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Title **Investigation of potential biases in the assessment of Antarctic toothfish in the Ross Sea fishery using outputs from a spatially explicit operating model**

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ABSTRACT

Toothfish stock assessment results are strongly influenced by tag-release and tag-recapture data, and rely on the assumption that tagged and untagged fish have constant probabilities of recapture regardless of the spatial distribution of releases or subsequent fishing effort for recaptures. Conceptually this assumption implies either that tagged and untagged fish mix equally in the population, or that fishing effort for recaptures is distributed in proportion to the underlying abundance. Neither of these conditions are likely to occur in practice, and violation of this assumption may lead to bias. In this paper we investigate such potential biases in the assessment of Antarctic toothfish in the Ross Sea fishery using simulated outputs from spatially explicit operating models.

Two spatially explicit operating models were developed: each was comprised of 189 discrete cells, with a cell size of about 25,000 km^2. The first model was restricted to those locations of the Ross Sea region that have been fished (restricted model), and the second model extended to encompass all areas (unrestricted model). Simulated observations were generated from these models, and used as inputs into a simplified non-spatial stock model based on the 2011 Ross Sea toothfish stock assessment.

Results suggested that the assessment model was biased low by 17% or 43% assuming movements defined by the restricted and unrestricted models respectively. The bias was thought to reflect the underlying distributions of tag-releases and subsequent fishing effort, and the limited mixing of fish between areas — more than half of tags have been released (and subsequently recaptured) from SSRUs 88.1H and 88.1I, while a large proportion of the fish are in remaining SSRUs where fewer tags were released and with lower fishing effort. This effect is accentuated in the unrestricted model, where about half of the fish are distributed in areas that had not been subject to fishing effort.

We note that the extent of bias will depend on both the proportion of fish in unfished areas and movement rates between fished and unfished areas, but that misspecification of other parameters in the assessment models (for example tag mortality rates and tag detection rates) or alternate spatial hypotheses may also introduce biases that we have not considered in this paper. While additional analyses need to be undertaken to confirm or improve the spatial models used here and alternative movement hypotheses should be tested, we consider that these simulation experiments provide a useful tool to evaluate potential bias and uncertainty in our understanding of the assessment in the Ross Sea toothfish stock and potentially similar tag-based assessments elsewhere in the CCAMLR Area. They are also useful in investigate the likely consequences of management strategies for stock assessments, including changes in fishing effort or tagging distributions. They can also be used to investigate the potential effects of alternative biological hypotheses for less well defined parameters, for example maturity and natural mortality rates.

Summary of findings as related to nominated agenda items

Agenda Item	*Findings*
4	We apply the SPM spatially explicit operating model to investigate potential biases and uncertainty in the single-area stock assessment model for the Ross Sea region

1. INTRODUCTION

The Antarctic toothfish exploratory fishery in the Ross Sea region was initiated in 1997[1]. Since then, vessels have returned each summer to fish in this area. Since 2007, catch limits for Antarctic toothfish in the Ross Sea region (3280 t in 2012) have been determined from yield estimates from a Bayesian sex and age-structured statistical catch-at-age assessment model (Mormede et al. 2011a, 2011b) using CASAL (Bull et al. 2012).

The standard assessment model used for the Ross Sea region was last updated in 2011 by Mormede et al. (2011b). It assumed a single area with three pseudo-geographically defined fisheries (shelf, slope, and north). Data included within the model were total catch, catch-at-age frequencies, and tag-release and recapture data, with estimation of stock status most strongly driven by the tag-release and recapture data (Dunn & Hanchet 2007, Mormede 2011). A key assumption in the model is that tagged and untagged fish have equal probabilities of recapture regardless of the locations at which tagged fish are released or the subsequent spatial distribution of fishing effort from which fish are scanned to detect recaptures. Conceptually this implies either equal mixing of tagged and untagged fish in the population, or fishing effort patterns that are distributed to ensure that removals are proportional to the underlying abundance of fish in each location. These conditions are unlikely to occur in the actual fishery, and there is concern that violation of this assumption could lead to bias in the stock assessment results (e.g. Welsford & Ziegler 2012). Dunn (2006) presented a preliminary investigation of the biases in the assessment model that could arise from spatial heterogeneity of the distribution of tag releases and subsequent tag recapture effort. He used a simple model that did not allow for movement of fish over time, and found that the standard single-area stock assessment model was likely to underestimate the true biomass. However, he cautioned that further investigations using plausible movement models were required to fully evaluate potential biases.

Dunn & Rasmussen (2008) developed a fully spatially explicit population model software (SPM) that allows for a wide range of potential spatial models to be implemented and evaluated, and was developed as a tool to inform evaluation of the potential effects of alternate spatial assumptions or management strategies. The latest release of the software is described by Dunn et al. (2012) .

Mormede et al. (2012) demonstrated how simulations from the spatial population operating models could be used as observations in a standard stock assessment model to evaluate bias in that assessment model. Their spatial population operating models were mainly at a ‘coarse-scale’ (cells of ~344 km square) and were restricted to that portion of the Ross Sea region that has previously been fished, although they carried out some preliminary runs using ‘medium-scale’ (cells of ~156 km square) and unrestricted models. In this paper, we present simulations using the spatial population operating model presented in Mormede et al. (2013). This operating model was at a ‘medium-scale’ (cells of ~156 km square) and extended into unfished portions of the Ross Sea region. A restricted medium–scale model, with the population restricted to only locations where fishing had historically occurred, was run for comparison.

We simulated a set of observations from the spatial operating model, and used these to estimate the initial and current biomass using the standard single area stock assessment model. Hence, an evaluation of bias and uncertainty can be made by comparing the value estimated by the standard single area stock assessment model using simulated observations with the value used by the operating model to simulate those observations.

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[1] Note that this report uses the CCAMLR split year that is defined from 1 December to 30 November. Hence, the term “year” refers to the fishing season in which most fishing occurs, e.g., the period 1 December 2004 to 30 November 2005 is labelled the 2005 year.

2. MODELS

2.1 Spatial population operating model

Details of the spatially-explicit age-structured population model that was used as an operating model is described by Mormede et al. (2013), and is only briefly summarised here. The SPM and CASAL packages used are described by Bull et at (2012) and Dunn et al. (2012).

We assumed a single sex, age-structured operating model with five categories of fish (immature, mature, pre-spawning, spawning and post-spawning). The unrestricted model covered the entire Ross Sea region, including areas that have not been fished, at the resolution of square cells of 156 km per side. A sensitivity was carried out replicating the process in Mormede et al. (2012), whereby this spatial operating model was run only in the areas which have been fished, and is referred to as the restricted model. It is plausible that the true extent of the stock may lie somewhere between these two extremes (Figure 1).

In developing the spatial operating model, all available fishery data were included as spatially explicit observations. These were the commercial catch, catch at age, proportions mature (i.e., proportions at age with a GSI greater than 1%), proportion spawning (i.e., proportions at age with a GSI greater than 2.5%), CPUE, and tag-release and tag-recapture observations from all vessels. Population and movement process parameters were estimated in the models. Initial recruitment (biomass) was fixed at the value obtained from the 2011 stock assessment (see Mormede et al. 2011b). Other parameters (e.g., M, growth) were the same as the values used in the 2011 assessment but averaged between sexes.

The spatial operating model appeared to broadly reflect the observed spatial distribution of Antarctic toothfish consistent with the hypothesized life cycle, suggesting that younger fish were found predominantly in the southern shelf areas, mature fish on the slope and spawning fish in the northern areas of the Ross Sea region. Population distribution in terms of numbers and biomass are presented in Figure 2 for the unrestricted model and Figure 3 for the restricted model.

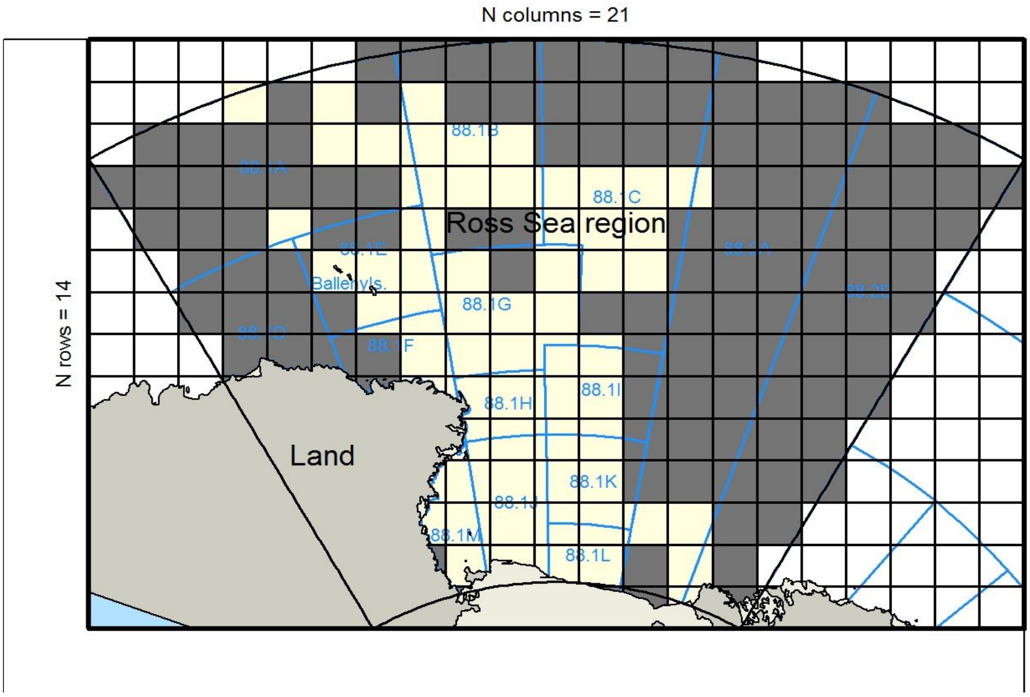
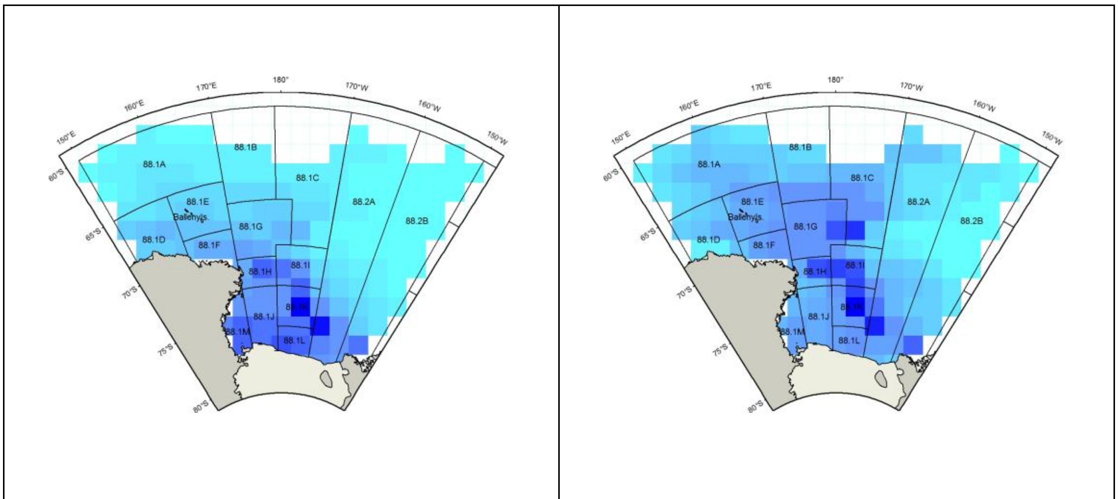
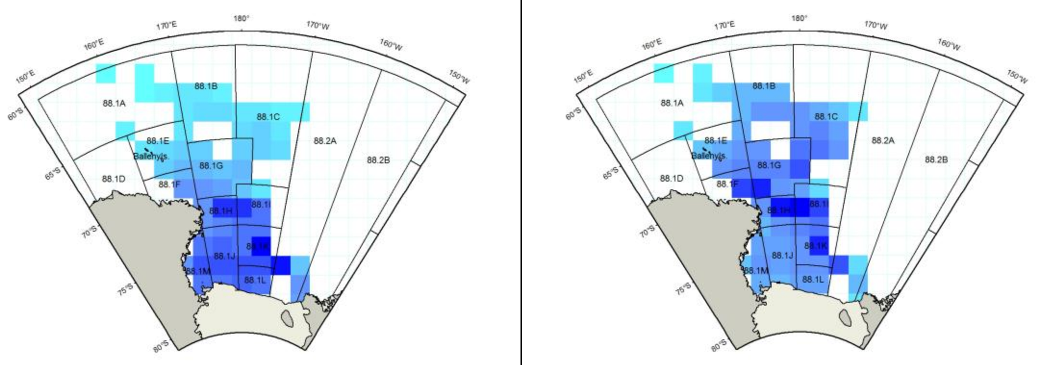


Figure 1: Spatial grid representation of the Ross Sea region used for the model (bounded region). Locations where fishing has occurred are showed in yellow; both yellow and grey cells are included in the unrestricted model whilst only yellow cells are included in the restricted model.



(a) Numbers (b) Biomass

Figure 2: Distribution of the fish population as estimated by the unrestricted spatial population operating model, in numbers (left) or biomass (right).



(a) Numbers (b) Biomass

Figure 3: Distribution of the fish population as estimated by the restricted spatial population operating model, in numbers (left) or biomass (right).

2.2

2.3 Simulations

We simulated 100 pseudo-observations from the operating model that replicated the observations that would have been gathered if the operating model were a true representation of the fish population. We simulated yearly catch-at-age, tag-release and tag-recapture observation from the locations where the historical fishery had fished in proportion to effort, and then aggregated these observations over shelf, slope and north areas separately. In both cases we assumed the biomass in the population was known, defined by the number of initial recruits R_0 = 1 021 000 individuals (see Mormede et al. 2012 for rationale).

Each observation was simulated assuming an error distribution used to fit the data, i.e., tag-recapture data were simulated using a binomial likelihood at age; catch-at-age data were simulated using a multinomial likelihood. The error values for each observation were assumed similar to that of the single-area stock assessment (see Mormede et al. 2011b), with catch-at-age process error of 150, and tag recapture dispersion of 1.2.

In order to simplify the model, we did not consider the tag-recaptures from the annual tag releases as separate cohorts within the model, but rather combined the tag-releases into a single tag-partition. While this simplification does not replicate the exact process used by the stock assessment model, it provided a similar mathematical outcome.

2.4 Estimation using the standard stock assessment model

The estimation model was a simplified version of that used for the stock assessment of toothfish in the Ross Sea region in 2011 (see Mormede et al. (2011b) for full details of that model). We simplified the 2011 stock assessment model by using a single-sex population, with the same growth and other population parameters as in the operating model described above. As with the 2011 assessment model, the estimation model was a single area, age-structured, three-fishery population model, with a known catch history, tag-releases, and observations of catch-at-age and tag-recaptures. The parameters estimated by the estimation model were initial biomass and the fishing selectivities for the shelf, slope, and north areas. Again, as in the spatial population operating model, we did not account for tag shedding, tag loss, tag growth loss, tag mortality, or a no-growth period after tagging.

For each of the operating models, 100 sets of simulated observations were randomly generated from and passed as observations to the CASAL single area stock assessment estimation model. Then, for each set, initial biomass and the selectivities were estimated in an MPD run.

We then compared the values of the estimated initial biomass (parameterised as initial recruitment, R_0) from the MPD runs with the simulated observations to that used in the operating model. Two measures were used, the percent bias (%bias) and the root mean squared error (%RMSE), with %bias defined as;

$$\%\text{bias} = \left(\hat{\theta} - \theta\right)\frac{100}{\theta}$$

And the %RMSE defined as,

$$\%\text{RMSE} = \sqrt{\frac{\sum_i \left(\hat{\theta}_i - \theta\right)^2}{n}}\frac{100}{\theta}$$

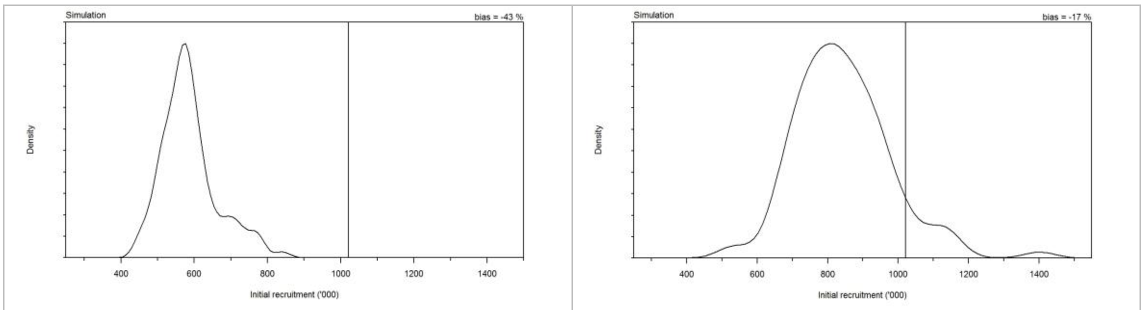
3. RESULTS

The distributions of the estimated R_0 from the pseudo-observations based on the spatial unrestricted and restricted models are shown in Figure 4. Estimates of R_0, %bias and %RMSE for the unrestricted and restricted models are summarised in Table 1.

The unrestricted model estimated values of initial recruitment (and hence biomass) that were biased low by 43%; the restricted model estimated values of initial recruitment that were biased low by 17%. This suggests that if the underlying spatial distribution of the population and movement functions for toothfish were as described by the operating model, then the standard single area stock assessment model was a conservative estimator of the true state, especially when estimating biomass over the entire Ross Sea region. The RMSE values were generally similar to the bias values, showing there was not much change in dispersion between models, with a slight increase in dispersion for the restricted model.

Table 1: Estimated R0, %bias and %RMSE for the operating model (unrestricted), and its restricted equivalent.

Model	‘True’ R_0	Estimated values		
		Mean (90% intervals)	%bias	%RMSE
Unrestricted model	1 021 100	587 100 (488 300-738 900)	-43%	43%
Restricted model	1 021 100	843 500 (672 100-1 105 200)	-17%	22%



(a) Unrestricted model (b) Restricted model

Figure 4: Distribution of the initial recruitment as estimated by the single area population model based on the pseudo-observations from the spatial population unrestricted (left) or restricted (right) models. The solid line represents the ’true‘ R0 (1 021 000) of the stock assessment carried out in 2011 (Mormede et al. 2011b). The bias of the estimation is specified.

4. DISCUSSION

In this paper we investigate potential biases in the assessment of Antarctic toothfish in the Ross Sea fishery using simulated outputs from spatially explicit operating models. Results from the models suggest that the standard single area stock assessment model for the Ross Sea was biased low by 17% and 43% for the restricted and unrestricted models respectively. These results are broadly consistent with those obtained in coarser scale models by Mormede et al. (2012).

Bias in the two models is likely to reflect the underlying distributions of tag-releases and subsequent fishing effort, and limited toothfish mixing between areas. Thus, over 50% of tags have been released (and subsequently recaptured) from SSRUs 88.1H and 88.1I, but a large proportion of the fish are in other SSRUs where fewer tags have been released and where fishing effort has been less consistent. This effect is accentuated in the unrestricted model, where more than 50% of the fish are distributed in areas which have not previously been fished. The extent of the negative bias will depend on the proportion of fish in the unfished area and movement rates between fished and unfished areas. However, it should be noted that these are only two of a range of plausible operating models and that the results are not directly comparable to the actual 2011 base case assessment due to the simplifications outlined above.

Further investigations could include adding tag mortality and imperfect detection rates in spatial models, and also re-parameterizing spatial models using a restricted tag-recapture data selection based on tagging performance indices (i.e., Mormede 2013) as per the stock assessment, rather than using data from the entire fleet as was done here.

The large difference between the bias stemming from the restricted and unrestricted spatial models suggest there is likely to be a substantial toothfish biomass in the Ross Sea region but outside of the historical fishing footprint. Although the biomass distribution proposed by the spatial population models (Figure 2) is not unlikely, further investigations into areas not currently or historically fished would be of great benefit to inform future spatial models and more accurately estimate the likely population size outside the main fishing grounds.

While we note that further analyses should be carried out and alternative movement hypotheses should be tested, we consider that simulation experiments using spatially explicit models can provide a useful tool to evaluate the direction and likely magnitude of potential bias and uncertainty in our understanding of the stock assessment in the Ross Sea region and elsewhere in the CCAMLR region. They can also be useful to investigate the likely consequences for stock assessments of alternate management strategies, including changes in fishing effort distribution or tagging schemes. They can also be used to investigate the potential effects of alternative biological hypotheses for less defined parameters, for example maturity of the entire stock.

5. ACKNOWLEDGMENTS

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