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*Title* **AN ILLUSTRATIVE MANAGEMENT PROCEDURE FOR EXPLORING DYNAMIC FEEDBACK IN KRILL CATCH LIMIT ALLOCATIONS AMONG SMALL-SCALE MANAGEMENT UNITS**

*Author(s)* Éva Plagányi and Doug Butterworth
*Affiliation(s)* University of Cape Town

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ABSTRACT

A Management Procedure (MP) approach is proposed to assist in advising regarding the subdivision of the precautionary catch limit for krill among 15 small-scale management units (SSMUs) in the Scotia Sea to reduce the potential impact of fishing on land-breeding predators. The Spatial Multi-species Operating Model (SMOM) developed in Plaganyi and Butterworth (2006) is used as an operating model which simulates the "true" dynamics of the resource with tests across a wide range of scenarios for the underlying dynamics of the resource. Unlike static catch allocation options, the illustrative MPs developed here have a feedback structure, and hence are able to react and self-correct. It is important, as with the static allocation options, to ensure that the likely performances of these MPs in terms of low risk to predators within each SSMU are reasonably robust to the primary uncertainties about such dynamics. A MP module separate from the operating model contains the methods and rules that are used to subdivide the krill catch between SSMUs. Different MPs are then simulation tested with their performances being evaluated on the basis of a set of performance statistics which essentially compare the risks of reducing the abundances of predators (and krill) below certain levels, as well as the variability in future average krill catches per SSMU associated with each MP. The key assumption made here is that data will be regularly available in future to monitor the impact/s of different krill catch limits. For illustrative purposes, it is assumed that two main sources of data will be available for use in a MP: (1) indices of absolute or relative abundance, or performance of the various predators (i.e. the CEMP series), and (2) survey estimates of krill absolute or relative abundance per SSMU. The approach proposed is readily modified if, for example, no krill abundance indices are available. Given that "future" data are required as inputs to test a MP including feedback, these data are generated with random variation about their underlying values and assuming the same variance as estimated from the past data.

SUMMARY OF FINDINGS AS RELATED TO NOMINATED AGENDA ITEMS

| *Agenda Item* | *Findings* |
|---|---|
| 2 (ii)-(iii), 5.3, 6.2 | An illustrative adaptive management framework is developed that could be used to assist in providing advice regarding the allocation of krill catches between SSMUs. An example is provided of an empirical Management Procedure (MP) which reacts to CEMP monitoring data in setting krill catches per SSMU. The advantages of including a feedback mechanism are demonstrated. |

# An Illustrative Management Procedure for exploring dynamic feedback in krill catch limit allocations among small-scale management units

*Éva Plagányi and Doug Butterworth*
*Marine Resource Assessment and Management Group (MARAM),*
*Department of Maths and Applied Maths, University of Cape Town,*
*Private Bag Rondebosch, 7700, South Africa*
*Email: eva@maths.uct.ac.za*

## ABSTRACT

A Management Procedure (MP) approach is proposed to assist in advising regarding the subdivision of the precautionary catch limit for krill among 15 small-scale management units (SSMUs) in the Scotia Sea to reduce the potential impact of fishing on land-breeding predators. The Spatial Multi-species Operating Model (SMOM) developed in Plaganyi and Butterworth (2006) is used as an operating model which simulates the "true" dynamics of the resource with tests across a wide range of scenarios for the underlying dynamics of the resource. Unlike static catch allocation options, the illustrative MPs developed here have a feedback structure, and hence are able to react and self-correct. It is important, as with the static allocation options, to ensure that the likely performances of these MPs in terms of low risk to predators within each SSMU are reasonably robust to the primary uncertainties about such dynamics. A MP module separate from the operating model contains the methods and rules that are used to subdivide the krill catch between SSMUs. Different MPs are then simulation tested with their performances being evaluated on the basis of a set of performance statistics which essentially compare the risks of reducing the abundances of predators (and krill) below certain levels, as well as the variability in future average krill catches per SSMU associated with each MP.

The key assumption made here is that data will be regularly available in future to monitor the impact/s of different krill catch limits. For illustrative purposes, it is assumed that two main sources of data will be available for use in a MP: (1) indices of absolute or relative abundance, or performance of the various predators (i.e. the CEMP series), and (2) survey estimates of krill absolute or relative abundance per SSMU. The approach proposed is readily modified if, for example, no krill abundance indices are available. Given that "future" data are required as inputs to test a MP including feedback, these data are generated with random variation about their underlying values and assuming the same variance as estimated from the past data.

## INTRODUCTION

In response to requests from the Commission regarding the allocation of Antarctic krill (*Euphausia superba*) catches in the Scotia Sea, Hewitt *et al.* (2004) presented five options with the allotment of catch per small-scale management unit (SSMU) as follows: (1) proportional to the historic catch within the SSMU; (2) proportional to the estimated predator demand in the SSMU; (3) proportional to the estimated standing stock of krill in the SSMU; (4) proportional to standing stock less predator demand and (5) a dynamic allocation based on land-breeding predator monitoring. Watters *et al*. (2005) used their model of krill-predator dynamics to make initial comparisons between these options. The Spatial Multi-species Operating Model (SMOM) of Plagányi and Butterworth (2006) can similarly be used for this purpose. In particular, the focus here is on the development of a management procedure with dynamic feedback. A Management Procedure (MP) is the combination of a prescribed set of data to be collected and the analysis procedure to be applied to these data, to provide a scientific recommendation for a management measure, such as a Total Allowable Catch (TAC), for a resource (Butterworth *et* *al*. 1997, Butterworth and Punt 1999, Cooke 1999). The MP approach involves testing across a wide range of scenarios for the underlying dynamics of the resource using computer simulation.

The methods described here are based on the standard use of MPs in the Scientific Committees of the International Whaling Commission (e.g. IWC 1994), the Commission for the Conservation of Southern Bluefin Tuna (e.g. CCSBT 2005), and as implemented in the fisheries management process for the major fisheries in South Africa since the early 1990's (e.g. Butterworth *et al.* 1997, Geromont *et al.* 1999, De Oliveira and Butterworth 2004, Johnston and Butterworth 2005, Plaganyi *et al.* 2006) – the one difference being that the current MP includes both spatial and (ecological) multi-species considerations (Fig. 1). The only similar ecosystem MP approach of which we are aware pertains to the use of the Atlantis model as an operating model (Fulton *et al.* 2004).

The simulation-testing framework used includes i) the operating model – in this case the SMOM (Plagányi and Butterworth 2006) which simulates the "true" dynamics of the resource, and ii) a separate MP module which contains the methods and rules that are used to compute krill allocations for each of the 15 SSMUs. Different MPs can then be simulation tested with the performance of alternative MPs being compared on the basis of an agreed set of performance statistics which in this case focus on the risks of reducing the abundance of various predator species in the SSMUs. The final choice of an MP seeks to ensure reasonably robust performance in terms of anticipated krill catches and risk to the krill and predator populations in each SSMU, given prevailing uncertainties about resource status and dynamics.

## METHODS

### QUANTIFYING THE OBJECTIVES

To move towards using a MP approach, it is first necessary to clarify the objectives and to translate these into quantitative criteria. Thus whilst it is clear in this case that the broad objectives are to allocate krill among the 15 SSMUs in the Scotia Sea to reduce the potential impact of fishing on land-based predators, for the purposes of comparing candidate MPs it is necessary to decide which set of the following quantitatively expressed objectives (for example) best encapsulate these broad objectives:

1. The abundance of all predators in a SSMU should (a) remain approximately at the current level; or (b) remain above a conservative level such as 0.4*K with less than 5% probability of falling below this level.
2. The krill biomass in a SSMU should (a) remain approximately at the current level; or (b) remain above a conservative level such as 0.4*K with less than 5% probability of falling below this level.
3. The krill catch per SSMU should not vary by more than a pre-specified percentage (e.g. 10%) from one year to the next – assuming that this is an important industrial stability issue.

Given that this aspect is still in need of clarification, for illustrative purposes, initial trials focused on stabilizing the abundance of predators in the various SSMUs and limited the extent of inter-annual variations in the TAC.

### COMPARISON OF CANDIDATE MANAGEMENT OPTIONS

The first four catch allocation options proposed by Hewitt *et al*. (2004) are static options and the SMOM has been projected forwards 20 years to compare the performance of these various options (Fig. 4-7 in Plaganyi and Butterworth (2006)). Note that the operating model (SMOM) used is in need of further refinement (for example with respect to parameter values) before final conclusions can be drawn as to which catch allocation option performs best over time.

## "FUTURE DATA"

To test a dynamic feedback management rule, "future data" in the form of, for example, CEMP indices of abundance are required by the MP program to calculate the krill allotment per SSMU for each of the years in the projection period. These data are generated from the operating model, assuming the same error structure as in the past, and are passed to the MP which in turn passes information back to the operating model.

In order to assess the efficacy of a particular allotment of catch per SSMU, it will be necessary to use monitoring data and/or introduce additional monitoring programs, especially if krill catches are increased in future. Such monitoring data could be as follows:

i) An index of krill abundance.
ii) An index of predator abundance (for one or several predator species).
iii) An index of predator performance (for one or several predator species)

Procedures to develop i) have yet to be defined and implemented (Hewitt *et al*. 2004), but the existing CEMP data partially serve the requirements for providing ii) and iii). A final choice of MP will need to be tailored to make the best use of available data. Ideally all available indices could be used with a MP control rule being tuned to provide the best performance based on the combination of indices. A Loess smoother could be applied to the data. If an index of predator performance is used (e.g. CEMP indices such as duration of incubation shift, weight of penguin) as opposed to an index which directly measures abundance, the Operating Model will need to include a model relating that index to true abundance, as well as the variance of the observed about the true index value. For this reason, as a starting point, only indices of penguin abundance have been used here. As no similar index was available for seals, a single predator performance index was assumed available for seals.

For illustrative purposes, an example is provided in which it is assumed data are available as follows:

i) A krill abundance index available for all SSMUs.
ii) An index of abundance available for penguins in all SSMUs except the three pelagic areas: 1 (APPA), 9 (SOPA) and 13 (SGPA) as these include fishing areas not in the vicinity of land-breeding predators.
iii) An index of predator performance (e.g. duration of fur seal cow foraging) available for seals in SSMUs 3 and 14 (Indices no. 13 and 14).

It is assumed for illustrative purposes that the CVs associated with Indices 1-12 are the average of the CVs associated with historic CEMP data from Bird Island and Stranger Point (Ramm and Turner 2005), namely 0.34, whereas the seal index "future" CV of 0.42 is similarly based on observed CVs associated with the CEMP data from Bird Island (Ramm and Turner 2005). These CVs are used when accounting for observation error i.e. noise in the CEMP monitoring data.

## THE KRILL SUBDIVISION CONTROL RULE

The initial MP developed here is 'model-free' (data-based, empirical) (see Rademeyer *et al.* 2006) and hence uses the data directly, for example in the form of recent upward or downward trends in abundance indices, to feedback appropriately through krill catch allocation changes in the same direction.

The recommended krill catch per SSMU fed back to the operating model is computed as follows:

$$Y_y^a = \Delta \cdot Y_{y-1}^a + (1-\Delta) * \sqrt{h\left(CEMPRat_y^{j,a}\right) h\left(KRILLRat_y^a\right)} * Y_{y-1}^a \qquad (1)$$

where

$Y_y^a$ is the precautionary krill catch limit in SSMU *a* in year *y*, renormalized after application of this equation to ensure that $Y = \sum_a Y_y^a$ ,

$\Delta$ is a control parameter which moderates the extent of the $Y_y^a$ annual variations, and is set to 0.5 for the computations reported here,

$h\left(CEMPRat_y^{j,a}\right)$ is a function which adjusts $Y_y^a$ depending on the ratio of the CEMP index $CEMP_y^{j,a}$ for predator *j* in SSMU *a* (averaged over the most recent three years after the first 3 years of the projection) compared to the starting index value (i.e that immediately preceding application of the MP) , and

$h\left(KRILLRat_y^{j,a}\right)$ is a function which adjusts $Y_y^a$ depending on the ratio of the krill survey index $KRILL_y^{j,a}$ in SSMU *a* (averaged over the most recent three years in the projection) compared to the starting index value (i.e that immediately preceding application of the MP).

The functions $h\left(CEMPRat_y^{j,a}\right)$ and $h\left(KRILLRat_y^{j,a}\right)$ which control the precautionary krill catch limit in SSMU *a* in year *y* depending on these ratios $\left(I_y^{rat}\right)$ are:

$$CEMPRat_y^{j,a} = \left( \frac{\frac{1}{3} \sum_{y'=y-3}^{y-1} CEMP_y^{j,a}}{CEMP_{2004}^{j,a}} \right) \qquad (2)$$

$$KRILLRat_y^{j,a} = \left( \frac{\frac{1}{3} \sum_{y'=y-3}^{y-1} KRILL_y^{j,a}}{KRILL_{2004}^{j,a}} \right) \qquad (3)$$

and

$$h\left(I_y^{rat}\right)=\begin{cases} r1 & \text{if } 0 < I_y^{rat} \le r1 \\ I_y^{rat} & \text{if } r1 < I_y^{rat} \le r2 \\ r2 & I_y^{rat} > r2 \end{cases} \quad (4)$$

There are a number of different options that can be tested in cases where there is more than one predator abundance index per SSMU. For example, one could take the average of the $CEMP_y^{j,a}$ values (normalized, to take account of different scales). From initial trials, a better (and more conservative) approach proved to be to use only the minimum of the $CEMP_y^{j,a}$ values.

*Control parameters:*

The values of *r1* and *r2* used in the results presented here are respectively 0.7 and 1.1. Additional constraints were also imposed such that the maximum permissible decrease/increase in the krill catch in one SSMU from one year to the next were both 10%.

After some initial experimentation, the method chosen to allocate the krill catch between SSMUs was as follows:

1) For all SSMUs for which "future" data were assumed available, an updated krill catch for the respective SSMUs was computed using Equation (1) and the associated constraints.

2) If no data were available for a SSMU with land-breeding predators, future catches remained at their existing level;

3) Once changes to all the SSMUs with land-breeding predators were computed, the differences between the $Y_{y+1}^a$ and $Y_y^a$ values were totaled and then shared equally between the three pelagic areas (APPA, APE and SGPA) such that $Y = \sum_a Y_y^a$ .

## AN ILLUSTRATIVE "IDEAL" MODEL-BASED MP

Model-free approaches have been reported here because they have the advantage of being simpler and quicker to implement on a computer (McAllister *et al*., 1999). In future, it may be preferable to move towards using an empirical-based rule for krill and a model-based approach for the predators. As an example, some initial explorations have been conducted using a simple Schaefer model to assess trends in the abundance of each predator in each SSMU:

$$N_{y+1}^{j,a} = N_y^{j,a} + r^a N_y^{j,a}\left(1 - N_y^{j,a} \middle/ K^a\right) \quad (5)$$

where

$K^a$ is the pre-exploitation carrying capacity of predator *j* in SSMU *a*; and

$r^a$ the intrinsic growth rate parameter.

The two parameters $K^a$ and $r^a$ are estimated at each application of the MP by fitting to the generated data.

## PERFORMANCE STATISTICS

The following performance statistics are presented for the MP tests. Core outputs for presentation purposes include the median and 10%- and 90%-iles of distributions. Projections are conducted over 20 years: 2005-2024.

*Resource status-related*

1) $N^{j,a}_{2015} / N^{j,a}_{2005}$

2) $N^{j,a}_{2025} / N^{j,a}_{2005}$

These are shown separately for each predator and for all SSMUs.

*Krill catch variability*

1) $AAV(per\ SSMU) = \frac{1}{19}\sum_{y=2006}^{2024} \left| C_y - C_{y-1} \right| / C_{y-1}$ (where *AAV* = Average Annual Variability)

In addition, time trajectories (both worm plots and probability envelopes) are plotted for predator abundance $N^{j,a}$ and krill biomass $B^a_y$.

## RESULTS AND DISCUSSION

The purpose of the results presented here was to demonstrate the usefulness of an adaptive management framework involving a move towards strategic advice based on stochastic probabilities rather than a short-term tactical approach based on deterministic outputs. One clear advantage of the approach outlined here is thus that management decisions are based on a trend in data - reducing the risk of responding simply to noise in monitoring data each year.

A large amount of initial experimentation has been conducted, but only a few selected examples are given here and are considered adequate as a starting point to direct further work. Following Hewitt *et al.* (2004), Catch Option 4 (standing stock less predator demand in the SSMU) has been used as the starting catch allocation in the simulations. The results of an illustrative run using the feedback control rule are shown in Figs. 2a-b. The run shown included the following features: low level of movement of krill between SSMUs (*Em* = 0.1); initially stable (i.e. *R*=0) rather than decreasing trends in the abundance of penguins and krill; parameter values as given in Plaganyi and Butterworth (2006). Fig. 3 gives an example of changes in the krill catch for one pelagic area (Area 1) with no land-breeding predators, and two areas with land-breeding predators (Areas 2 and 3). From this it can be seen that in response to the declining predator abundance trends in the SSMUs with land-breeding predators, application of the feedback control rule results in successive decreases (subject to constraints as described in the Methods section) in krill catches in these SSMUs, with the catch correspondingly being increased in the pelagic areas. This is useful as an illustration of the outputs of a catch control rule in which catches are adjusted upwards or downwards based on the trend/s in CEMP monitoring data. However, in this case it is not actually the catches themselves that are driving a population decline (the krill catches have a relatively small impact on the predator population dynamics) and hence there is almost no detectable difference between the feedback and non-feedback scenarios (Fig. 4).

The following two difficulties thus confounded a clear demonstration of the advantages of a feedback management rule:

1) The current krill catches are not sufficiently large to have a significant effect on predator population dynamics as currently configured in the model;
2) As previously mentioned, the Operating Model is currently preliminary as further discussion is needed regarding the choice of parameter values.

Given the above, some further illustrative scenarios were run as follows.

1) The krill catch was assumed to increase by 10% per year – note that this is purely for illustrative purposes to see a greater response when using the current model configuration. However, it is useful to note that the MP proposed is useful not only in comparing different krill allocation options under a situation in which the total annual krill catch remains constant, but can also be used to advise on future increases in krill catches.
2) One of the problems in the current Operating Model is that the illustrative parameter values selected for the penguin population are in need of revision. This is particularly evident in situations in which the calculated “current” *N/K* ratio is unrealistically low (and hence set to a lower bound of 0.01). From Equation (12) in Plaganyi and Butterworth (2006), it is evident that this could be due to several parameter settings, but perhaps the most obvious is that the juvenile survival rate is set too low[1] . Rather than the Reference Set choices of 0.5 to 0.6 $yr^{-1}$, a scenario is used with juvenile penguin survival rates of 0.6-0.8 $yr^{-1}$.

Selected results from a modified run as above are given in Fig. 5 and show trajectories of penguin abundance (i.t.o. numbers) in SSMUs 2, 3, 10, 11 and 12 and seal abundance (i.t.o numbers) in SSMU 3, compared under a scenario with feedback introduced into the krill catch allocation equation (top panel) versus a no feedback example (lower panel). By focusing on a comparison of the median trend under each scenario (particularly evident for Areas 10 and 11), it is clear that the introduction of a feedback mechanism is partially successful in reversing the extent of the downward trends in abundance that would otherwise have occurred. An example of such a comparison for Area 3 is presented in Fig. 6. It is important to note that this is an illustrative example only and as such the MP applied has not been finely tuned as is done in the later stages of developing a MP.

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[1] Parameter values chosen need to be consistent with the observed trends in the abundance of a species and need to meet additional constraints such as a lower feasible bound for *N/K* when balancing the model equations.

A final result of interest pertains to an illustration of the importance of having as much monitoring information available as possible to effectively monitor future changes in the abundance of predators (and krill) in the various SSMUs. To illustrate this, it was assumed that survey information was available for all SSMUs (as above) *EXCEPT* for SSMU 3 (Fig. 6). Results obtained were intermediate between those with and without feedback – interestingly this was partly because some movement of krill between SSMUs was assumed and hence the SSMU without survey data still benefited from having healthier krill populations maintained in neighbouring areas.

The results and candidate MP presented here are still in the early stages of development. Further work would include testing the robustness of candidate MPs to a wide range of alternative hypotheses. For example, it is possible to use robustness tests (see Rademeyer *et al.* 2006) as part of the framework presented here to test the effect of future environmentally-driven changes, such as a change in the overall carrying capacity of krill.

In summary, an illustrative adaptive management framework is developed that could be used to assist in providing advice regarding the allocation of krill catches between SSMUs. An example is provided of an empirical Management Procedure (MP) which reacts to CEMP monitoring data in setting krill catches per SSMU. The advantages of including a feedback mechanism are demonstrated.

## ACKNOWLEDGEMENTS

We are grateful to the South African National Antarctic Program (SANAP) which provided a research grant to fund this work and EP's attendance at CCAMLR's 2006 WG-EMM meeting. We also thank Rebecca Rademeyer for laying some of the foundations upon which this work is built.

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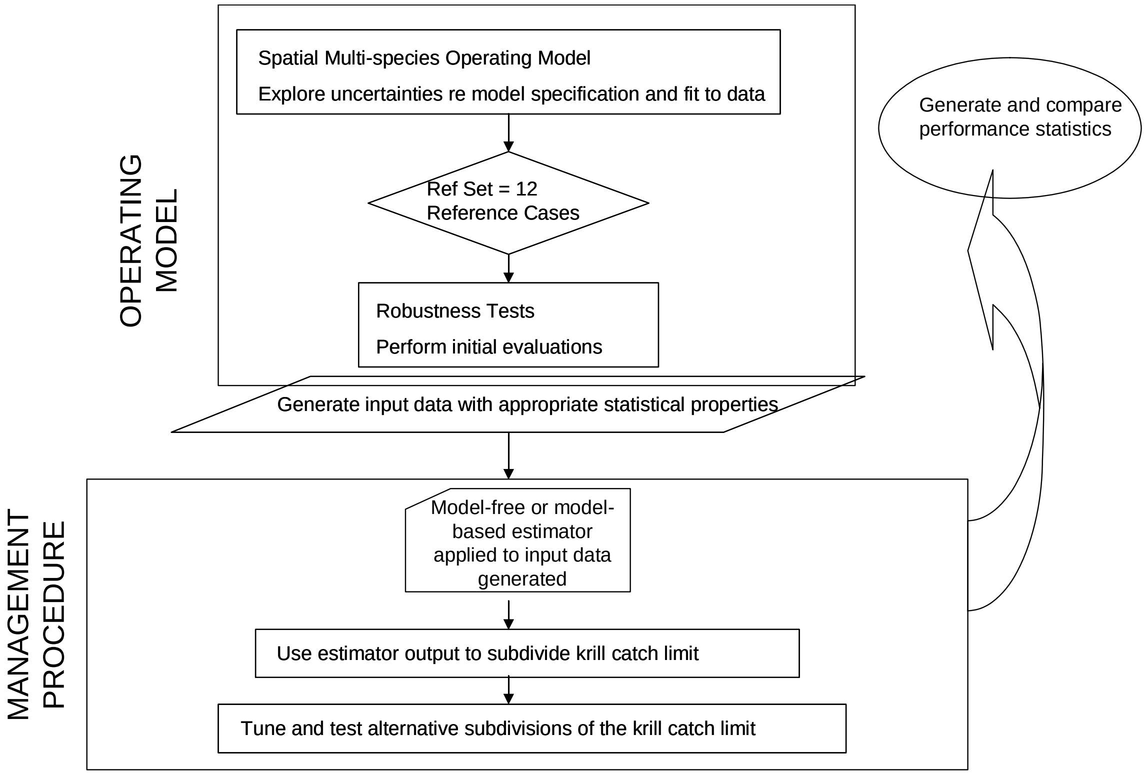


Fig. 1. Schematic (modified from Rademeyer *et al*. 2006) of the processes and linkages involved in constructing a management procedure with a feedback mechanism (see text).

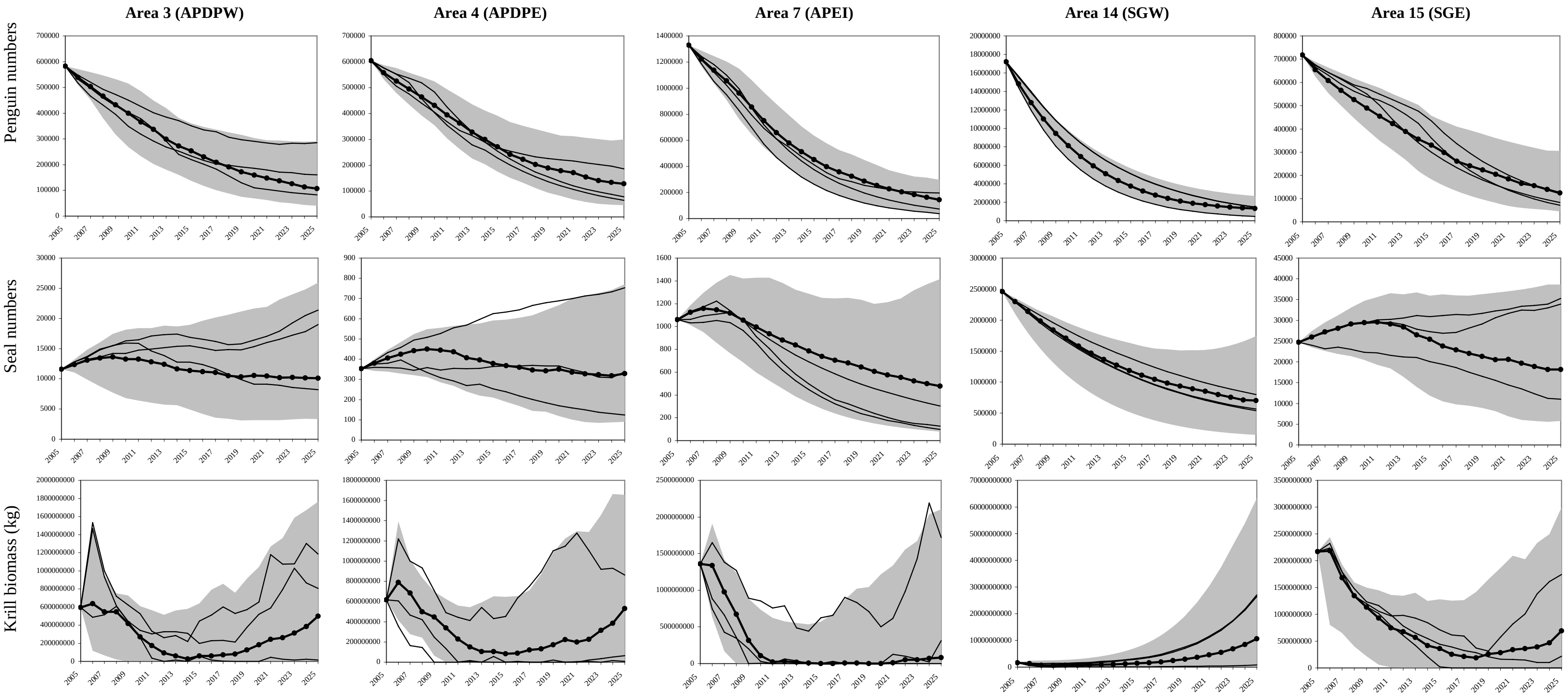


**Fig. 2a**. Results from an illustrative MP with starting krill catch allocation ***Option 4*** showing trajectories of krill biomass, penguin and seal abundance (i.t.o. numbers) in all SSMUs with both penguins and seals present, from 120 model representations and when using a model version that assumes some krill movement (*Em* = 0.1). Three individual trajectories are shown, with the median a dark dotted line and the shaded areas showing 90% probability envelopes.

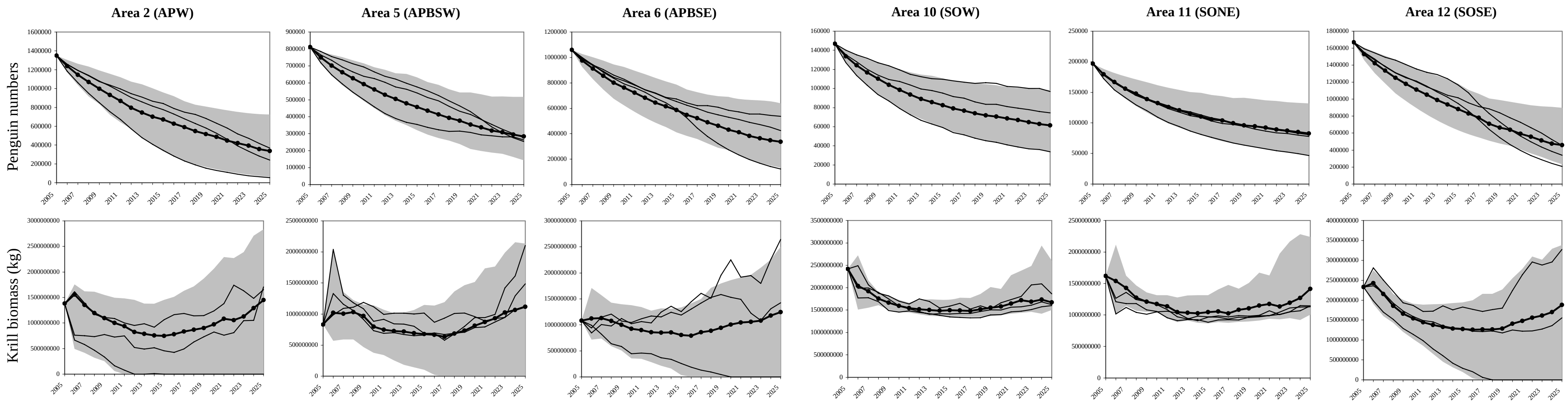


**Fig. 2b**. Results from an illustrative MP with starting krill catch allocation ***Option 4*** showing trajectories of krill biomass and penguin abundance (i.t.o. numbers) in all SSMUs **without seals** present, from 120 model representations and when using a model version that assumes no krill movement (*Em* = 0). Three individual trajectories are shown, with the median a dark dotted line and the shaded areas showing 90% probability envelopes.

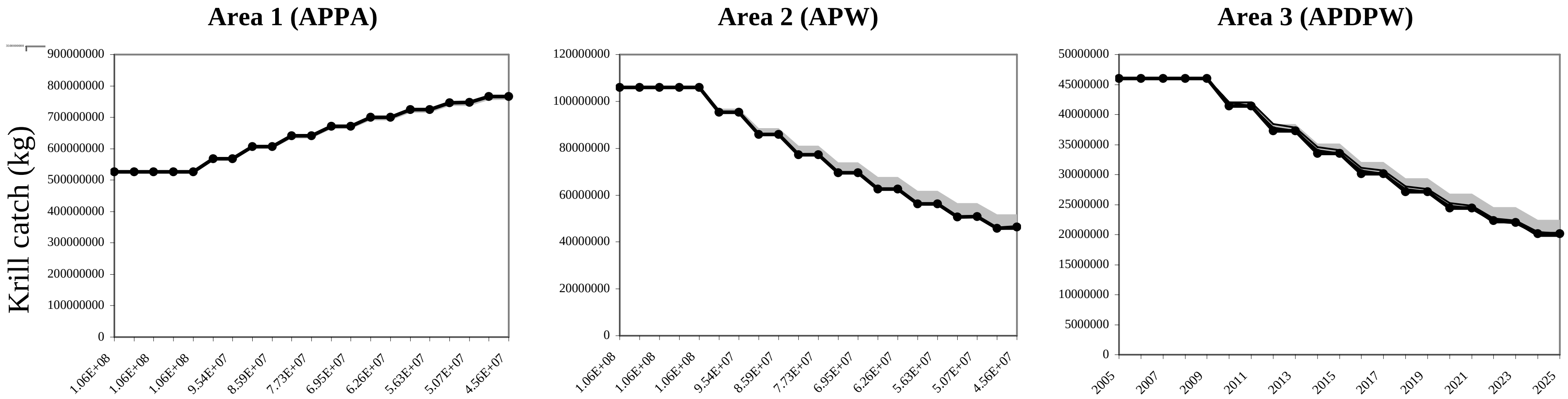


Fig. 3. Results from an illustrative MP with starting krill catch allocation ***Option 4*** showing changes in the krill catch for one pelagic area (Area 1) with no land-breeding predators, and two areas with decreasing trends in the abundance of land-bredding predators (Areas 2 and 3). Note that the illustrative candidate MP applied assumes catches remain at the current level for the first 3 years and thereafter are adjusted upwards or downwards based on the trend/s in CEMP monitoring data and subject to constraints as outlined in the text.

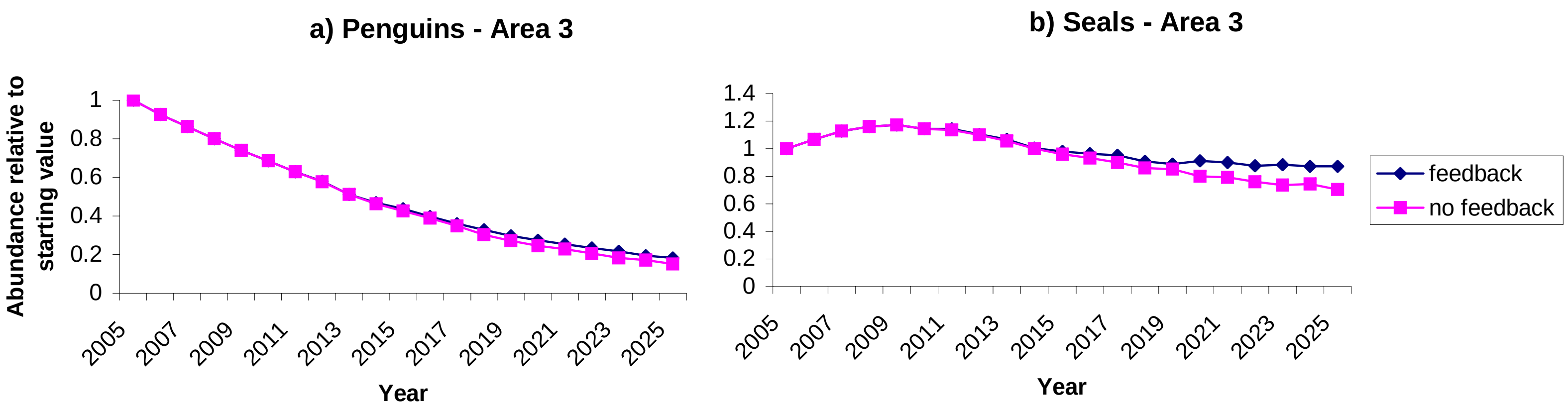


Fig. 4. Plots of the change in abundance relative to the starting value for a) penguins and b) seals in Area 3 compared under a scenario with no feedback in catch allocations (i.e. catches constant as per Catch Option 4) versus when using a feedback control rule.

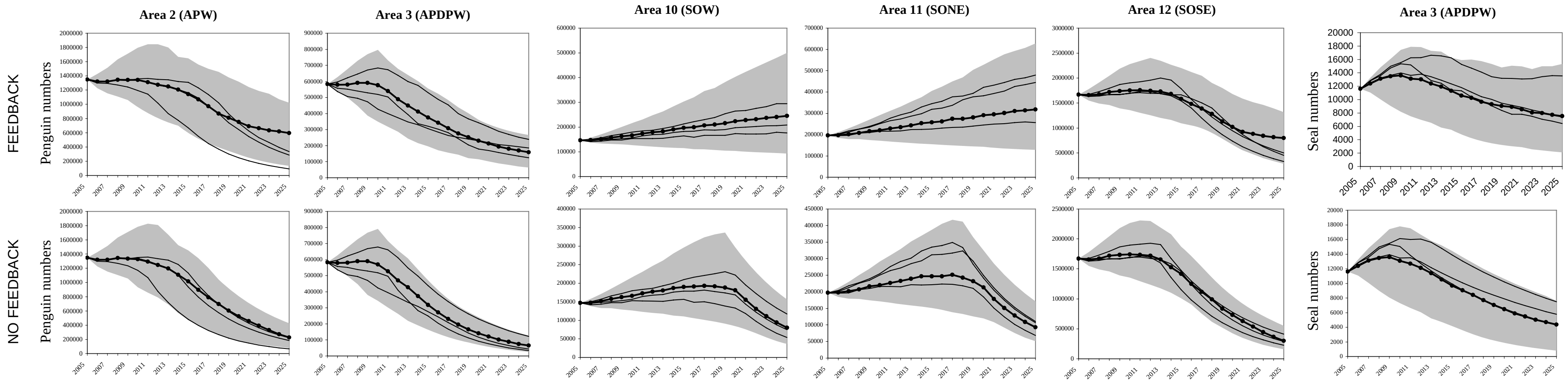


**Fig. 5**. Selected trajectories of penguin abundance (i.t.o. numbers) in SSMUs 2, 3, 10, 11 and 12 and seal abundance (i.t.o numbers) in SSMU 3, compared under a scenario with feedback introduced into the krill catch allocation equation (top panel) versus a no feedback example (lower panel) – in both cases future catches are increased by 10% each year. The scenario shown assumes a higher predator juvenile survival rate than the base-case model. Results are from 120 model representations and when using a model version that assumes some krill movement (*Em* = 0.1). Three individual trajectories are shown, with the median a dark dotted line and the shaded areas showing 90% probability envelopes.

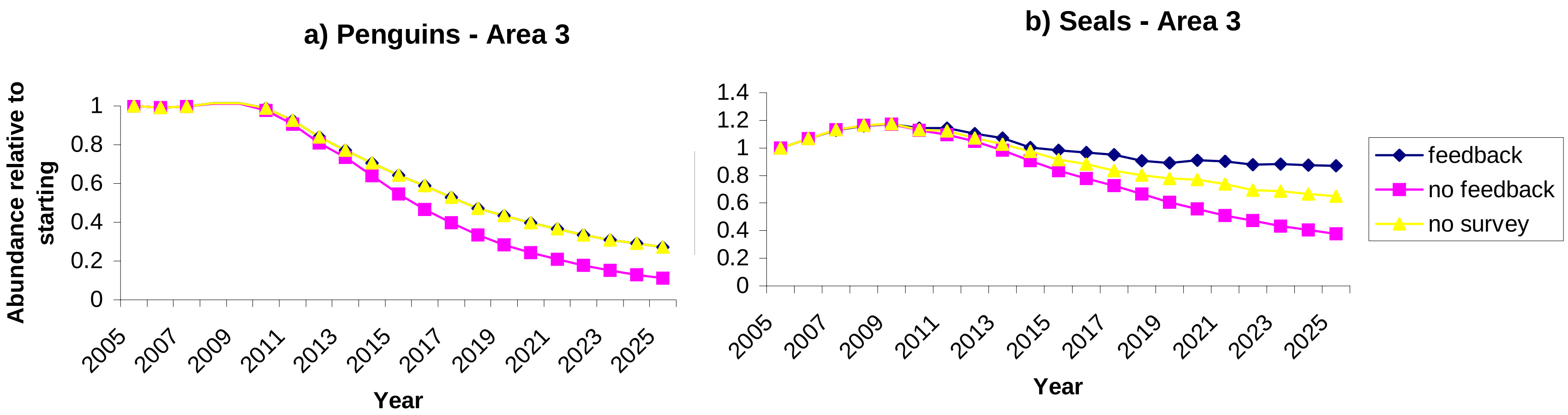


Fig. 6. Plots of the change in abundance relative to the starting value for a) penguins and b) seals in Area 3 compared under three scenarios with a) no feedback in catch allocations (i.e. catches constant as per Catch Option 4); b) using a feedback control rule based on survey information available for all SSMUs and c) using a feedback control rule but with no survey information available for SSMU 3, but with survey information nonetheless assumed available for the other SSMUs.