qu'il calcule les trajectoires des stocks et les taux de capture sur une période de simulation donnée. La procédure incorpore, sous forme numérique, un jeu d'équations différentielles comportant des fonctions qui spécifient la croissance, la mortalité, la sélectivité selon l'âge et les tendances saisonnières de la mortalité par pêche. Les résultats du modèle sont comparés aux analyses existantes du modèle de rendement de krill. L'historique des captures, s'il est connu, peut être introduit dans le modèle pour permettre d'effectuer des évaluations du rendement de pêcheries existantes. Un exemple est donné pour la légine australe, *Dissostichus eleginoides*, autour de l'île de Géorgie du Sud.

Резюме

В данной работе описывается общая модель прогнозирования состояния рыбных запасов, предназначенная для расчета такого размера долгосрочного ежегодного вылова, который отвечает требованиям поддержания уровня нерестующей биомассы запаса в соответствии с критериями АНТКОМа. Эти критерии ограничивают вероятность истощения нерестующей биомассы ниже какого-либо уровня в течение какого-либо периода, а также определяют долговременное состояние запаса в зависимости от его предэксплуа-тационной биомассы. Данная модель дает возможность оценить влияние роста разного типа, естественной смертности, нереста и промысла на расчеты вылова и вылова на рекрута. Она также может применяться для проведения стохастичесих прогнозов при определенном режиме промысла. Модель использует адаптивный алгоритм типа 'Рунге-Кутта' для вычисления прогностических траекторий запаса и интенсивности лова на протяжении конкретного периода имитации. Согласно этой процедуре осуществляется интеграция набора дифференциальных уравнений, которые включают в себя функции, определяющие рост, смертность, зависящую от возраста селективность и сезонные тенденции промысловой смертности. Результаты модели сравниваются с результатами имеющихся анализов модели вылова криля. В эту модель можно включить ретроспективные данные по промыслу, что позволит выполнить оценки вылова современных промыслов. Дается пример по патагонскому клыкачу, *Dissostichus eleginoides*, в районе острова Южной Георгии.

Resumen

Este documento presenta un modelo general de proyección de los stocks de peces para evaluar el rendimiento anual a largo plazo que satisface los objetivos (según el criterio de la CCRVMA) que conducen a la mantención de la biomasa del stock en desove. Estos objetivos definen un límite en la probabilidad de que la biomasa del stock en desove disminuya más allá de un nivel indicado durante un período determinado de tiempo, y estipulan una restricción adicional en el estado del stock a largo plazo con respecto a la biomasa antes de la explotación. El modelo proporciona un método flexible para evaluar la influencia de modalidades diferentes del crecimiento, mortalidad natural, desove y pesca en las estimaciones del rendimiento y del rendimiento por recluta. También puede utilizársele para evaluar trayectorias estocásticas del stock bajo regímenes de captura determinados. El modelo utiliza un algoritmo Runge-Kutta adaptado para calcular las trajectorias del stock y las tasas de captura durante un período determinado de simulación. El procedimiento integra numéricamente a un conjunto de ecuaciones diferenciales que incorporan funciones que describen el crecimiento, la mortalidad, la selectividad por edades y las modalidades estacionales de la mortalidad causada por la pesca. Se compararon los resultados obtenidos del modelo con análisis existentes del modelo de rendimiento del kril. El modelo puede incluir datos históricos de captura y por lo tanto permite que se hagan evaluaciones del rendimiento para pesquerías existentes. Como ejemplo se presenta una aplicación del modelo a la pesca del bacalao de profundidad, *Dissostichus eleginoides*, alrededor de la isla Georgia del Sur.

Keywords: CCAMLR, fisheries management, population dynamics, stock assessment, sustainable yield, yield per recruit

INTRODUCTION

CCAMLR has developed policies which specify, in general terms, desirable levels of relative abundance at or above which exploited fish stocks should be maintained. Initially, CCAMLR decided that the catch rate from any stock was not to exceed $F_{0.1}$ (CCAMLR, 1987). This level of fishing was thought to allow maximum fishing effort while ensuring that the reproductive performance of the stock was not jeopardised (SC-CAMLR, 1987). In addition, this was thought to obviate the need for estimating the pre-exploitation status of the population (a difficult task in any fishery). However, it is based on the assumption that the population parameters are relatively invariant over time and can be measured reasonably precisely.

When uncertainty in some of these parameters is taken into account, along with variable recruitment, this strategy is inappropriate for some fish stocks because it may lead to a substantial depletion of the spawning stock biomass, particularly in short-lived species (de la Mare and Constable, 1990; SC-CAMLR, 1991). For short-lived species such as myctophids, CCAMLR considered that a fishing mortality consistent with an escapement of 50% of the spawning stock biomass was necessary (CCAMLR, 1991).

Since 1991, CCAMLR has adopted objectives for the maintenance of exploited Antarctic marine living resources in terms of their abundance relative to the pre-exploitation abundance, so that: (i) escapement of the spawning stock must be sufficient to avoid the likelihood of declining recruitment; and (ii) abundance under exploitation must maintain a sufficient reserve for the needs of dependent species (usually predators). These objectives have been endorsed by CCAMLR for assessing yields of krill and have been adopted in principle for determining yields of other fish stocks (CCAMLR, 1994; see SC-CAMLR, 1994, paragraphs 5.18 to 5.26 for discussion).

The decision rules associated with these objectives provide the foundation for incorporating uncertainties regarding population parameters and stock status into assessments of fishing strategies designed to meet the above objectives (e.g. de la Mare and Constable, 1990; Butterworth et al., 1991, 1994). Butterworth et al. (1991, 1994) produced a model specifically for evaluating catch limits for krill. This model was tailored to the assumptions applicable to krill growth patterns, fishing seasons and the timing of the spawning season. Furthermore, the model determines yields only as proportions of an estimated pre-exploitation biomass.

This paper presents a more general structure for a model to assess long-term annual yields against CCAMLR objectives. This model allows for flexibility for assessing the influence of different patterns of growth, natural mortality, spawning and fishing. It can be used to calculate yield per recruit and levels of yield or fishing mortality that meet criteria specified in CCAMLR decision rules. Stock trajectories can be calculated using estimates of absolute levels of recruitment, or estimates of absolute abundance, along with time series of recorded catches. The model uses an adaptive Runge-Kutta algorithm to calculate stock trajectories and catch rates over a specified simulation period. This procedure integrates a set of differential equations which incorporate functions that specify parameters such as growth, mortality, age-dependent selectivity and seasonal patterns in fishing mortality.

THE BASIC POPULATION MODEL

The model is a cohort model, with the annual advance of each cohort being calculated by numerical integration over a one-year period. The model is initialised by setting up the number of fish in each age class at the start of the simulation period. Each age class is projected through one year by numerical integration of the basic population differential equations. Catch and spawning stock is calculated for each age class during the projection. At the completion of the one-year projection, the exit numbers in each age class are assigned to the next highest age class and the lowest age class is assigned from a recruitment function. The process is repeated until the required time span is modelled to produce a single realisation of a stock trajectory.

Stock Projection for Each Age Class

The model is based on the usual differential equations which describe the numbers in each age class over one year. The number in each age class satisfies the differential equation:

$$\frac{dN_{a,y}}{dt} = -\left(M \cdot \mathrm{m}(a+t) + F_y \cdot \mathrm{f}(a,t)\right)N_{a,y} \qquad (1)$$

where $N_{a,y}$ is the number of fish in age class a at time of year t in year y. The term $M{\cdot}\mathrm{m}(a + t)$ gives the rate of natural mortality which applies to age class a at time of year t. M is the average rate of natural mortality over the life of a cohort and $\mathrm{m}(\tau)$ is a function which gives the ratio of the natural mortality rate for fish of total age $\tau = a + t$ to the average value over the lifetime of a cohort. This requires that:

$$\frac{\int_0^T \mathrm{m}(\tau)d\tau}{T} = 1 \qquad (2)$$

Expressing natural mortality by an average level, which can be modified by relative patterns against age and time of year, is a convenient method for incorporating Monte-Carlo integration over the effects of uncertainty in natural mortality rates into the assessments. This is because only the average value needs to be modified for each stock trajectory. The ability to specify a relative pattern allows sensitivity analyses of age-specific and seasonal effects on natural mortality to be readily investigated.

F_y in equation 1 is the average fishing mortality over all age classes in year y, and $\mathrm{f}(a,t)$ is a function which gives the relative distribution of the fishing mortality of age class a at the time of year t. This is partitioned to facilitate the numerical solution for fishing mortality in each year so that only the single parameter F_y needs to be evaluated. The age and season-specific multipliers allow for a number of different effects to be combined, including the effects of age and size-specific selectivity, and the effects of seasonality in fishing. Specifically, $\mathrm{f}(a,t)$ is derived from three functions: a size-selectivity function, $\mathrm{s}(a,t)$ (the usual modification to F arising from mesh selectivity, which is re-expressed as an age selection function, which depends on t because of growth during the year); an age-selectivity function, $\alpha(a)$ (allows for a fishery that targets specific age classes due to, for example, geographic or depth stratification of the stock according to age); and variation in fishing effort through the year, $\varepsilon(t)$ (e.g. open and closed seasons or relative fishing effort at different times based on the number of vessels). Thus:

$$\mathrm{f}(a,t) = \mathrm{s}(a,t)\alpha(a)\varepsilon(t) \qquad (3)$$

The size-selectivity function currently used in the computer program for the model is based on length as described in Butterworth et al. (1994) where:

$$\mathrm{s}(a,t) = \begin{cases} 0 & ; \quad \lambda(a+t) < l_1 \\ (\lambda(a+t) - l_1)/(l_2 - l_1) & ; \quad l_1 \le \lambda(a,t) \le l_2 \\ 1 & ; \quad \lambda(a,t) > l_2 \end{cases} \qquad (4)$$

where $\lambda(\tau)$ is a function (growth curve) which gives the mean length of fish at age $\tau = a + t$, and l_1 and l_2 are constants which specify the range over which selection changes from 0 to 1. However, alternative functional forms can be readily incorporated in the program. The program input parameters, l_1 and l_2, are specified from their midpoint and range, that is:

$$l_1 = l_\mathrm{m} - \frac{l_\mathrm{r}}{2}$$
$$l_2 = l_\mathrm{m} + \frac{l_\mathrm{r}}{2}$$

where l_m and l_r are the midpoint and range of l_1 and l_2 respectively. The biomass $B_{a,y}$ in each age class in each year satisfies the equation:

$$\frac{dB_{a,y}}{dt} = \mathrm{w}(a+t)\frac{dN_{a,y}}{dt} + N_{a,y}\frac{d\,\mathrm{w}(a+t)}{dt} \qquad (5)$$

where $\mathrm{w}(\tau)$ is a growth function which gives the average weight of fish of total age τ, where $\tau = a + t$, for fish of age a at time of year t. The growth function covers the entire lifespan of a cohort.

The yield from each age class satisfies the equation:

$$\frac{dY_{a,y}}{dt} = F_y \cdot \mathrm{f}(a,t) \cdot B_{a,y} \qquad (6)$$

The yield from each class taken over one year is calculated by simultaneous numerical integration of equations 1, 5 and 6 using an adaptive Runge-Kutta procedure (Press et al., 1992). The total yield is the sum of the yields from all age classes.

Spawning Stock Biomass

The spawning stock is specified in terms of its biomass. The biomass of each age class, a, at time t during the year is determined during the projection from equation 5. The proportion of each age class that is able to spawn at time t during the year is determined from three functions: $\mathrm{g}(l,t)$, the proportion of fish of length l being mature at time of year t; $\mathrm{h}(a,t)$, the proportion of fish of age a being mature; and $\mathrm{p}(t)$, the proportion of the mature stock spawning at t (spawning seasonality). Thus, the proportion of an age class spawning is given by:

$$\theta(a,t) = \mathrm{g}(l,t)\,\mathrm{h}(a,t)\,\mathrm{p}(t) \qquad (7)$$

This formulation allows for considerable flexibility in taking account of age and size-specific maturity: $\mathrm{g}(l,t) = 1$ if maturity is purely age-dependent; similarly, $\mathrm{h}(a,t) = 1$ if maturity is purely size-dependent. The size-specific maturity function used in this model is based on length as described in Butterworth et al. (1994) where:

$$\mathrm{g}(l,t) = \begin{cases} 0 & ; \quad l < m_1 \\ (l - m_1)/(m_2 - m_1) & ; \quad m_1 \le l \le m_2 \\ 1 & ; \quad l > m_2 \end{cases} \qquad (8)$$

where $l = \lambda(\tau)$, the mean length of fish at age $\tau = a + \tau$, m_1 and m_2 are constants which specify the range over which selection changes from 0 to 1 (in the computer program, input parameters m_1 and m_2 are specified from their midpoint m_m and range m_r).

The spawning stock at time t during the year is given by:

$$S(t)=\sum_{a}\theta(a,t)\cdot B_a(t) \tag{9}$$

The mean spawning biomass over a spawning period is calculated as:

$$\overline{S}=\frac{\int_{t_s}^{t_e} S(t)\cdot dt}{t_e-t_s} \tag{10}$$

where t_s and t_e are the respective start and end times of the spawning season within the year.

Computation of the Functions During Numerical Integration

In order to speed up computation, the time-dependent functions $\mathrm{m}(\tau)$, $\mathrm{w}(\tau)$, $\mathrm{f}(a,t)$ and $\theta(a,t)$ are calculated as vectors of discrete numeric values prior to numerical integration. Similarly, other functions such as the selection and maturation functions are also calculated as vectors at discrete values of the appropriate variable. The discrete points are calculated at a series of fixed points with a constant interval. The interval can be selected to be sufficiently small to adequately approximate the required functional forms. The values of the functions at any instant are calculated by linear interpolation between the nearest points included in the vectors of discrete values. Thus, the functions are replaced by continuous linear approximations. In the case of functions which have fixed transition points (corners), for example the selection and maturity functions (equations 4 and 8), the corners may be cut by linear interpolation, as shown in Figures 3a and 4a.

Recruitment

There are currently three options for setting the numbers of recruits in each year:

(i) numbers of recruits are independently and identically distributed according to a lognormal distribution;

(ii) proportions of recruits are independently and identically distributed according to a beta distribution (see de la Mare, 1994, for full details of this method);

(iii) numbers of recruits are drawn randomly with replacement from a vector of recruitment estimates.

In case (a) recruitment (R_y) is drawn each year at random from a lognormal distribution based on a specified mean, $\overline{R}$, and variance, σ_R^2, such that

$$R_y=\overline{R}\cdot\exp\left(\eta-\frac{\sigma_R^2}{2}\right) \tag{11}$$

where η is drawn randomly from $N(0;\sigma_R^2)$, which is a normal distribution with zero mean and variance σ_R^2.

In the simplest case, recruitment is considered to be independent of stock size. A stock recruitment relationship can be incorporated, however, where recruitment declines proportionately to spawning biomass when the spawning biomass is less than a specified proportion (0.2, say) of the estimated median of the pre-exploitation spawning biomass, $\hat{S}_0$ (after Butterworth et al., 1994).

Median Pre-exploitation Spawning Biomass

The approximation for the median pre-exploitation spawning biomass used in the program is similar to the one in Butterworth et al. (1994), where an initial age structure of the stock is set up such that the number at age a is:

$$N_a=\overline{R}\cdot\exp\left(-\frac{\sigma_R^2}{2}-M\int_0^a \mathrm{m}(\tau)d\tau\right) \tag{12}$$

This stock is then projected over one year to numerically solve equation 10, in the absence of fishing, to determine the approximate median unexploited spawning biomass, $\tilde{S}_0$.

CONCEPTUAL MODEL FOR PROJECTIONS AND ASSESSMENT OF YIELD

The application of the CCAMLR decision rules requires multiple stochastic realisations of stock trajectories in order to produce statistical distributions of stock abundance for a given level of catch, and to allow for Monte Carlo integration of uncertainty in key demographic parameters. Monte Carlo integration is carried out by drawing key demographic parameters for each stock trajectory at random from appropriate statistical distributions. Figure 1 shows the basic steps in calculating a single realisation of a stock trajectory. A single realisation consists of three parts: (i) setting basic demographic parameters; (ii) setting up the initial population age structure; and (iii) projecting the stock over the required simulation period.

Setting Basic Demographic Parameters

Recruitment variability, σ_R, mean recruitment, $\overline{R}$, and mean natural mortality, M, are determined for each run from specified distributions to take account of uncertainty in the estimates of these parameters. There are two options for determining $\overline{R}$, σ_R and M:

(i) they are drawn at random from uniform distributions over specified ranges (for use when uncertainty cannot be statistically quantified from data); and

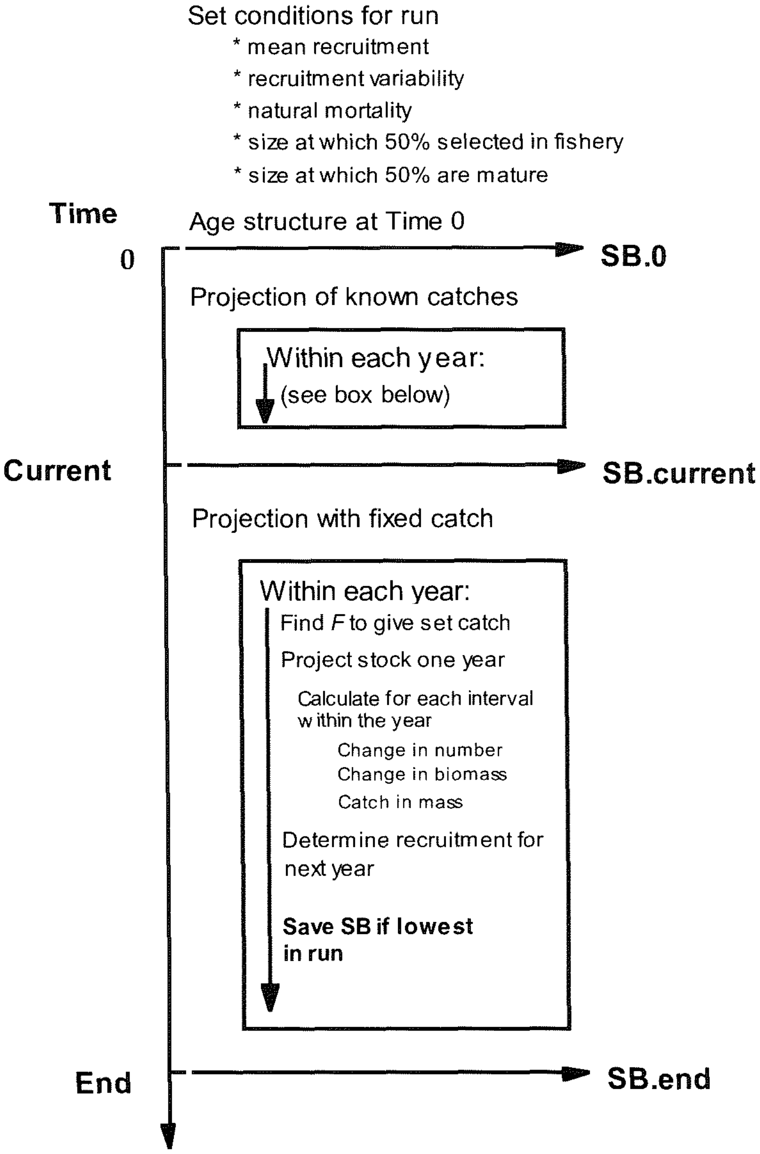


Figure 1: Flow chart of a single realisation of a stock trajectory in the generalised yield model. *SB.0, SB.current, SB.end* and *SB.lowest* refer to, respectively, the spawning biomass at: time 0 (pre-exploitation), time following the period of known catches, the end of the projection run and the lowest biomass between the current and end times.

(ii) they are drawn at random according to the method of de la Mare (1994) (used when recruitment parameters can be estimated from data).

Uncertainties in the sizes at which 50% of fish are mature, m_m, and 50% are recruited to the fishery, l_m, are taken into account by drawing these at random from uniform distributions, each with a specified range.

Setting the Initial Age Structure

The initial age structure can be determined by using either of two methods of computation. The first method maintains strict comparability with Butterworth et al. (1994). It starts with a set number of recruits (in the case of Butterworth et al., 1994, this was equal to 1.0 at age 0) and applies the value of M for the run (modified by the age-specific mortality coefficient) to each successive age class to obtain a deterministic age structure in accordance with equation 12. This age structure is projected for a number of years, equivalent to at least the number of age classes in the stock, with recruitment varying from year to year as specified in the recruitment function. This removes the influence of the initial deterministic age structure.

The second method of computation introduces recruitment variability into the formulation of the initial age structure, eliminating the need to project the stock forward one generation. In this formulation, each age class is assigned a different number of recruits at age 0 (or a specified starting age). Each of these recruitments is then adjusted for survival to the required age using the natural mortality function in accordance with equation 12, but with the $\bar{R}$ term replaced by a randomly drawn recruitment. The resulting age structure is projected forward one year so that S_0 is estimated over the same period as the spawning biomass in each other year in the simulation*. A plus class has been included in the computer program for this formulation by extending the calculations for a sufficient number of age classes and summing them.

If estimates of recruitment are in absolute numbers of fish, the calculated spawning biomass at time $t = 0$ will be an estimate of the absolute spawning biomass of the stock. A distribution of these estimates is produced from all the trajectories. This spawning stock distribution incorporates the effects of both recruitment variability and parameter uncertainty. This is different to the model of Butterworth et al. (1994) because those authors were seeking the proportion of the estimate of pre-exploitation biomass that could be exploited while satisfying the objectives established for the fishery by CCAMLR. As a consequence, their model outputs were relative to the initial biomass B_0 and not in the domain of actual biomasses.

Projecting the Stock

The main projection extends from the current time to the end of the projection period shown in Figure 1. In a single run, the model can project the stock forward under three different options: (i) a constant catch set as a specified proportion (γ) of an estimate of the pre-exploitation stock (B_0); (ii) a constant specified catch; or (iii) a constant fishing mortality, for example $F_{0.1}$.

The first option allows for the precautionary yield calculations of the type calculated by the program of Butterworth et al. (1994). This option does not require estimates of mean recruitment, but it does need an estimate of B_0 (see Butterworth et al., 1991, for discussion). Uncertainty in the estimate is incorporated into the simulation by using the coefficient of variation in the survey estimate of biomass, κ. The value of γ results in the calculation of the constant yield where yield for the single projection run is

$$Y = \gamma B_0 \exp\left(\varepsilon - \frac{\sigma_S^2}{2}\right) \quad ; \quad \varepsilon \text{ from } N\left(0;\sigma_S^2\right) \qquad (14)$$

where $N(0;\sigma_S^2)$ is a normal distribution with mean 0 and variance $\sigma_S^2 = \ln(1+\kappa^2)$.

The second option allows projection of the stock under a constant catch specified by total weight. In this case, estimates of parameters for mean recruitment must reflect actual levels of recruitment.

Either of these latter two options requires the determination of values of F_y which produce the

---

* This differs in detail from the original formulation of the model used at the meeting of the Working Group on Fish Stock Assessment (WG-FSA) in 1995. The original version calculated the spawning biomass using the age structure set up using the second method and using the maturity-at-age and length functions and the weight-at-age function specified in the input parameters for time of year $t = 0$.

expected catch when projecting the stock forward. F_y will depend on the numbers in each age class at the beginning of the year; and is solved iteratively using Brent's method (Press et al., 1992). In a year when the stock is at a low level, the average annual F_y needed to achieve a solution may be extremely high. An upper limit to F_y, F_{max} (see Table 1), is specified so as to keep the solution within reasonable bounds, although this produces a lower catch than required.

The third option allows the performance of the stock to be examined under a given fishing mortality.

The effects of known (e.g. historic) catch can also be taken into account in the period before the forward projection. For each year with known catch, F_y is calculated to obtain the catch specified in the catch history.

Measures of Performance under a Long-term Yield Strategy

The two estimates required by CCAMLR for the evaluation of a long-term annual yield are: (i) the probability of depletion at any time during the projection period, where the spawning biomass falls below a specified proportion, p_{dep} (e.g. 0.2), of its pre-exploitation median level; and (ii) the overall escapement, E, of spawning biomass, given by the ratio of the median spawning biomass at the end of the specified period to the median pre-exploitation spawning biomass.

These estimates are obtained by undertaking a large number of projection runs (e.g. 1 001). For each trajectory, the program calculates the status of the spawning stock and the minimum spawning biomass, S_{min}, that occurred during the forward projection period. In addition, the spawning stock is calculated for year 0, S'_0; at the end of the known historic catch period (current), S'_C; and at the end of the projection period, S'_E. The median spawning biomasses at the three times are determined over the set of all trajectories. $\hat{S}_0$ and $\hat{S}_E$ are used to designate the medians of the distribution of the values obtained for S'_0 and S'_E respectively over all trajectories.

Depletion Probability

The probability of depletion below the specified level is determined as the proportion of runs satisfying the condition:

$$S_{min} < p_{dep} S_0 \qquad (15)$$

where p_{dep} is the bound below which the probability of stock depletion is to be calculated as a proportion of S_0, the median of the unexploited spawning biomass.

There are currently two options included in the program for approximating S_0. The first is that arising from the use of equation 12, as used in Butterworth et al. (1994), whereby the estimated probability of depletion is calculated from the proportion of runs where:

$$S_{min} < p_{dep} \tilde{S}_0 \qquad (16)$$

The second option uses $\hat{S}_0$ in place of $\tilde{S}_0$ in estimating the probability of depletion, that is:

$$S_{min} < p_{dep} \hat{S}_0 \qquad (17)$$

The two options should give similar results when there is no Monte Carlo integration over uncertainty in demographic parameters. For cases where Monte Carlo integration is included, it would be expected that the second option may be somewhat more conservative, particularly if the range of uncertainty in the parameters is large. The method of Butterworth et al. (1994) is not applicable in the case where the recruitments are drawn randomly with replacement from a vector of known recruitments.

A third option is to be included in a future revision to the program which will allow S_0 to be estimated within each trajectory from multiple applications of the method used to set up the initial age structure. This option has the advantage over $\tilde{S}_0$ of being unbiased, but requires more computation and is subject to sampling variability. However, this option will avoid the problem arising with the second option when Monte Carlo integration is included. This method can also be applied when recruitments are drawn randomly from a vector of known recruitments.

Median Spawning Escapement

Two options are available in the program for calculating median spawning escapement. The

Table 1: Input parameters for projections of the generalised yield model for two examples - krill, *Euphausia superba* (derived from Butterworth et al. 1994) and *D. eleginoides* around South Georgia Island. These values are derived from SC-CAMLR, 1995 and may in some cases be best estimates of WG-FSA rather than being based on empirical data.

Category	Parameter	*E. superba*	*D. eleginoides*
Age composition	Minimum age in stock	0	4
	Maximum age (plus class)	7	35
	Years in plus class	1	21
Times within year	Number of increments	360	360
Natural mortality	Mean annual M	0.4 - 1.0	0.16
	Age-specific variation in M (m_{a+t})	constant = 1	constant = 1
Fishing mortality	Length when 50% of that size are recruited to fishery (l_m)	38-42	70
	Length range over which recruitment occurs (l_r)	10	10
	Age-specific selection	none	none
	Reasonable upper bound for annual fishing mortality	1.5	5
	Tolerance (error) for determining fishing mortality in each year	1E-05	1E-05
von Bertalanffy growth	time 0	0	0
	L_∞	60	170.8
	K	0.45	0.088
	No of increments in which growth occurs from start of year	90	360
Weight-length ($W = aL^b$)	a	1	2.5E-05
	b	3	2.8
Spawning biomass	Length when 50% of that size are mature (m_m)	34-40	maturity by age
	Length range over which maturity occurs (m_r)	12	
	Years over which maturity occurs	maturity by size	1-17
	Vector of proportions of each age mature		0.0001, 0.0005, 0.0014, 0.0055, 0.013, 0.036, 0.078, 0.2, 0.33, 0.54, 0.74, 0.84, 0.91, 0.96, 0.98, 0.99, 1.0
	Increment in year when spawning occurs	90	180
	Number of increments in spawning season	120	1
Recruitment	$\mu_{\bar{R}}$ for calculating mean recruitment	0	14.6372
	$\sigma_{\bar{R}}$ for calculating mean recruitment	0	0.4105
	Standard deviation of recruitment (σ_R)	0.4-0.6	1.1612
	Proportion of $\tilde{S}_0$ at which recruitment depletion begins to occur	0.2	0
Total biomass	Increment in year when biomass is estimated	45	1
	Coefficient of variation of S_0' estimated	0.3	0
	Coverage of survey	1	1
Simulation characteristics	Number of runs in simulation for each gamma	1001	1001
	Years to project stock to remove effects of initial age structure	1	1
	Vector of real catches for projecting over known catch period	0	8501000,4206000,7309000, 5589000,6605000,6171000
	Number of years to project stock following known catch period	20	35
Decision rules	Depletion level for assessment of long-term annual yield	0.2	0.2
	Maximum probability of falling below depletion level	0.1	0.1

first is comparable with the method used in Butterworth et al. (1994), which is the median value of escapement from each trajectory divided by the same median, but for a period when no yield is taken (e.g. $\gamma = 0$), that is:

$$\tilde{E} = \frac{\text{median}\left(\frac{S'_E}{\tilde{S}_0}\right)}{\text{median}_{\gamma=0}\left(\frac{S'_E}{\tilde{S}_0}\right)} \qquad (18)$$

The second option is to calculate the ratio of the median of the spawning stock biomass at the end of the simulation period to that in the pre-exploitation stock, that is:

$$\hat{E} = \frac{\hat{S}_E}{\hat{S}_0} \qquad (19)$$

A third option will be incorporated into a future revision of the program comparable to equation 18, but which will use the median of the pre-exploitation biomass to be estimated within each trajectory (as described above). This is required to deal with the case where recruitments are drawn from a vector of recruitment estimates and should obviate the need in equation 18 for dividing by the median final stock size in the absence of fishing.

RESULTS AND DISCUSSION

Example 1: Yield Determined as a Proportion (γ) of Estimated B_0

In this example, long-term annual yields are determined according to equation 14, where the annual yield is a proportion of the estimated pre-exploitation biomass. This has been developed for krill and presented by Butterworth et al. (1994). Their krill production model takes account of uncertainties described above and examines the performance of the spawning stock under various fishing regimes. This model considers a year of 360 days, consisting of 12 monthly (30-day) intervals where the krill grow in the first three months (90 days), the median spawning time is in month 4 (Day 120) and the biomass survey occurs in month 3 (Day 90). Their model has a similar conceptual structure to the one described in this paper despite the calculations being undertaken in a different manner. However, their computer program is written specifically for krill and can only be generalised after considerable revision.

The input parameters for the model derived from Butterworth et al. (1994) are shown in Table 1. The following development of the coefficients is for the three-month fishing season over summer (days 31 - 120) (their model 2). Figure 2 shows the conversion of the punctuated von Bertalanffy krill growth function into a piecewise weight-at-age function. In this model, natural mortality remains constant across all ages and during the year. Consequently, the function $m(a+t)$ is constant. Figure 3 shows how the function $f(a+t)$ for modifying F_y in the differential equations is derived from piecewise continuous functions of its component functions (equations 3 and 4). The proportion of an age class spawning at time t, given by $\theta(a+t)$ (equations 7 and 8), is illustrated in Figure 4. The resultant functions $m(a+t)$, $f(a,t)$ and $s(a,t)$ are shown in Figure 5.

Three fishing patterns were analysed, as in Butterworth et al. (1994) (their models 2, 3 and 4):

(i) three months over summer (days 31 - 120; $\varepsilon_t = 4$ during this period, 0 for the rest of the year);

(ii) six months over winter (days 151 - 330; $\varepsilon_t = 2$ during this period, 0 for the rest of the year) and;

(iii) all year (days 1 - 360; $\varepsilon_t = 1$).

Simulation conditions are shown in Table 1. Results of our simulations for values of γ comparable with their results are shown in Table 2. The results of both tests of depletion (equations 16 and 17) are shown for a critical level of depletion, p_{dep}, of 0.2 of the pre-exploitation spawning biomass. Assessments of spawning stock escapement using both methods (equations 18 and 19) are shown also.

The results of the model in this paper are comparable with the verified model of Butterworth et al. (1994). However, the ratio $\hat{E}$ is not exactly equivalent to the ratio $\tilde{E}$ used by Butterworth et al. (1994) although the results are generally similar. In the calculation of probability of depletion below $p_{dep}S_0$, the results using

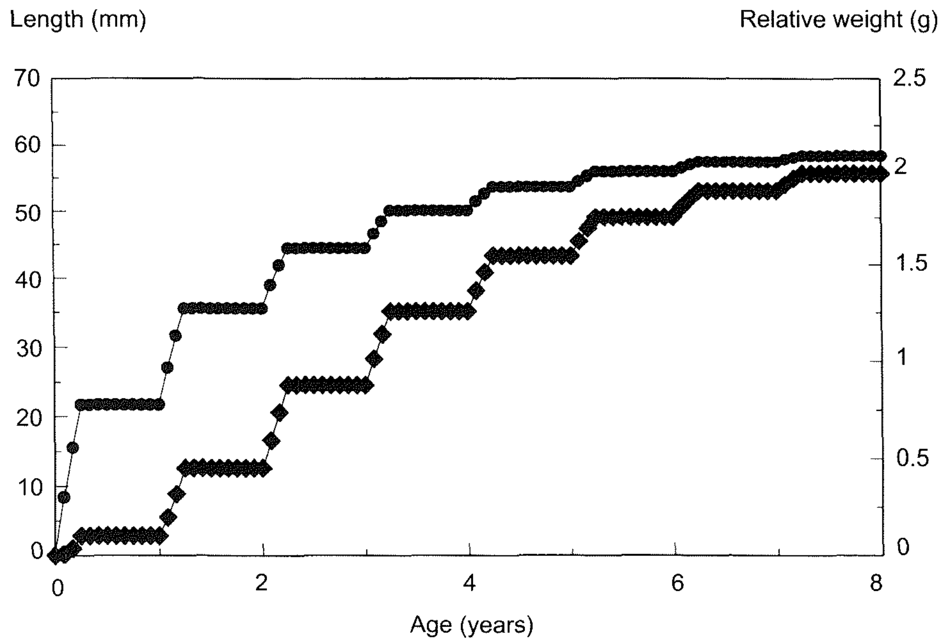


Figure 2: Length-at-age (circles) and relative weight-at-age (diamonds) for krill using the von Bertalanffy growth parameters and weight-length conversions from Butterworth et al. (1994) shown in Table 1.

Table 2: Results of projections for krill. Long-term annual yields were determined for each run as a proportion, γ, of the estimated pre-exploitation biomass. Probability of depletion was assessed using two methods: one described in this paper ($S_{min} < 0.2\hat{S}_0$) and the other as described in Butterworth et al. (1994) ($S_{min} < 0.2\tilde{S}_0$). Status of the spawning stock at the end of the projection run relative to the pre-exploitation biomass was assessed using two methods: one described in this paper ($\hat{E}$) and the other as described in Butterworth et al. (1994) ($\tilde{E}$). The model was run for the three fishing seasons described in Butterworth et al. (1994) - summer (December-February), winter (April - September) and whole year.

Fishing Season	γ	Probability of Depletion Below Bound		Spawning Stock Proportional Depletion$^+$	
		$S_{min} < 0.2\hat{S}_0$	$S_{min} < 0.2\tilde{S}_0$	$\hat{E}$	$\tilde{E}$
December - February	0.1	0.101	0.025	0.755	0.769 (0.768)
	0.136*	0.181	0.091	0.649	0.702
	0.15	0.251	0.126	0.613	0.662 (0.645)
	0.2	0.394	0.271	0.461	0.523 (0.511)
April-September	0.1	0.083	0.007	0.767	0.778 (0.787)
	0.15	0.149	0.048	0.642	0.683 (0.673)
	0.2	0.232	0.087	0.552	0.569 (0.573)
	0.202*	0.259	0.091	0.546	0.583
Whole Year	0.1	0.101	0.020	0.755	0.767 (0.775)
	0.15	0.182	0.071	0.617	0.663 (0.656)
	0.165*	0.242	0.104	0.578	0.628
	0.2	0.287	0.134	0.510	0.535 (0.539)

* Values of γ given by Butterworth et al. (1994) for which the probability that the stock will fall below 0.2 of the median pre-exploitation spawning biomass at some time over the 20-year projection period is equal to 10%.

+ Values in parentheses are those given by Butterworth et al. (1994).

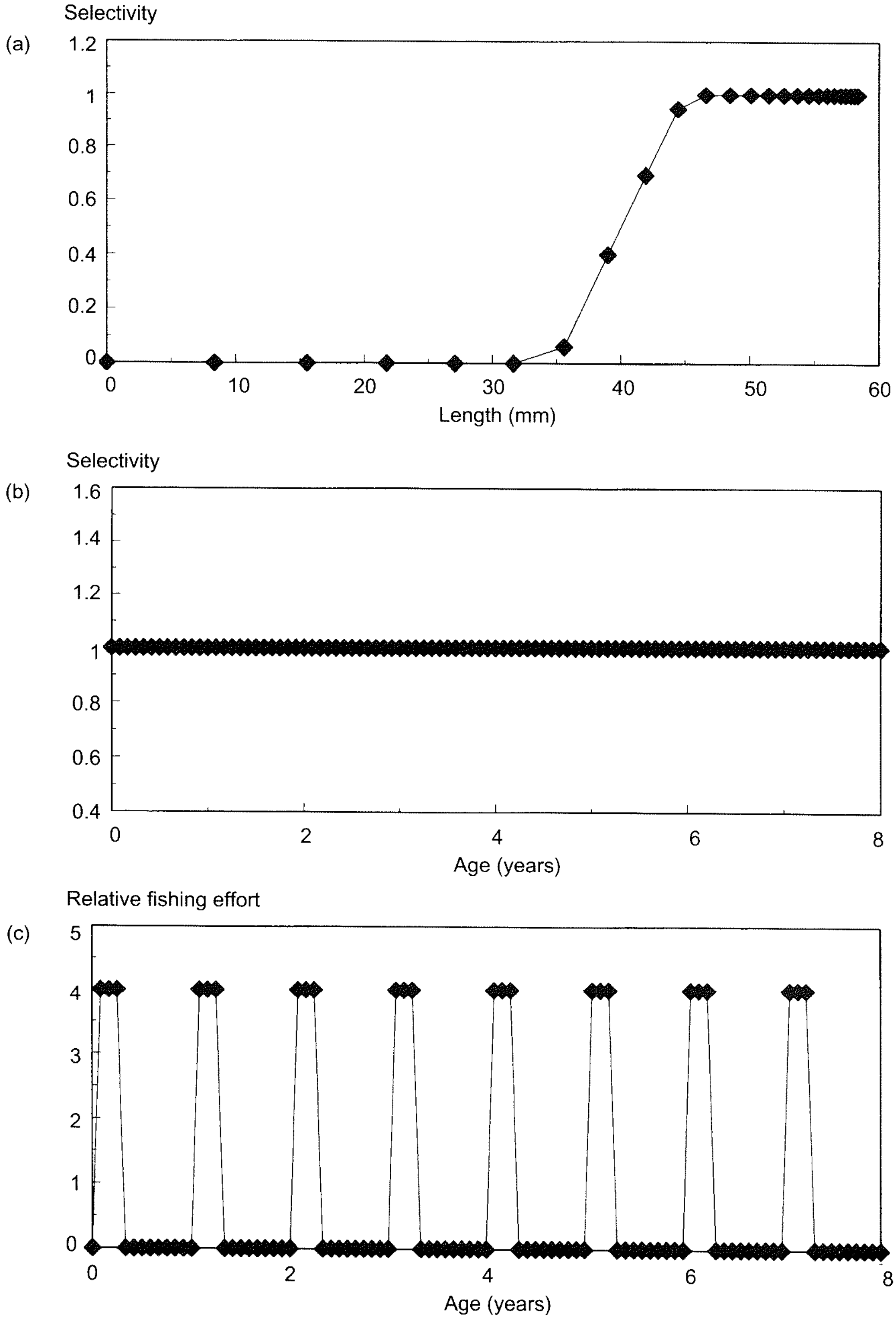


Figure 3: Components of the fishing mortality coefficient, *f*, for krill using parameters from Butterworth et al. (1994) shown in Table 1.

(a) Fishing selectivity as a function of length.

(b) Relative fishing selectivity as a function of age.

(c) Relative fishing effort during the year.

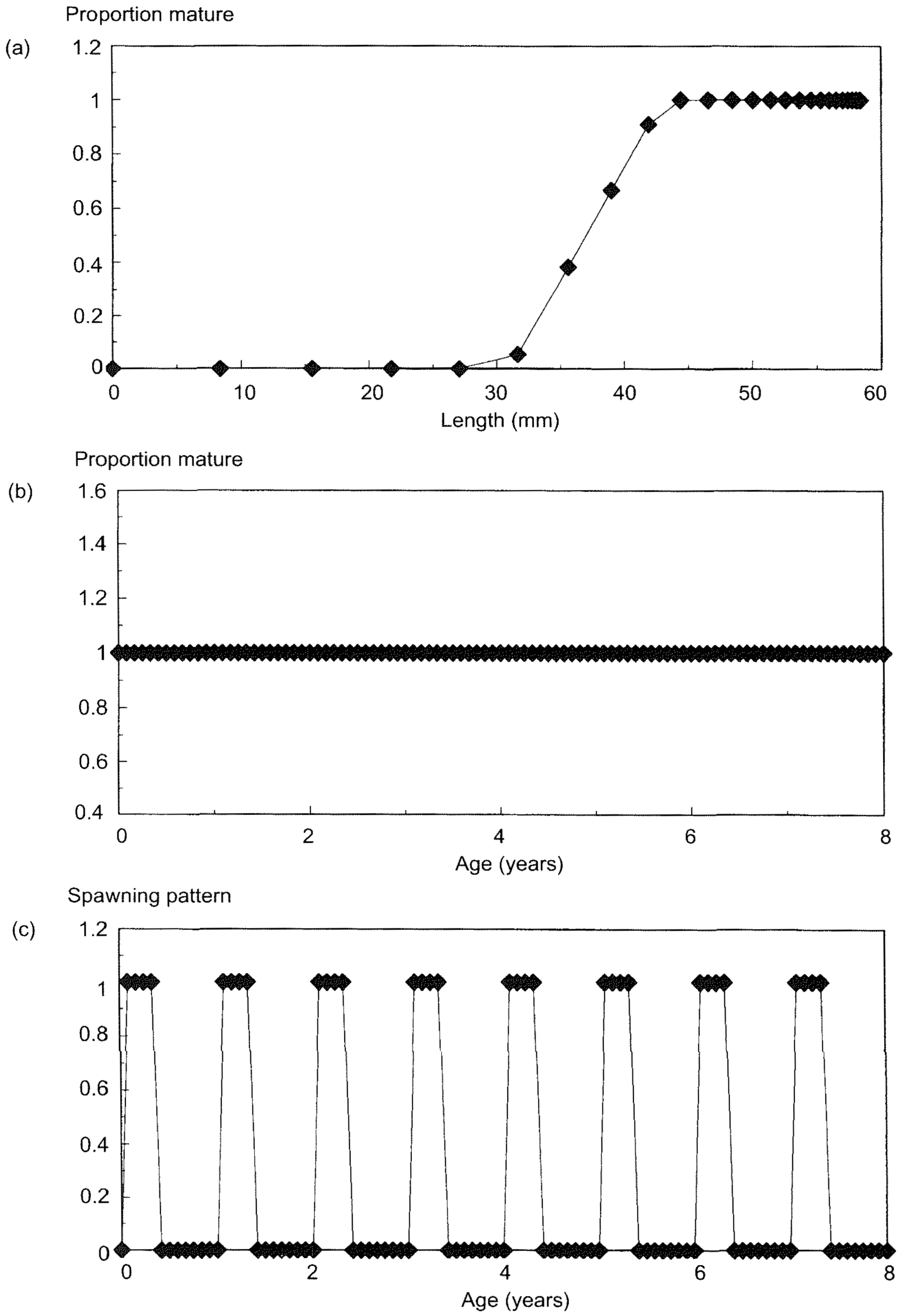


Figure 4: Components of the maturity coefficient, *sp*, for krill using parameters from Butterworth et al. (1994) shown in Table 1.

(a) Maturity versus length.

(b) Maturity versus age. This is set to 1 when maturity-at-length is the primary factor influencing the state of maturity.

(c) Spawning pattern during the year. This indicates the proportion of the spawning stock that would be spawning at each interval in the year.

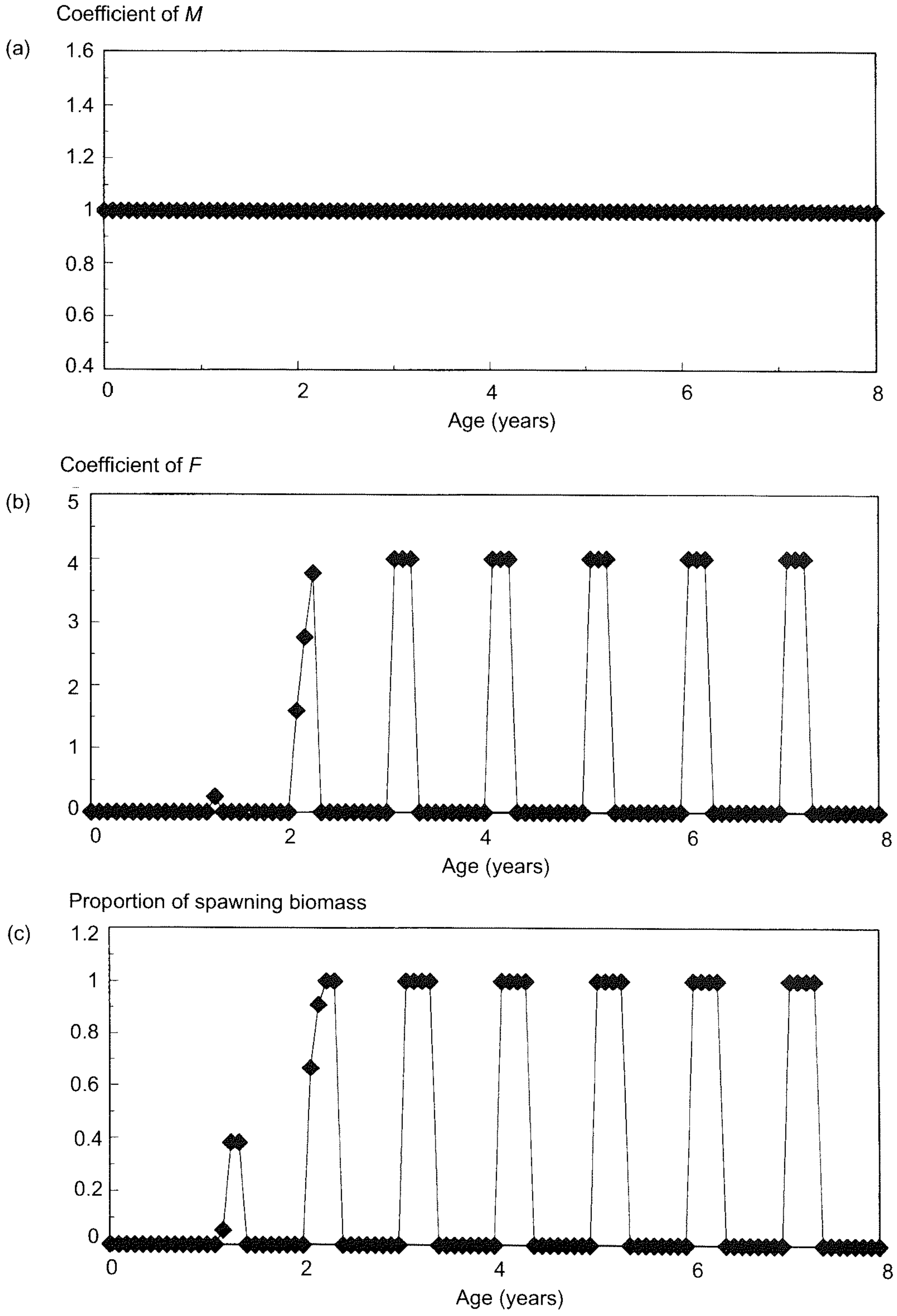


Figure 5: Functions for modifying *M*, *F*, and spawning biomass by age and time of year.

(a) Natural mortality coefficient, *M*.

(b) Composite fishing mortality coefficient, *F*.

(c) The proportion of the biomass spawning at each age and at each time of the year, θ.

equation 17 are, as expected, more conservative than those of the model of Butterworth et al. (1994).

Example 2: Yield Based on Direct Estimates of Recruitment

This method is suitable for assessing yield when the spawning biomass has not been estimated, but estimates of recruitment and the other parameters discussed above are available. In this case, the performance of the spawning stock is evaluated under a fishing regime with long-term annual yields according to actual biomass. This method was applied at the meeting of WG-FSA to evaluate potential long-term annual yields of Patagonian toothfish (*Dissostichus eleginoides*) (SC-CAMLR, 1995). The input parameters for this model were developed at the working group meeting and are shown in Table 1 (see SC-CAMLR, 1995, for a discussion of the derivation of these parameters). Note that the model evaluates the probability of depletion using equation 17.

The potential behaviour of a projection is illustrated in Figures 6 and 7. These figures show two runs from the simulation testing the performance of the stock under a long-term annual yield of 4 000 tonnes. They show the initial and final age structures and the trajectories of spawning biomass, recruitment and the changes in fishing mortality F_y which produce the specified annual yield. Note that the age structure is dependent on the random recruitments, producing a structure that is different to a deterministic stable age distribution (Figure 6). The difference between the initial age structures of the two runs arises from the random recruitments generated by the recruitment function combined with the different values of mean recruitment drawn randomly for each run.

In the first run, the stock is dominated by the large recruitments that occurred only early in the projection (Figure 7a), resulting in little long-term change in the size structure of the stock (Figure 6a). In contrast, the second run shows the consequences of poor recruitment over the duration of the projection resulting in depletion of the stock (Figure 7b) and a decline in the frequency of older individuals in the stock (Figure 6b). These two runs illustrate possible trajectories of the real stock given the uncertainties in the parameter estimates and the variability in recruitment. They demonstrate the need to account for uncertainty in stock parameters when assessing the potential effects of long-term annual yields on the stock.

The overall effects of six given levels of long-term annual yield on the spawning stock are presented in Table 3. Figure 8 shows the frequency distributions and medians of spawning biomass prior to exploitation, currently and at the end of the projections under a constant yield of 4 000 tonnes. Figure 8 also shows the frequency distribution of the lowest spawning biomasses in the projection period and how this relates to the specified depletion criterion. These results show that the refinement made since the meeting of WG-FSA in 1995 gives slightly lower probabilities of depletion (0.083 compared to 0.1 at the working group meeting), as well as slightly greater proportional escapement of the spawning stock at the end of the projections (0.79 compared to 0.74). These, and other refinements currently under development, will need to be considered at future meetings of the working group.

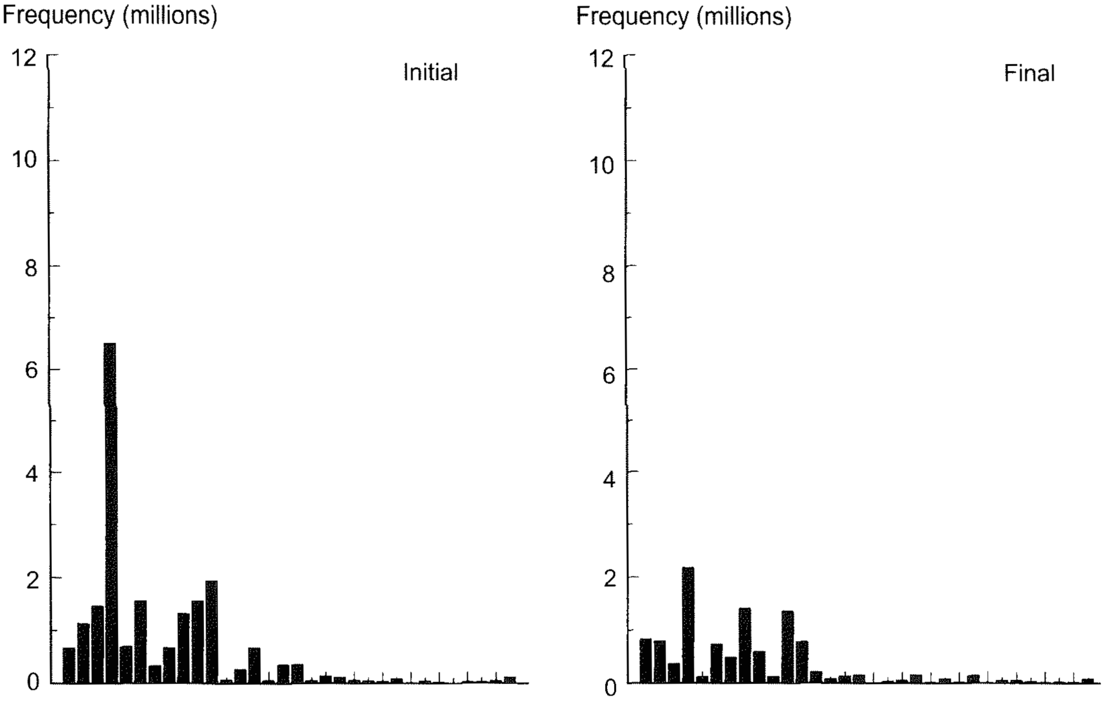
CONCLUDING REMARKS

The model presented in this paper provides comparable results to those obtained in CCAMLR using existing projection software. The advantage of this model over the existing software is that it

Table 3: Results of projections for *D. eleginoides* from South Georgia Island for six long-term annual yields. The probability of depletion below $p_{dep} = 0.2$ and proportional escapement of the spawning stock at the end of the projection run relative to the pre-exploitation biomass was assessed using the methods described in this paper.

Long-term Annual Yield (tonnes)	Probability of Depletion Below Bound $S_{min} < 0.2\hat{S}_0$	Spawning Stock Escapement $\hat{E}$
3500	0.068	0.823
4000	0.083	0.794
4500	0.097	0.785
5000	0.122	0.758
5500	0.170	0.689
6000	0.188	0.648

(a) Run 1



(b) Run 2

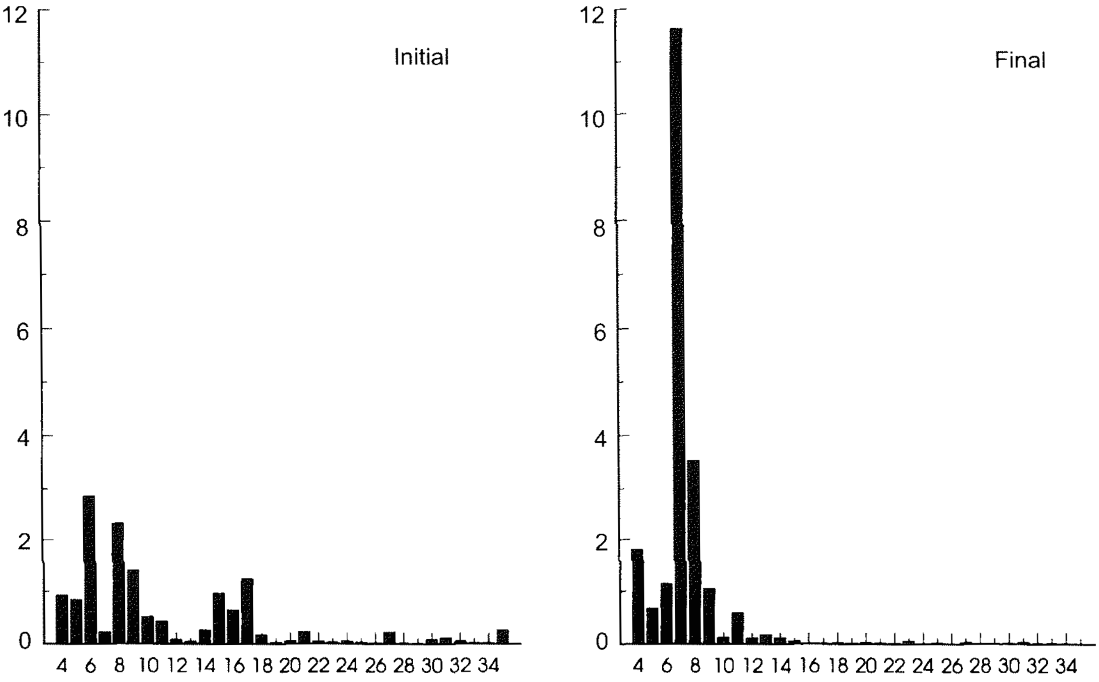
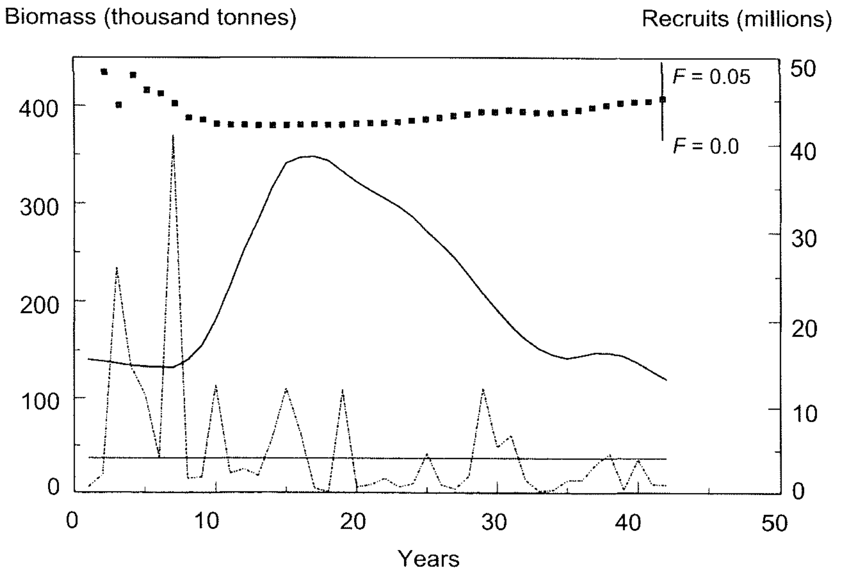


Figure 6: Age structures from two projections for *D. eleginoides* in Subarea 48.3 with parameters as shown in Table 1. The long-term annual yield for these projections was 4 000 tonnes. Age frequency distributions are shown for the stock at Time 0 and at the end of the projection in both runs.

(a) Run 1



(b) Run 2

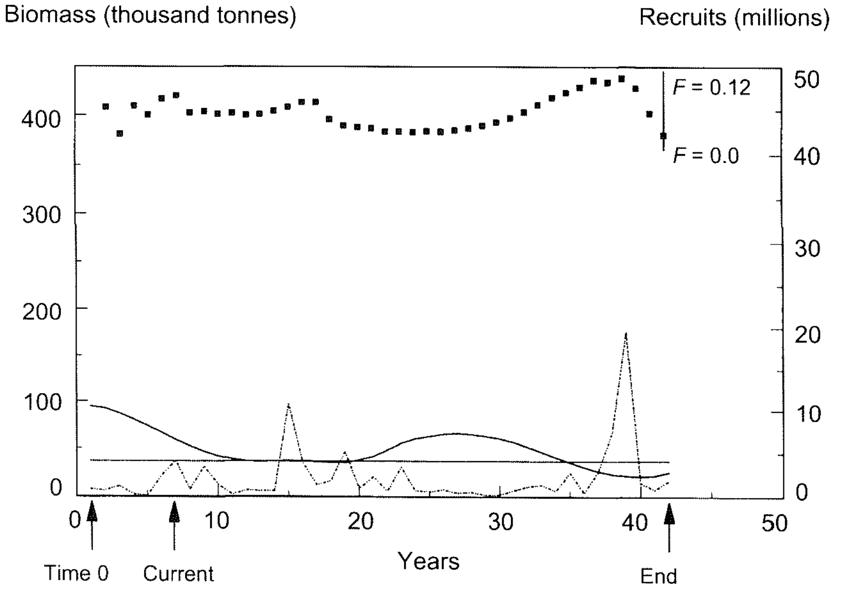


Figure 7: Spawning biomass (solid line), recruitments (dashed line) and levels of *F* (squares) in the two example projection runs for *D. eleginoides* in Subarea 48.3 that gave the age structures in Figure 6. The long-term annual yield for these projections was 4 000 tonnes. The biomass depletion level (straight horizontal line) was 0.2 of the median spawning biomass ($\hat{S}_0$) at Time 0 (see Figure 8). The three times important for stock assessment indicated in Figure 1 are shown as 0, Current, End.

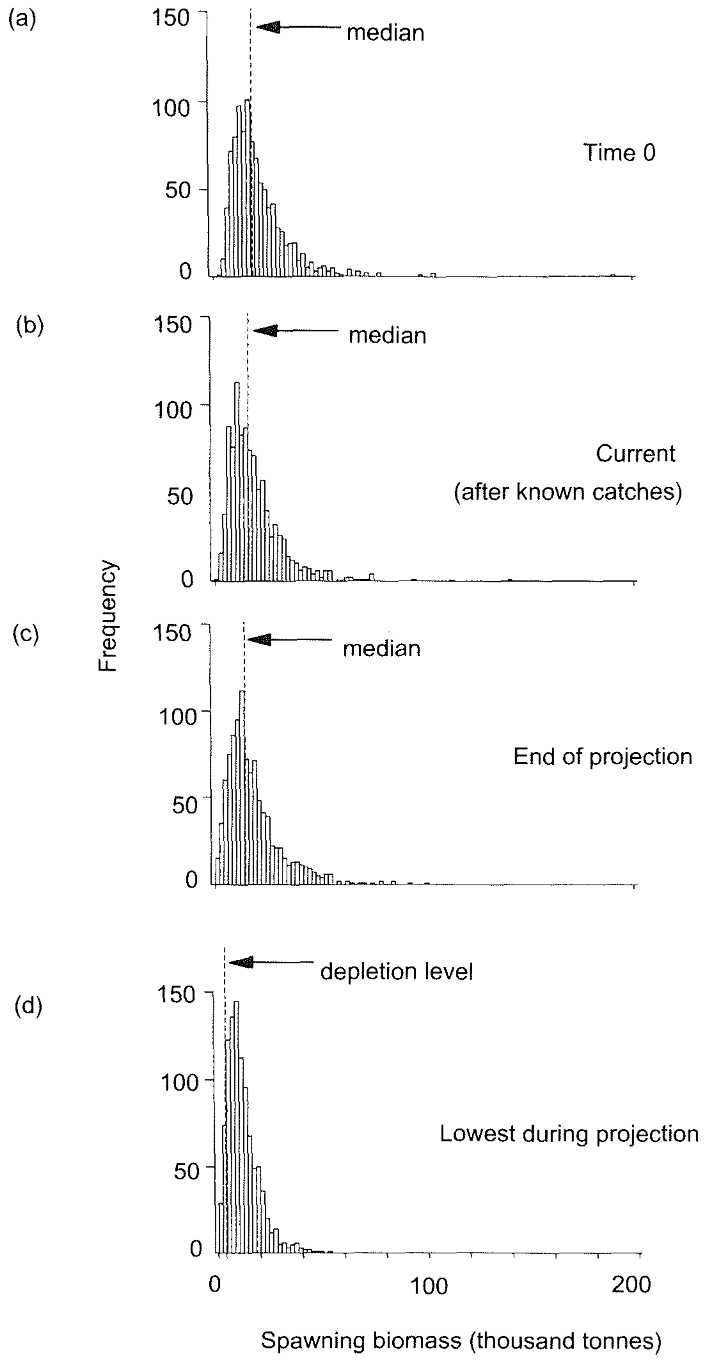


Figure 8: Frequencies of spawning stock biomass for *D. eleginoides* in Subarea 48.3 at different times during the projections aimed at the assessment of the effects of a fixed long-term annual yield of 4 000 tonnes.

(a) Spawning stock biomass at Time 0. Dotted line shows median pre-exploitation spawning biomass ($\hat{S}_0$).

(b) Spawning stock biomass following the period of known catches (Current time). Dotted line shows median spawning biomass before projection period.

(c) Spawning stock biomass at the end of the projection run. Dotted line shows median spawning biomass at the end of the projection period. The ratio of this value over the median pre-exploitation biomass gives the proportional escapement of the stock at the end of the projection ($\hat{E}$).

(d) Lowest spawning stock biomass during the projection run. Dotted line shows the 10% probability bound on depletion (0.2 x median pre-exploitation spawning biomass, $\hat{S}_0$). In this case, the spawning biomass fell below this line in 0.083 of the projections.

provides increased flexibility in the types of stock projections and yield assessments that may need to be undertaken. Further refinements could be made to examine the effect of great interannual variation in natural mortality, as may occur in the case of the icefish *Champsocephalus gunnari* (SC-CAMLR, 1994).

ACKNOWLEDGEMENTS

We would like to thank members of WG-FSA for their constructive comments on the development of this model and for their work on providing the input parameters to the model of *Dissostichus eleginoides*. Many thanks to David Agnew for his encouragement and comments throughout and to Frank Stagnetti for general comments. We are grateful for careful reviews of the paper by Doug Butterworth and Pavel Gasiukov. Financial support for Andrew Constable was provided by the Australian Antarctic Division and a Deakin University Research Development Fellowship/Australian Commonwealth Staff Development Grant.

REFERENCES

Butterworth, D.S., A.E. Punt and M. Basson. 1991. A simple approach for calculating the potential yield from biomass survey results. In: *Selected Scientific Papers, 1991 (SC-CAMLR-SSP/8)*. CCAMLR, Hobart, Australia: 207-215.

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. 1987. *Report of the Sixth Meeting of the Commission (CCAMLR-VI)*. CCAMLR, Hobart, Australia.

CCAMLR. 1991. *Report of the Tenth Meeting of the Commission (CCAMLR-X)*. CCAMLR, Hobart, Australia.

CCAMLR. 1994. *Report of the Thirteenth Meeting of the Commission (CCAMLR-XIII)*. CCAMLR, Hobart, Australia.

de la Mare, W.K. and A.J. Constable. 1990. Refinements to the strategy for managing depleted fish stocks based on CCAMLR objectives. *Selected Scientific Papers, 1990 (SC-CAMLR-SSP/7)*. CCAMLR, Hobart, Australia: 467-475.

de la Mare, W.K. 1994. Modelling krill recruitment. *CCAMLR Science*, 1: 49-54.

Press, W.H., S.A. Teukolsky, W.T. Vetterling and B.P. Flannery. 1992. *Numerical Recipes in Fortran: the Art of Scientific Computing*. Second edition. Cambridge University Press, Cambridge, UK.

SC-CAMLR. 1987. Report of the Ad Hoc Working Group on Fish Stock Assessment. In: *Report of the Sixth Meeting of the Scientific Committee (SC-CAMLR-VI)*, Annex 5. CCAMLR, Hobart, Australia.

SC-CAMLR. 1991. *Report of the Tenth Meeting of the Scientific Committee* (SC-CAMLR-X). CCAMLR, Hobart, Australia.

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

SC-CAMLR. 1995. Report of the Working Group on Fish Stock Assessment. In: *Report of the Fourteenth Meeting of the Scientific Committee (SC-CAMLR-XIV)*, Annex 4. CCAMLR, Hobart, Australia.

Liste des tableaux

Tableau 1: Paramètres d'entrée pour les projections du modèle de rendement généralisé. Deux exemples sont donnés: le krill, *Euphausia superba* (à partir de Butterworth et al. 1994) et *D. eleginoides* autour de la Géorgie du Sud. Ces valeurs sont dérivées de SC-CAMLR, 1995 et peuvent, en certains cas, représenter les meilleures estimations du Groupe de travail chargé de l'évaluation des stocks de poissons plutôt que reposer sur des données empiriques.

Tableau 2: Résultats des projections relatives au krill. Les rendements annuels à long terme ont été déterminés pour chaque passage en tant que proportion, γ, de l'estimation de la biomasse de pré-exploitation. La probabilité d'épuisement a été estimée par deux méthodes : l'une est décrite dans cette communication ($S_{min} < 0.2\hat{S}_0$), l'autre provient de Butterworth et al. (1994) ($S_{min} < 0.2\tilde{S}_0$). L'état du stock reproducteur à la fin du passage de la projection relative à la biomasse de pré-exploitation a été estimé par deux méthodes : l'une décrite dans cette communication ($\hat{E}$), l'autre dans Butterworth et al. (1994) ($\tilde{E}$). Le modèle a été utilisé pour les trois saisons de pêche décrites dans Butterworth et al. (1994) - été (décembre-février), hiver (avril-septembre) et année entière.

Tableau 3: Résultats des projections relatives à *D. eleginoides* de la Géorgie du Sud pour six rendements annuels à long terme. La probabilité d'épuisement au delà de p_{dep} = 0,2 et l'évitement proportionnel du stock reproducteur à la fin du passage de projection relativement à la biomasse de pré-exploitation ont été estimés par les méthodes décrites dans cette communication.

Liste des figures

Figure 1: Organigramme de la réalisation d'une trajectoire des stocks dans le modèle de rendement généralisé. *SB.0*, *SB.current*, *SB.end* et *SB.lowest* se réfèrent respectivement à la biomasse reproductrice : au moment 0 (pré-exploitation), après la période de captures connues, à la fin du passage de projection, et à la biomasse la plus faible entre le moment présent et celui de la fin de la projection.

Figure 2: Longueur selon l'âge (cercles) et poids relatif selon l'âge (losanges) du krill selon les paramètres de croissance de von Bertalanffy et les clés âge-longueur de Butterworth et al. (1994) figurant dans le tableau 1.

Figure 3: Composantes du coefficient de mortalité par pêche, *f*, relativement au krill, par les paramètres de Butterworth et al. (1994) figurant dans le tableau 1.

(a) Sélectivité de la pêche en fonction de la longueur.
(b) Sélectivité relative de la pêche en fonction de l'âge.
(c) Effort de pêche relatif pendant l'année.

Figure 4: Composantes du coefficient de maturité, *sp*, relativement au krill, par les paramètres de Butterworth et al. (1994) figurant dans le tableau 1.

(a) Maturité en fonction de la longueur.
(b) Maturité en fonction de l'âge. Valeur fixée à 1 quand la maturité selon la longueur est le facteur influençant le plus le stade de maturité.
(c) Rythme du frai pendant l'année. Il indique la proportion du stock reproducteur qui se reproduirait à chaque intervalle pendant l'année.

Figure 5: Fonctions pour modifier *M*, *F* et la biomasse reproductrice selon l'âge et l'époque de l'année.

(a) Coefficient de mortalité naturelle, *M*.
(b) Coefficient composite de mortalité par pêche, *F*.
(c) Proportion de la biomasse reproductrice pour chaque âge et chaque époque de l'année, θ.

Figure 6: Structures d'âges de deux projections de *D. eleginoides* de la sous-zone 48.3 avec les paramètres donnés dans le tableau 1. Le rendement annuel à long terme de ces projections était de 4 000 tonnes. Les distributions de fréquences des âges sont indiquées pour le stock au moment 0 et à la fin de la projection, pour les deux passages.

Figure 7: Biomasse reproductrice (trait plein), recrutements (ligne en tirets) et niveaux de *F* (carrés) dans les deux exemples de passages de projection pour *D. eleginoides* de la sous-zone 48.3 qui ont donné les structures d'âges de la figure 6. Le rendement annuel à long terme de ces projections était de 4 000 tonnes. Le niveau d'épuisement de la biomasse (ligne droite et horizontale) était égal à 0,2 de la biomasse

reproductrice médiane ($\hat{S}_0$) au moment 0 (cf. figure 8). Les trois moments importants pour l'évaluation des stocks sont indiqués sur la figure 1 en tant que 0, Current (en français : heure actuelle) et End (fin).

Figure 8: Fréquence de reproduction de la biomasse du stock de *D. eleginoides* de la sous-zone 48.3 à différentes époques, dans les projections visant à évaluer les effets d'un rendement annuel fixe à long terme de 4 000 tonnes.

(a) Biomasse du stock reproducteur à un moment 0. Les lignes en pointillés montrent la médiane de la biomasse reproductrice avant l'exploitation ($\hat{S}_0$).

(b) Biomasse du stock reproducteur après la période de captures connues (moment présent). Les lignes en pointillés montrent la médiane de la biomasse reproductrice avant la période de la projection.

(c) Biomasse du stock reproducteur à la fin de la projection. Les lignes en pointillés montrent la médiane de la biomasse reproductrice à la fin de la période de la projection. Le rapport entre cette valeur et la médiane de la biomasse de pré-exploitation donne l'évitement proportionnel du stock à la fin de la projection ($\hat{E}$).

(d) Biomasse la plus faible du stock reproducteur pendant la projection. La ligne en pointillés donne la limite de la probabilité de 10% (0,2 x la médiane de la biomasse reproductrice de pré-exploitation, $\hat{S}_0$). Dans ce cas, la biomasse reproductrice est tombée en dessous de cette ligne dans 0,083 des projections.

Список таблиц

Таблица 1: Вводные параметры обобщенной модели вылова в случае криля, *Euphausia superba* (из работы Баттеруорта и др., 1994), и *D. eleginoides* в районе Южной Георгии. Эти значения получены из отчета SC-CAMLR, 1995, и в некоторых случаях являются наилучшими оценками Рабочей группы по оценке рыбных запасов, а не оценками, выведенными на основе эмпирических данных.

Таблица 2: Результаты прогонов по крилю. Значения долгосрочного ежегодного вылова были определены для каждого прогона в виде доли, γ, оценочного значения предэксплуатационной биомассы. Вероятность истощения была рассчитана при помощи двух методов: один описан в настоящем документе ($S_{min} < 0.2\hat{S}_0$), а другой в работе Баттеруорта и др. (1994) ($S_{min} < 0.2\tilde{S}_0$). Состояние нерестующей биомассы запаса к концу прогностического прогона относительно предэксплуатационной биомассы было оценено при помощи двух методов: один из них описан в данном документе ($\hat{E}$), а другой в работе Баттеруорта и др. (1994) ($\tilde{E}$). Модель прогонялась по трем промысловым сезонам, описанным в работе Баттеруорта и др. (1994) - лето (декабрь-февраль), зима (апрель-сентябрь) и весь год.

Таблица 3: Результаты прогонов по *D. eleginoides* в районе острова Южной Георгии при шести значениях долгосрочного ежегодного вылова. При помощи описанных в настоящем документе методов была рассчитана вероятность истощения ниже p_{dep} = 0,2, а также размер необлавливаемой части нерестующей биомассы запаса в конце прогностического прогона относительно объема предэксплуатационной биомассы.

Список рисунков

Рисунок 1: График одного прогона прогностической траектории обобщенной модели вылова. *SB.0*, *SB.current*, *SB.end* и *SB.lowest* относятся соответственно к нерестующей биомассе: при времени 0 (до начала эксплуатации), при времени, следующем за периодом известного лова, в конце прогностического прогона и при наиболее низком значении биомассы между текущим и конечным временем.

Рисунок 2: Длина криля при определенном возрасте (кружки) и относительный вес криля при определенном возрасте (ромбики), рассчитанные при помощи приведенных в Таблице 1 параметров роста по фон Берталанффи и коэффициентов пересчета 'вес-длина' из работы Баттеруорта и др. (1994).

Рисунок 3: Компоненты коэффициента промысловой смертности, f, в случае криля, выведенные при помощи приведенных в Таблице 1 параметров из работы Баттеруорта и др. (1994).

(a) Промысловая селективность как функция длины.
(b) Относительная промысловая селективность как функция возраста.
(c) Относительное промысловое усилие в течение года.

Рисунок 4: Компоненты коэффициента половозрелости, sp, в случае криля, выведенные при помощи приведенных в Таблице 1 параметров из работы Баттеруорта и др. (1994).

(a) Половозрелость относительно длины.
(b) Половозрелость относительно возраста. Это значение принято за 1, когда половозрелость при определенном возрасте является основным фактором, влияющим на стадию половозрелости.
(c) Нерест в течение года. Указана доля нерестующей биомассы запаса в какой-либо период года.

Рисунок 5: Функции для модификации M, F и величины нерестующей биомассы по возрасту и времени года.

(a) оэффициент естественной смертности, M.
(b) Сложный коэффициент промысловой смертности, F.
(c) Доля нерестующей биомассы по возрасту и времени года, θ.

Рисунок 6: Возрастные структуры по двум прогнозам по *D. eleginoides* в Подрайоне 48.3 с параметрами, показанными в Таблице 1. Долгосрочный ежегодный вылов по этим прогнозам составил 4 000 тонн. Частотные распределения возраста показаны для этого запаса при Времени 0 и в конце прогностического периода для обоих прогонов.

Рисунок 7: Нерестующая биомасса (сплошная линия), пополнение (пунктирная линия) и уровни F (квадраты) в двух прогностических прогонах *D. eleginoides* Подрайона 48.3, по которым были получены возрастные структуры Рисунка 6. Долгосрочный ежегодный вылов для этих прогонов составил 4000 тонн. Уровень истощения биомассы (прямая горизонтальная линия) равнялся 0,2 медианной нерестующей биомассы ($\hat{S}_0$) при Времени 0 (см. Рисунок 8). Три значения времени для оценки запаса - 0, Current, End.

Рисунок 8: Частотные распределения оценок нерестующей биомассы *D. eleginoides* Подрайона 48.3 в разное время в ходе прогонов, проведенных с целью оценки влияния зафиксированного долгосрочного ежегодного вылова в 4 000 тонн.

(a) Нерестующая биомасса запаса при Времени 0. Пунктирной линией показана медианная предэксплуатационная нерестующая биомасса ($\hat{S}_0$).
(b) Нерестующая биомасса запаса по окончании периода известного лова (Текущее время). Пунктирной линией показана медианная нерестующая биомасса до начала периода прогноза.
(c) Нерестующая биомасса запаса по окончании периода прогноза. Пунктирной линией показана медианная нерестующая биомасса в конце прогностического периода. Отношение этого значения к медианной предэксплуатационной биомассе дает часть необлавливаемого резерва запаса в конце периода прогноза ($\hat{E}$).
(d) Самое низкое значение нерестующей биомассы запаса в ходе периода прогноза. Пунктирной линией показан 10%-ный предел вероятности истощения (0,2 x медианная предэксплуатационная биомасса, $\hat{S}_0$). В данном случае нерестующая биомасса упала ниже этого уровня в 0,083 прогнозов.

Lista de las tablas

Tabla 1: Parámetros de entrada de las proyecciones del modelo generalizado de rendimiento para dos ejemplos - kril, *Euphausia superba* (Butterworth et al. 1994) y *D. eleginoides* alrededor de la isla Georgia del Sur. Estos valores se obtuvieron de SC-CAMLR, 1995 y pueden en algunos casos constituir las mejores estimaciones del Grupo de Trabajo de Evaluación de las Poblaciones de Peces, en vez de basarse en datos empíricos.

Tabla 2: Resultados de las proyecciones para el kril. Se determinaron los rendimientos anuales a largo plazo para cada pasada de proyección en forma de una proporción, γ, de la biomasa estimada antes de la explotación. La probabilidad de agotamiento se evaluó utilizando dos métodos: uno descrito en este documento ($S_{min} < 0.2\hat{S}_0$) y el otro en Butterworth et al. (1994) ($S_{min} < 0.2\tilde{S}_0$). El estado del stock en desove al final de la pasada de proyección con respecto a la biomasa antes de la explotación fue evaluado mediante dos métodos: uno descrito en este documento ($\hat{E}$) y el otro en Butterworth et al. (1994) ($\tilde{E}$). Se aplicó el modelo a las tres temporadas de pesca descritas en Butterworth et al. (1994) - verano (diciembre-febrero), invierno (abril - septiembre) y año completo.

Tabla 3: Resultados de las proyecciones (para seis rendimientos a largo plazo) de *D. eleginoides* alrededor de la isla Georgia del Sur. Utilizando los métodos descritos en este documento, se evaluó la probabilidad de que el stock disminuya a un nivel menor que $p_{dep} = 0.2$, y la fracción del stock en desove que escapa al final de la pasada de proyección comparado con el nivel de biomasa antes de la explotación.

Lista de las figuras

Figura 1: Diagrama de flujo de una pasada de proyección del stock en el modelo generalizado de rendimiento. *SB.0, SB.actual SB.final* y *SB.mínimo* se refieren a la biomasa en desove: en el tiempo 0 (antes de la explotación), después del período de capturas conocidas, al final de la pasada de proyección y la biomasa mínima entre el momento actual y el final de la pasada de proyección, respectivamente.

Figura 2: Tallas por edad (círculos) y pesos relativos por edad (diamantes) para el kril utilizando los parámetros de crecimiento de von Bertalanffy y las conversiones peso-tallas de Butterworth et al. (1994) que figuran en la tabla 1.

Figura 3: Componentes del coeficiente de mortalidad por pesca, *f*, para el kril utilizando los parámetros de Butterworth et al. (1994) que figuran en la tabla 1.
(a) Selectividad de la pesca en función de la talla
(b) Selectividad relativa de la pesca en función de la edad.
(c) Esfuerzo pesquero relativo durante el año.

Figura 4: Componentes del coeficiente de madurez, *sp*, para el kril utilizando los parámetros de Butterworth et al. (1994) que figuran en la tabla 1.
(a) Madurez en función de talla.
(b) Madurez en función de edad. Esta está fijada en 1, cuando la madurez por talla es el factor principal que influye en el estadio de madurez.
(c) Características del desove durante el año. Esto indica la proporción del stock en desove que desovaría en cada intervalo durante el año.

Figura 5: Funciones para modificar *M*, *F*, y la biomasa en desove por edad y temporada anual.
(a) Coeficiente de mortalidad natural, *M*.
(b) Coeficiente compuesto de la mortalidad por pesca, *F*.
(c) La proporción de la biomasa del stock que desova según la edad y por temporada en el año, θ.

Figura 6: Estructura de edades de dos proyecciones de *D. eleginoides* en la Subarea 48.3 con parámetros tal como aparecen en la tabla 1. El rendimiento anual a largo plazo para estas proyecciones fue de 4 000 toneladas. Se muestran las distribuciones de frecuencias de edades para el stock en el tiempo 0 y al final de la proyección en ambas pasadas.

Figura 7: La biomasa en desove (línea continua), reclutamientos (línea entrecortada) y niveles de *F* (cuadrados) en los dos ejemplos de pasadas de proyección para *D. eleginoides* en la Subárea 48.3 que dio las estructuras de edades de la figura 6. El rendimiento anual a largo plazo de estas proyecciones fue de 4 000 toneladas. El nivel de agotamiento de la biomasa (línea derecha horizontal) fue 0.2 de la mediana de la biomasa en desove ($\hat{S}_0$) en el tiempo 0 (ver la figura 8). Los tres momentos cruciales para la evaluación del stock indicados en la figura 1 se indican como 0, Actual, Final.

Figura 8: Frecuencias de la biomasa del stock de *D. eleginoides* en desove en la Subárea 48.3, en diferentes momentos, durante las proyecciones que intentan hacer una evaluación de los efectos de un rendimiento anual de 4 000 toneladas fijo a largo plazo.
(a) Biomasa del stock en desove en el tiempo 0. La línea punteada representa la mediana de la biomasa del stock en desove antes de la explotación ($\hat{S}_0$).

(b) Biomasa del stock en desove luego del período de capturas conocidas (Tiempo actual). La línea punteada muestra la mediana de la biomasa del stock en desove antes del período de la proyección.

(c) Biomasa del stock en desove al final de la pasada de proyección. La línea punteada representa la mediana de la biomasa del stock en desove al final del período de la proyección. El cuociente entre este valor y el de la mediana de la biomasa antes de la explotación representa la fracción del stock que ha escapado al final de la proyección ($\hat{E}$).

(d) Biomasa mínima del stock en desove durante la proyección. La línea punteada indica un límite en la probabilidad de agotamiento de 10% (0.2 x la mediana de la biomasa del stock en desove antes de la explotación ($\hat{S}_0$). En este caso, la biomasa del stock en desove disminuyó a un nivel menor en 0.083 de las proyecciones.