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Selectivity and two biomass measures in an age-based assessment of Antarctic krill (*Euphausia superba*)

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ABSTRACT

An integrated, age-structured model was fitted to different combinations of survey data using two forms of selectivity (logistic or double-logistic) with time-constant or annually varying selectivity to investigate the population dynamics of Antarctic krill (*Euphausia superba*) near the Antarctic Peninsula. The data were from surveys conducted by the U.S. Antarctic Marine Living Resources Program around the South Shetland Islands from 1992 to 2011. Two indices of krill biomass based on (1) trawl-net samples and (2) hydroacoustic sampling were combined with length-compositions from the nets. Sixteen model configurations using different combinations of the two biomass surveys with the various options for modeling selectivities were examined. Parameters were estimated in phases with the sequential order of the phases randomized until an invertible Hessian matrix was obtained. Model consistency for the estimates of derived quantities was tested using simulated data. Annual trends in the estimates of total biomass, spawning biomass, and recruitment were similar among different configurations assuming time-constant selectivity, but the absolute scaling ranged widely depending on which biomass indices were used. All configurations with time-constant selectivities were able to reproduce the derived quantities of the operating model when fitted to simulated data. Annually varying selectivities produced more variable estimates of the trends in population biomass, but less variable estimates of scale, compared to time-constant configurations fitted to the same data. The models with annually varying selectivities did not produce invertible Hessian matrices, and four of these configurations could not reproduce the derived parameters of their operating model when fitted to simulated data. Using AIC, the model with logistic, time-constant selectivities was selected as the best configuration to fit both sources of biomass data. The two-stage approach of first randomizing the phase order until an invertible Hessian matrix is achieved and then verifying the reproducibility of the estimates of derived quantities using simulated data could be employed in any integrated stock assessment with parameters estimated in phases.

1. Introduction

Antarctic krill (*Euphausia superba*, hereafter krill) have a circumpolar distribution (Siegel, 2005; Hofmann and Hüsrevoğlu, 2003; Atkinson et al., 2009). The multinational fishery for krill is regulated by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). At present, krill catches are about 200,000 tons yr^{-1}, and there is interest in increasing this catch (Nicol et al., 2012). In recent decades, the catches have been from the Scotia Sea (Fig. 1), and annual removals are believed to be less than 1% of the 60.3 million tons (mt) standing stock estimated from a multinational acoustic survey conducted by Members of CCAMLR in 2000, referred to as the "CCAMLR 2000 Survey" (Hewitt et al., 2004; CCAMLR, 2010).

The total catch limit of krill from the Scotia Sea (5.61 mt) was established using the "generalized yield model", an age-structured simulation model (Constable and de la Mare, 1996; Constable et al., 2003; CCAMLR, 2010). This model does not statistically connect a model to data using a likelihood function, but instead treats all inputs for a single simulation as known (Kinzey et al., 2013). Variability among simulations is represented as process error, with recruitments for each simulation randomly selected from a pre-defined probability distribution. Each single simulation is deterministic. Quantities of interest (e.g., spawning biomass) are calculated from many thousands (typically 10,000) randomized

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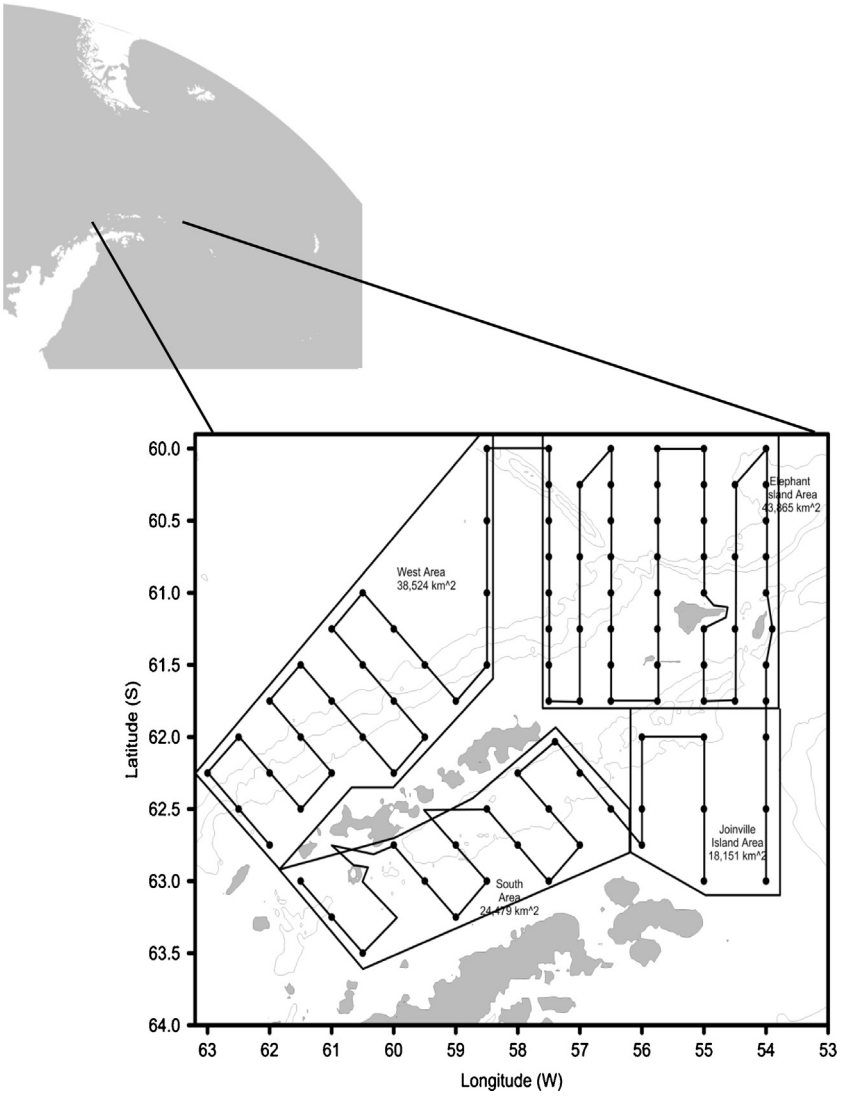

Fig. 1. The U.S. AMLR study area in the Scotia Sea between South America and the Antarctic Peninsula. Survey strata are defined by polygons enclosing several acoustic transects and net-tow stations.

replicates, and statistics of these quantities (e.g., the median spawning biomass) are compared to decision criteria that are considered to be precautionary. Precautionary catch limits are those that meet the decision criteria based on the simulation results.

The objectives of this paper are threefold. First, we aim to develop a statistical modeling framework to assess the status and productivity of Antarctic krill in the Scotia Sea. Second, we conduct a general examination of the effects of different structural assumptions about the forms of selectivity for different data sources. Our third objective is to develop procedures that improve the ability to achieve convergence in integrated stock assessments employing complex, nonlinear likelihood models with mixed data sources. We evaluate the effects of combining or ignoring separate biomass indices (from net trawls and hydroacoustics), allowing selectivity to either vary annually or be time-constant. We use 20 years of survey data on Antarctic krill from around the Shetland Islands in the Antarctic Peninsula.

The models described here do not include fishery-dependent data. To date, catches taken by the krill fishery are believed to be a small fraction of the total krill population in the Scotia Sea and are thus expected to have minimal effect at the population level. Fishery catches and size-composition data will be incorporated into future models to compare projected outcomes from increasing catches to the CCAMLR decision rules. At this stage of development, however, our aims are to evaluate the internal consistency of the model estimates when fitting to different sources of survey data using different assumptions about selectivity, and increase the prospects of achieving model convergence through the use of randomized phase sequences.

2. Materials and methods

The biomass density of Antarctic krill ($g\,m^{-2}$, or equivalently, tons km^{-2}) in the Scotia Sea has been measured using samples from zooplankton nets and acoustic backscatter methods. While there is overlap in the resulting biomass values produced using the two methods, nets often produce biomass densities at the lower end of those produced using acoustics. Previous studies comparing estimates of the biomass density of krill from zooplankton nets and acoustic methods have noted several issues (Everson, 1982; Hewitt and Demer, 1996; Wiebe et al., 2004, 2011; Hewitt et al., 2003; Fielding et al., 2004, 2012; Reiss et al., 2008; Atkinson et al., 2009). Krill of different sizes may differ in net-avoidance capabilities. Krill size, density within aggregations, and swimming orientation affects their acoustic target strength. Diurnal migrations can move krill above the range susceptible to acoustic observation so that