Description and use of parameters within Antarctic krill (*Euphausia superba*) assessment models conducted with the Grym

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Abstract

The Commission for the Conservation of Antarctic Marine Living Resources has recently decided to re-adopt the generalised yield model (GYM) as an assessment tool to progress the management of Antarctic krill (*Euphausia superba*). To this end, the GYM has been re-implemented in the open source R package Grym. This document describes the model parameters required to conduct a krill stock assessment with Grym and, where possible, provide guidance as to how these parameters can be estimated.

Résumé

La Commission pour la conservation de la faune et la flore marines de l'Antarctique a récemment pris la décision de réadopter le modèle de rendement généralisé (GYM pour *generalised yield model*) comme outil d'évaluation pour faire progresser la gestion du krill antarctique (*Euphausia superba*). À cette fin, le GYM a été réécrit dans le package R *open source* dénommé « Grym ». Ce document décrit les paramètres du modèle requis pour mener une évaluation de stock de krill en utilisant le Grym et, lorsque c'est possible, explique de quelle manière ces paramètres peuvent être estimés.

Абстракт

Комиссия по сохранению морских живых ресурсов Антарктики недавно приняла решение вновь использовать обобщенную модель вылова (GYM) в качестве инструмента оценки для дальнейшего управления ресурсами антарктического криля (*Euphausia superba*). С этой целью GYM повторно включена в программу Grym на языке R с открытым исходным кодом. В данном документе описаны параметры модели, необходимые для проведения оценки запасов криля с помощью модели Grym, и, по возможности, даны рекомендации по оценке указанных параметров.

Resumen

La Comisión para la Conservación de los Recursos Vivos Marinos Antárticos ha decidido recientemente volver a adoptar el modelo de rendimiento generalizado (GYM) como una herramienta para evaluar el progreso de la ordenación del kril antártico (*Euphausia superba*). A fines de alcanzar este objetivo, se decidió volver a implementar el modelo GYM en un programa de código abierto que ha resultado en el desarrollo del paquete en R "Grym". El presente documento describe los modelos de parámetros que se requieren para realizar una evaluación de stocks de kril con Grym y, cuando sea posible, brindar asesoramiento en cuanto a cómo se pueden estimar estos parámetros.

Introduction

The CCAMLR Scientific Committee (SC-CAMLR) last estimated a precautionary har-vest rate (gamma) used for management advice in the Area 48 (Figure 1) krill fisheries in 2007 (SC-CAMLR, 2007, Annex 4, paragraphs 2.38 and 2.39) using the generalised yield model (GYM, Constable and de la Mare, 1996). Subsequently, a range of methods have been tried to produce both input parameters and stock assessments which can be used for management advice. Following the work plan outlined by the Scientific Committee and the Commission (SC-CAMLR, 2019, Annex 4, paragraphs 2.60 to 2.64; CCAMLR, 2019, para-graph 5.53) the GYM software was reimplemented in R as the Grym package, with the intention of updating the previously conducted krill assess-ment. However, the methods used to estimate some input parameters for the previous assessment were not documented in detail and there remains con-siderable ambiguity as to how to compute these inputs, and how these inputs are used within the assessment.

This study aims to clarify what each parameter within the Grym assessment models is used for and, where possible, provide examples as to how they have been calculated. This is desi

people who are already familiar with the basics of stock assessment models and are looking to either develop their own model within the Grym or esti-mate parameters for Grym models. For a descrip-tion of how the Grym models work, and how they differ from the models implemented in the GYM, see Maschette et al. (2020) and code repositories described within.

Methods

The model parameters have been divided into two categories: (i) those calculated based on observed data, and (ii) those which control the structure of the model (Table 1).

For each parameter, we outline: (i) how the parameter is used within the current implementation of the Grym model, and (ii) examples of how the parameter can be calculated (where appropriate) to be consistent with either the previous implementa-tion of the krill assessment, or the current accepted CCAMLR practices in other fisheries.

When searching through reports of the Working Group on Ecosystem Monitoring and Management (WG-EMM), there are no recent examples of many of these parameters being calculated. Whilst many
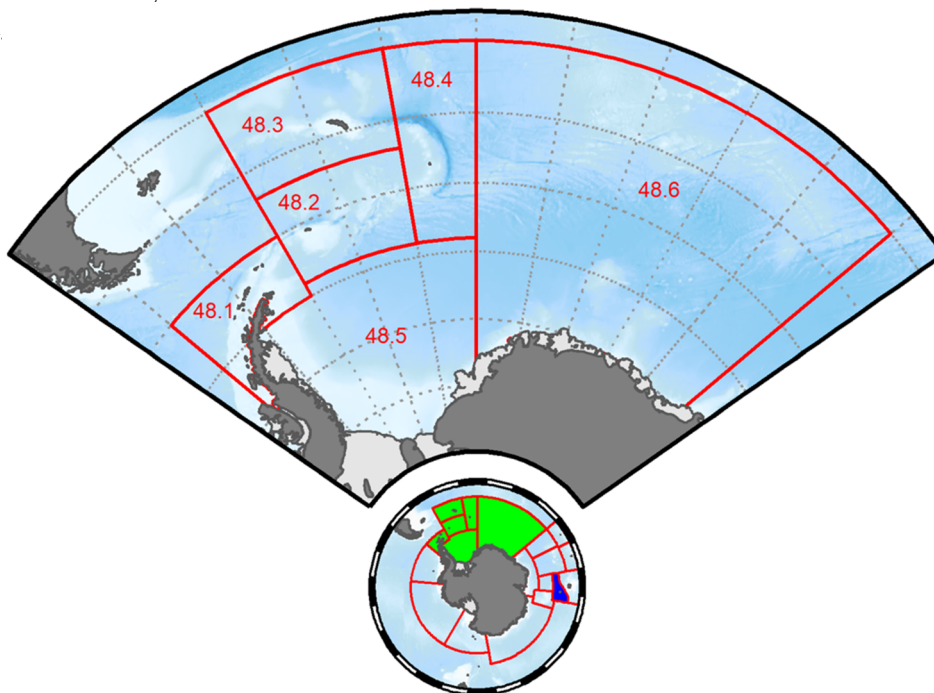

Figure 1: CCAMLR subareas within the Statistical Area 48 (green). Division 58.5.2 is highlighted in blue.

Table 1: Grym parameters required for initial krill assessment. Origin describes if a parameter is 'Calculated' based of observed data, a 'Decision' made to implement the model, or an 'Output' of the model is expected to fall within a given this range. Note: units related to length and weight are arbitrary, as long as they are consistent throughout the model. For example, for length you could use mm, cm or m.

Parameter group	Parameter	Unit	Origin
Age classes	First age class	-	Decision
	Last age class	-	Decision
	t_0	year	Calculated
	L_∞	mm	Calculated
Length-at-age relationship	k	year^{-1}	Calculated
	Start growth period	dd/mm	Calculated
	End growth period	dd/mm	Calculated
Weight-at-length relationship	Weight-length parameter – A	g	Calculated
	Weight-length parameter – B	-	Calculated
Maturity	Min length, 50% mature	mm	Calculated
	Max length, 50% mature	mm	Calculated
	Range over which maturity occurs	mm	Calculated
Spawning season	Start of spawning season	dd/mm	Calculated
	End of spawning season	dd/mm	Calculated
	Recruitment function		Decision
Recruitment	Mean proportional recruitment	-	Calculated
	SD of proportional recruitment	-	Calculated
	Proportional recruitment age class	-	Decision
	Number of surveys in recruitment	-	Calculated
Selectivity	Min length, 50% selected	mm	Calculated
	Max length, 50% selected	mm	Calculated
	Range over which selection occurs	mm	Calculated
	FutureSurveyCV		Calculated
Future fishing parameters	Fishing season	dd/mm	Decision
	Reasonable upper bound for annual F	year^{-1}	Decision
	Reference date	dd/mm	Decision
	Target escapement		Decision
Model decisions	Model iterations		Decision
	Model time steps		Decision
	Projection period	years	Decision
	Monitoring interval	dd/mm	Decision
Output	Natural mortality range	year^{-1}	Output

parameters had papers reporting on data collection, which could have been used to estimate them, and changes in the data tracked and linked to anticipated environmental effects, the follow-on steps of calculating the parameters used in the assessment were not conducted. This provides limited scope to refer to previous methods used.

Age classes

Model use

Age classes in the Grym are defined so that the model simulates the age range for which information is available, either from the fishery, or from surveys, or both. As krill are assumed to not live past seven years (Siegel, 1987), and krill below 1 year old are rarely seen in the fishery or the synoptic surveys, the assessment uses the age classes 1–7 years.

A note when referring to ages in the models compared to biological age, there appears to be a mismatch between the terms age and age+ (or year class, or age class). Within the models, if referring to the 2+ year class, or the 2-year-old cohort, it means any krill that are between the ages of 2, up to but not including age 3, conversely krill referred to as two years old are assumed to be an exact age of 2 in the model. The latter of these is very rarely used

within stock assessments as they tend to model year classes, not krill of an exact age, it is, however, more common in biology publications.

Length-at-age

Model use

The growth model is used for calculating the length for each age class at every time step in the model. This is then used for calculating at spe-cific time steps what proportions of the population are available to the fishery, are mature, and what weight each individual will be at that time.

Growth consists of five parameters: the first three relating directly to the von Bertalanffy growth model (L_∞, k, t_0), and the last two relating to the growth period of krill.

Method

Currently, there are no recent estimates, nor an agreed upon method to estimate von Bertalanffy growth parameters for krill.

Whether estimated as continual or punctu-ated (only growing for part of the year), growth is integral to the Grym models, and effort should be focused towards identifying a method that is both reliable and for which the required data either exists or can be obtained.

Drawing examples from allied comparable fish-eries may provide examples of how krill growth parameters may be estimated. In the Division 58.5.2 (Figure 1) mackerel icefish (*Champsocephalus gun-nari*) fishery for example, where direct age infor-mation is not available, a von Bertalanffy growth model was fitted to the modal length estimates of each cohort identified by the CMIX analysis (de la Mare, 1994a) from survey data between 2010 and 2017 using non-linear least squares with the func-tion *nls*() in R:

$$L(t) = L_\infty(1 - e^{-k(t-t_0)}). \tag{1}$$

Here L_∞ is the asymptotic mean length, k is the growth rate and t_0 the hypothetical age at length zero. Ages were assigned to cohorts as propor-tion of the year since the nominal birthdate of 1 December to the time of survey, and each cohort

was weighted by the inverse square of the standard error of the modal length (Maschette et al., 2017).

Aside from the von Bertalanffy parameters, the growth period of krill within the year also needs to be either estimated or assumed. For calculating the growth period, Thanassekos et al. (2021) estimated the growth period by fitting a loess regression to area averaged, daily photosynthetically active radi-ation (PAR) satellite data between 2002 and 2020. The time period for an area where PAR was above 25 Einsteins m^{-2} day^{-1} was assumed to be the likely growth period for krill in that area.

Weight-at-length

Model use

Together with the length-at-age relationship, a weight-at-length relationship is used to determine the average weight of an individual for each age class at each time step. The Grym then scales these weights by the modelled abundance in each age class to determine a total biomass for each age class at each time step. This biomass is then multiplied by the fraction mature (see below) in each age class and averaged over the nominated spawning season to determine the spawning biomass in each year.

Method

The parameters of the weight-at-length rela-tionship, a and b, are estimated by non-linear least squares assuming a power law relationship:

$$W = aL^b \tag{2}$$

where W is the weight (g) and L is the length (mm) of individual krill.

This most recent implementation for fitting this relationship for krill within CCAMLR was Cox et al. (2021), who estimated the parameters using the *nls*() function with parametric bootstrap in R (R Development Core Team, 2020) fitting meas-urements of survey-caught krill.

Maturity

Model use

The maturity ogive is used within the Grym model to determine the proportion of each length class, and in turn age class, that is mature. This

determines the overall proportion of individuals in the population which are considered to be part of the spawning stock.

Method

A Bayesian non-linear binomial random effects model was recently used to estimate the width and slope of a ramp-shaped maturity ogive as required by the Grym, details are contained in Maschette et al. (2021, Appendix 3).

Spawning season

Model use

The spawning season provides the time period for which the model calculates spawning stock biomass. It also tells the model the spawning period used when estimating virgin spawning stock biomass.

Method

Spawning season is estimated from observations of gravid females getting ready to spawn through to the presence of spent females being more common in the population (see Kawaguchi, 2016).

Recruitment

Model use

The Grym estimates both the variability in recruitment and the natural mortality from the fraction of the population that are recruits.

Natural mortality can be estimated from the proportion of the population that are recruits. If natural mortality is low, individuals live longer, the proportion of the population that is old is larger and the proportion that are recruits is lower. But as natural mortality increases, lifespans are shortened, the fraction of the population that is old diminishes and the proportion that are recruits increases. For example, if 60% of the population are recruits, then natural mortality must be high as very few must survive four years beyond recruitment. Conversely, if the proportion of recruits is low, then natural mortality must also be low (see Pavez et al., 2021).

Variability in recruitment is estimated from the variability in the proportion of recruits. In a year with stronger recruitment, the recruits will be a greater fraction of the population, and in a year with weaker recruitment, the recruits will be a smaller fraction of the population.

Method

Proportional Recruitment (PR) is fitted to survey data as outlined by de la Mare (1994a, 1994b) and expanded by Pavez et al. (2021). The PR model expects four parameters to be provided: Mean PR (R.mean), standard deviation (SD) of PR (R.SD), PR age class and number of surveys used in estimating PR (N.surveys). Whilst the PR model itself as proposed by Pavez et al. (2021) has been implemented within the setup of the krill assessments, the calculation of the four input parameters for this model has been discussed at length within the Scientific Committee working groups (see WG-SAM-2021, paragraphs 3.2 to 3.20; WG-FSA-2021, paragraphs 5.8 to 5.12; WG-FSA-2021, paragraphs 7.15 to 7.19). Upon reviewing the original work by de la Mare (1994a, 1994b), as well as considering the way in which survey and length-frequency data is treated in other CCAMLR fisheries, the flow chart and notes presented in Appendix A have been developed.

Selectivity

Model use

The selectivity ogive is used within the Grym model to indicate what proportion of each length class, and in turn age class, is available to the fishery. This determines the overall proportion of individuals in the population which are subject to fishing mortality.

Method

Selectivity was estimated by Krag et al. (2014) using the standard International Council for the Exploration of the Sea (ICES) methods to fit a logistic model (Wileman et al., 1996) to catch data:

$$r(l, L50, SR)$$

$$= \frac{\exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)}{1.0 + \exp\left(\frac{ln(9)}{SR} \times (l - L50)\right)} \tag{3}$$

where $L50$ is the length at which there is 50% retention likelihood for the individual in the net and SR is the selection range.

Future fishing parameters

The model requires three parameters for estimating future fishing effort: Fishing season, Reasonable upper bound for annual F (fishing mortality) and FutureSurveyCV.

Model use

Fishing season (dd/mm): Period of the year during which krill fishing occurs.

Reasonable upper bound for annual F: In each year of a projection, the Grym determines the fishing mortality required to attain the target catch from the projected biomass. In extreme scenarios, the target catch may require an impossibly high fishing mortality. This parameter sets the maximum fishing mortality the Grym can apply in attempting to attain the target catch.

FutureSurveyCV: The Grym uses FutureSurveyCV to add variability to the calculated biomass at time zero (B_0) at the beginning of each run. This is to account for the sampling and methodological error in surveys during the forward projections. Historically, this parameter was called B0logSD within the GYM.

Method

FutureSurveyCV: The Grym requires an estimate of the expected measurement error in future surveys. This can be calculated in a number of ways: (i) take the coefficient of variation (CV) from the most recent survey, (ii) average across the time series of surveys, or (iii) estimate the expected CV of future planned surveys.

Model decisions and output

The remainder of the parameters are decisions to control aspects of the model:

Reference date (dd/mm): This is the start day of the year in the model. It dictates the day on which the youngest age class enters the model, and what day each age class progresses to the next age class.

All other dates are calculated as an increment from this date.

Target escapement: The target median spawning stock status to be achieved after the projection period. For krill, under the current CCAMLR decision rules, this is 75% (SC-CAMLR, 1994, paragraph 5.18).

Model iterations: How many projection runs of the model should be conducted.

Model time steps: How many time steps should the year be split into within the model. Typically, this is daily time steps.

Projection period (years): How many years should the model project forward for. Currently for krill, this is 20 years (Maschette et al., 2021).

Monitoring interval (dd/mm): Time of the year in which surveys are done to estimate B_0.

Natural mortality range: Natural mortality is an output from the PR model (see 'Recruitment' section above), it can be compared to an expected range to see if the recruitment parameters R.mean, R.SD and N.surveys make ecological sense.

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Proportional recruitment input parameter calculations

This appendix outlines the steps to calculate input parameters for the proportional recruitment model from research surveys as outlined within de la Mare, 1994a, 1994b.

The steps are mostly simple and have two possible end points (Figure A1).

Whichever point you plan to exit the flow chart, the first three steps are needed. The first two steps are straightforward, although there are some core assumptions associated with them:

(i)   surveys should have adequate hauls to representatively sample the population

(ii)   krill should be sampled randomly and in sufficient quantity to ensure measurements are representative of the overall catch.

Once these steps have been done, step 3 of Figure A1 is to convert haul-by-haul counts in each length bin into a density per unit of volume. Typically, this is either per m^3 or per 1 000 m^3. Where density of krill d at length l in krill per m^3 was estimated for each haul as:

$$d_l = \frac{N_l C}{Ac}$$

(1)

where N_l is the numbers at length l, A is the swept volume of the net for that haul, C is the total catch numbers of the haul and c is the total count of the sample from the haul.

Mixture analysis

For the mixture analysis, the CMIX mixture model is fitted to the entire survey to estimate the total density in each age cohort.

As a single mixture model is fitted across all strata, the haul densities are scaled to account for unequal sampling effort in each stratum (step 4). The data is rescaled so that the mean of the rescaled data is the same as the stratified mean of the raw data. For each haul in k strata, the density data is rescaled by the composite sampling fraction following de la Mare and Williams (1996):

$$D_{i,j} = d_{i,j} \frac{A_i}{\sum_k A_k} \times \frac{\sum_k n_k}{n_i}$$

(2)

where $D_{i,j}$ is the re-scaled density for haul i in stratum j, $d_{i,j}$ is the original density estimate for that haul, and A_i and n_i are the area and the number of hauls in stratum i respectively.

Step 5b involves fitting the mixture model to the rescaled length-density distributions in order to calculate cohort densities. These densities can then be used in step 6 to calculate the proportion of recruits in the population (see de la Mare, 1994b).
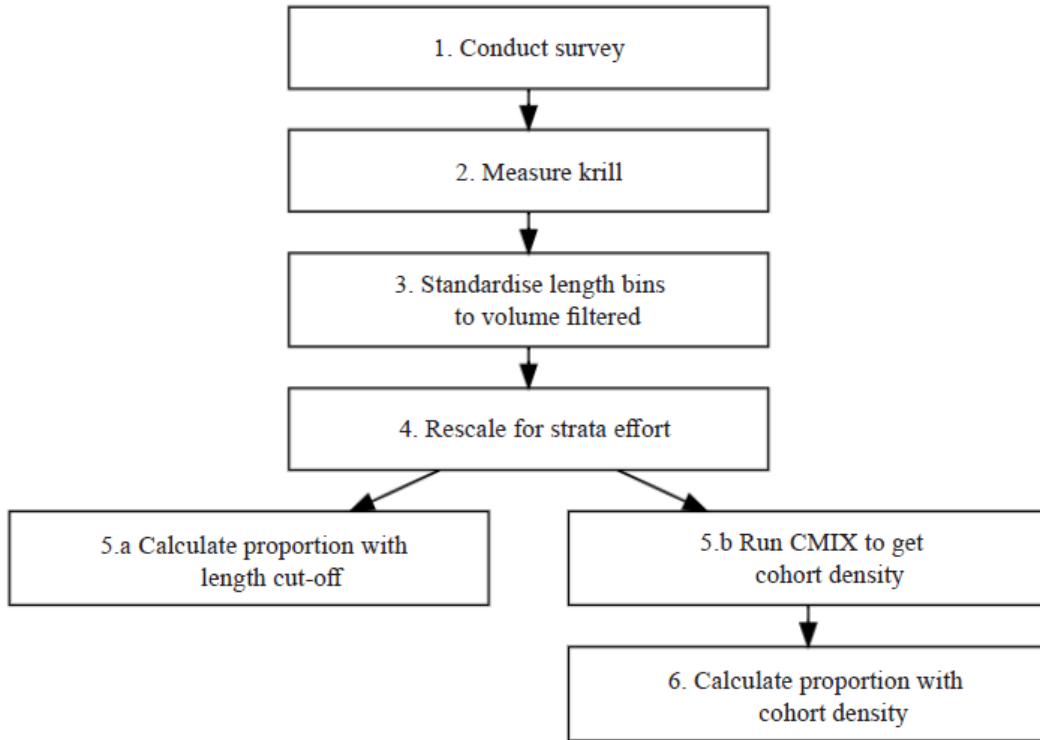
Threshold

The alternative analysis identifies recruits through a simple length threshold.

Individuals of length 36 mm or shorter are identified as recruits and larger individuals are identified as adults (Thanassekos et al., 2021). Within each haul, the length densities for lengths at or below 36 mm are summed to give the total density $d_{i,j}^{(r)}$ of recruits in haul i and stratum j, and the length densities for lengths greater than 36 mm are summed to give the total density $d_{i,j}^{(a)}$ of adults in haul i and stratum j.

Similar to the mixture analysis, threshold calculations need to account for unequal sampling effort in each stratum. Within each stratum these densities are scaled to indices of relative abundance

$$d_{i,j}^{(r)} = d_{i,j}^{(r)} \frac{A_i}{\sum_k A_k}$$

$$d_{i,j}^{(a)} = d_{i,j}^{(a)} \frac{A_i}{\sum_k A_k} \qquad (3)$$

where again A_i are the strata areas.

The mean and variance of these indices are then calculated within each stratum, and then summed across strata to give the estimated mean relative abundance $\hat{r}$ of recruits and $\hat{a}$ of adults, and their corresponding variances σ_r^2 and σ_a^2. The proportion of recruits is then calculated as $R = \dfrac{\hat{r}}{\hat{r} + \hat{a}}$, with variance $\sigma_R^2 = (\hat{r}^2 \sigma_a^2 + \hat{a}^2 \sigma_r^2)/(\hat{r} + \hat{a})^4$.

The final part of the process for situations with multiple surveys is to combine the estimates to get an inverse variance weighted mean and variance for use in the proportional recruitment model of the krill simulation fitted in the Grym (de la Mare, 1994b; Maschette et al., 2020).

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