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Further Updated progress report: A multi-stock model for North Pacific sei whales

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INTERNATIONAL
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ABSTRACT

The age-, sex-, and season-structured population dynamics model developed to conduct an assessment of North Pacific sei whales is updated based on the recommendations of the IA sub-committee in 2018. The model can now utilize minimum abundance estimates, account for differential probabilities of tag reporting as a function of number of hits, and better handle situations in which catches in some years are high relative to the estimates of available numbers. Preliminary base-case models are undertaken for single-stock, 3-stock, and 5-stock hypotheses. The base-case model for the 5-stock hypothesis cannot convergence as it appears to be over-parameterized so the (draft) sensitivity tests are based on the single-stock and 3-stock hypotheses. Several issues arising from the results require additional consideration by the IA sub-committee.

INTRODUCTION

The Scientific Committee of the IWC is conducting an in-depth assessment of North Pacific sei whales (e.g. IWC 2016, 2017, 2018, 2019). To date this work has led to identification two broad hypotheses regarding stock structure (a single stock in the entire North Pacific and a multi-stock hypothesis), along with boundaries for data analysis. The data available for assessment purposes are catches, indices of absolute abundance (including some that are minimum estimates), indices of relative abundance, as well as mark recapture data. The model that has been developed to analyze these data is a deterministic age- and sex-structured model that tracks the population numbers by stock, sex, and age, and the number of marked animals by stock, age, sex and number of hits.

IWC (2019) recommended that given the difficulties with the Mixed sub-area (abundance is too small to enable all the catches to be taken), that this sub-area should be treated as an area of overlap between multiple adjacent feeding groups (potentially the Eastern North Pacific, Pelagic and Aleutian sub-areas), such that whaling in the Mixed sub-area could take whales from any of the overlapping feeding groups. This document outlines the updated model specifications.

Preliminary models runs are conducted for three potential base-case models that are based on (i) a single-stock assumption, (ii) the assumption there are three stocks of sei whales in the North Pacific, and (iii) the assumption there are five stocks of sei whales in the North Pacific. The results of these analyses raise further questions for the IA sub-committee.

MATERIALS AND METHODS

The Data

Catches, abundance and marking data are used when applying the modelling framework to estimate population numbers by stock, year, sex, season and feeding ground (when there is more than one feeding ground and one breeding stock). The raw data have to be adjusted prior to inclusion in the model, as outlined below.

Catch data

The catch data (Cooke, 2019a) are catches by year, sex, and sub-area (see Figs 1-3). All catches are assumed to be taken during the summer season (and hence recaptures of marked animals only occur in summer). Also available are the catches by year, sex and sub-area that could have reported recaptures of marked sei whales (J.G. Cooke, pers.comm).

Abundance estimates

"Best" estimates of absolute abundance (with sampling CVs) are available for the Pelagic and Western Coastal sub-areas (two for the latter sub-area) (IWC, 2019). There are two "minimum" abundance estimates (for the Eastern North Pacific and Eastern Coastal sub-areas) (IWC, 2019) and two zero estimates (for the Aleutian and Mixed sub-areas).

Cooke (2019b) summarizes the estimates of relative densities by feeding ground (and their associated CVs) for various temporal blocks[1].

Mark-recapture data

Marking data are available from summer and winter marking cruises. The analyses of this paper use the data from winter markings by assuming that distribution of stocks in winter is the same as in summer. This is valid for the single-stock hypotheses, but is an approximation for the multi-stock hypotheses. There are too few winter marks to enable estimation of the spatial distribution of multiple stocks in winter.

The mark-recapture data have been updated substantially by the interessional group from the data set used previously based on the issues identified by Cooke (2019c). The marking data set is now in the form of numbers of marked animals by year, categorized into the number of successful hits (1-3). The recapture data indicate for each recaptured animal the season (years and summer/winter) of marking and recapture, the sub-area of marking and the sub-area of recapture, sex (male, female, unknown) and number of hits on the whale.

The Model

The model distinguishes 'breeding stocks' and 'feeding grounds'. Breeding stocks are demographically and genetically independent and multiple breeding stocks may be found on each feeding ground (see Fig.1 for the feeding grounds). There is no dispersal between breeding stocks. The year is divided into two seasons, nominally 'summer' and 'winter' to account for within-year recaptures from the lower latitudes to the higher latitudes (all catches and hence recaptures occur during summer).

Each breeding stock is found in a set of feeding grounds, each of which may have catches, and indices of relative or absolute abundance.

Basic Population Dynamics

The population dynamics are based on a two-season (w=winter; s=summer) version of the standard age- and sex-structured model used by the IWC Scientific Committee, with the 'start of the year' defined as the start of winter, i.e.:

$$\begin{array}{lll} N^{\mathrm{w,m/f},i}_{t+1,0} = 0.5B^{i}_{t+1} & \text{if } a = 0 & \\ N^{\mathrm{w,m/f},i}_{t+1,a} = (N^{\mathrm{s,m/f},i}_{t,a-1} - C^{\mathrm{s,m/f},i}_{t,a-1})\,(S_{a-1})^{1/2} & \text{if } 1 \le a \le x-1 & (1.1\text{a}) \\ N^{\mathrm{w,m/f},i}_{t+1,x} = (N^{\mathrm{s,m/f},i}_{t,x-1} - C^{\mathrm{s,m/f},i}_{t,x-1})\,(S_{x-1})^{1/2} + (N^{\mathrm{s,m/f},i}_{t,x} - C^{\mathrm{s,m/f},i}_{t,x})(S_{x})^{1/2} & \text{if } a = x & \end{array}$$

$$N^{\mathrm{s,m/f},i}_{t,a} = N^{\mathrm{w,m/f},i}_{t,a}(S_a)^{1/2} \qquad (1.1\text{b})$$

where:

$N^{\mathrm{w},m/f,i}_{t,a}$	is the number of males/females of age *a* in breeding stock *i* at the start of the winter season of year *t*;
$N^{\mathrm{s},m/f,i}_{t,a}$	is the number of males/females of age *a* in breeding stock *i* at the start of the summer season of year *t*;
$C^{s,m/f,i,f}_{t,a}$	is the catch of males/females of age *a* in breeding stock *i* during season *s* of year *t* (whaling is assumed to take place in a pulse at the start of summer); and
S_a	is the annual survival rate of animals of age *a* (assumed to be the same for males and females):

$$S_a = \begin{cases} S_0 & \text{if } a = 0 \\ S_{1+} & \text{if } a > 0 \end{cases} \qquad (1.2)$$

S_0 is the calf survival rate; S_{1+} is the survival rate for animals aged 1 and older; B^i_t is the number of births to breeding stock *i* during year *t*; and *x* is the maximum (lumped) age-class (all animals in this and the *x*-1 class are assumed to be recruited and to have reached the age of first parturition). *x* is taken to be 15 (this value must be above the ages at full recruitment and full maturity).

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[1] These estimates were updated by Cooke from the data presented in Cooke (2019b) and the final version of the IA sub-committee report will include the corrected estimates.

Births and density-dependence

The number of births at the start of year *t* for breeding stock *i*, B_t^i , is given by:

$$B_t^i = b_t^i \, N_t^{\mathrm{f},i} \tag{2.1}$$

where $N_t^{\mathrm{f},i}$ is the number of mature females in breeding stock *i* at the start of the winter season of year *t*:

$$N_t^{\mathrm{f},i} = \sum_{a=a_m}^{x} N_{t,a}^{\mathrm{w},\mathrm{f},i} \tag{2.2}$$

a_m is the age-at-maturity (the convention of referring to the mature population is used here, although this actually refers to animals that have reached the age of first parturition); b_t^i is the probability of birth/calf survival for breeding stock *i* in year *t*:

$$b_t^i = \max(0, b_K\{1 + A^i(1-(N_t^{1+,\mathrm{w},i} / K^{1+,\mathrm{w},i})^{z^i}\}) \tag{2.3}$$

b_K is the average number of live births per year per mature female at carrying capacity; and A^i is the resilience parameter for breeding stock *i*, and z^i is the degree of compensation for breeding stock *i*. The number of 1+ animals in breeding stock *i* at the start of season *s* of year *t* is given by:

$$N_t^{1+,s,i} = \sum_A N_t^{1+,s,i,A} = \sum_A X^{A,s,i} \sum_{a=1}^{x} (N_{t,a}^{s,\mathrm{m},i} + N_{t,a}^{s,\mathrm{f},i}) \tag{2.4}$$

$K_t^{1+,s,i}$ is the carrying capacity for breeding stock *i* at the start of season *s*:

$$K^{1+,s,i} = \sum_A K^{1+,s,i,A} = \sum_A X^{A,s,i} \sum_{a=1}^{x} (N_{-\infty,a}^{s,m,i} + N_{-\infty,a}^{s,\mathrm{f},i}) \tag{2.5}$$

$X^{A,s,i}$ is the proportion of animals of breeding stock *i* that are found in feeding ground *A* during season *s*.

Catches

The catch by breeding stock is determined by apportioning the catches by feeding ground, taking account of mixing (i.e. exposure to harvesting) matrices, according to:

$$C_{t,a}^{s,\mathrm{m/f},i} = \sum_A C_{t,a}^{s,\mathrm{m/f},i,A} = \sum_A \Omega^A X^{A,s,i} N_{t,a}^{s,\mathrm{m/f},i}(1-e^{-F_t^{s,\mathrm{m/f},A}}) = \sum_A \Omega^A X^{A,s,i} N_{t,a}^{s,\mathrm{m/f},i} E_t^{s,\mathrm{m/f},A} \tag{3.1}$$

where Ω^A is a factor to allow the Mixed sub-area to act as an area of overlap (Ω^A =10 for the Mixed sub-area and 1 for all other sub-areas), $E_t^{s,\mathrm{m/f},A}$ is the exploitation rate (constrained to lie between 0 and 1), and only animals of age 1+ and older are subject to removal by whaling. The values for the fishing mortality rates are selected so that the observed and predicted values for $C_t^{s,\mathrm{m/f},A}$, the number of males/females caught in feeding ground *A* during season *s* of year *t*, are matched exactly, i.e.:

$$C_t^{s,\mathrm{m/f},A} = \sum_i \Omega^A X^{A,s,i} \sum_{a>0} N_{t,a}^{s,\mathrm{m/f},i}(1-e^{-F_t^{s,\mathrm{m/f},A}}) \tag{3.2}$$

Initialising the parameter vector

The numbers at age in the pristine population are given by:

$$\begin{aligned} N^{\mathrm{w,m/f},i}_{-\infty,a} &= 0.5\, N^{i}_{-\infty,0} \prod_{a'=0}^{a-1} S_{a'} && \text{if } a < x \\ N^{\mathrm{w,m/f},i}_{-\infty,x} &= 0.5\, N^{i}_{-\infty,0} \prod_{a'=0}^{x-1} S_{a'} / (1-S_x) && \text{if } a = x \end{aligned} \tag{4.1}$$

The value for $N^{i}_{-\infty,0}$ is determined from the value for the pre-exploitation size of the 1+ component of breeding stock *i* using the equation:

$$N^{i}_{-\infty,0} = K^{1+,\mathrm{w},i} \Big/ \left(\sum_{a=1}^{x-1} \left(\prod_{a'=0}^{a-1} S_{a'} \right) + \frac{1}{1-S_x} \prod_{a'=0}^{x-1} S_{a'} \right) \tag{4.2}$$

Likelihood function

Absolute abundance estimates

Under the assumption that the estimates of absolute abundance for the sub-area *A* are log-normally distributed, the negative of the logarithm of the likelihood function for the absolute abundance estimates ("best") for sub-area *A* and year *t* is given by:

$$-\ell n L_{1a} = \ell \mathrm{n} \sigma^{A}_{t} + \tfrac{1}{2(\sigma^{A}_{t})^2} (\ell \mathrm{n} N^{A,\mathrm{obs}}_{t} - \ell \mathrm{n} \hat{N}^{1+,A}_{t})^2 \tag{5.1}$$

where $N^{A,\mathrm{obs}}_{t}$ is survey estimate of abundance for feeding ground *A* during year *t*:

$$\hat{N}^{1+,A}_{t} = \sum_{i} X^{A,\mathrm{s},i} \sum_{a>0} (N^{\mathrm{s,m},i}_{t,a} + N^{\mathrm{s,f},i}_{t,a}) \tag{5.2}$$

and σ^{A}_{t} is the CV of $N^{A,\mathrm{obs}}_{t}$.

Some of estimates of abundance are "minimum" estimates. Such estimates provide some information on the lower bound for abundance but not the upper bound. These estimates are included in the negative log-likelihood in the form of the mixture of a log-normal and a uniform distribution. A "smoothing function" is used to transition between the two components of the negative log-likelihood to avoid (additional) problems with differentiability.

$$-\ell n L_{1b} = \{\ell n \sigma^{A}_{t} + \tfrac{1}{2(\sigma^{A}_{t})^2} (\ell n \hat{N}^{1+,A}_{t} - \ell n N^{A,\mathrm{obs}}_{t})^2\} \tfrac{\exp(-\Delta(\hat{N}^{1+,A}_{t} - N^{A,\mathrm{obs}}_{t})}{1+\exp(-\Delta(\hat{N}^{1+,A}_{t} - N^{A,\mathrm{obs}}_{t})} + \ell n \sigma^{A}_{t} \tfrac{1}{1+\exp(-\Delta(\hat{P} - N^{A,\mathrm{obs}}_{t})} \tag{5.3}$$

where Δ is a "large" number (here 30).

Relative abundance estimates

The estmates of relative abundance (assumed to relate the middle of each period for which data are available) are also assumed to be log-normally distributed. However, account needs to be take of the variance-covariance structure of these data (see Cooke [2019b]), i.e.:

$$-\ell n L_{2} = 0.5 \sum_{A,t} \sum_{A',t'} (\ell \mathrm{n} \tilde{N}^{A,\mathrm{obs}}_{t} - \ell \mathrm{n}(q N^{1+,A}_{t}))[V^{-1}]^{A,t}_{A',t'} (\ell \mathrm{n} \tilde{N}^{A',\mathrm{obs}}_{t'} - \ell \mathrm{n}(q N^{1+,A'}_{t'})) \tag{5.4}$$

where $\tilde{N}^{A,\mathrm{obs}}_{t}$ is the relative abundance for feeding ground *A* during year *t*, *V* is the variance-covariance matrix for the relative abundance indices (Table 5 of Cooke [2019b]), and *q* is the catchability coefficient (assumed to be same for all sub-areas and years).

Mark-recapture data

The mark-recapture data are incorporated in the likelihood function by tracking the number of marks in each breeding stock that were marked in each year (separately by the number of hits), i.e.:

$$\tilde{N}^{\text{w,m/f},i,s',A'}_{t+1,a,t',h} = \begin{cases} (\tilde{N}^{\text{s,m/f},i,s',A'}_{t,a-1,t',h}(1-\sum_{A} X^{A,s,i}\Omega^{A}E^{\text{s,m/f},A}_{t}) + \chi^{\text{s,m/f},A'}_{t',a-1}T^{\text{s},A'}_{t',h}e^{-F^{\text{s,m/f},A'}_{t'}}(S_a)^{1/2} \\ (\tilde{N}^{\text{s,m/f},i,s',A'}_{t,x,t',h}(S_x)^{1/2} + \tilde{N}^{\text{s,m/f},i,s',A'}_{t,x-1,t',h}(S_{x-1})^{1/2})(1-\sum_{A} X^{A,s,i}\Omega^{A}E^{\text{s,m/f},A}_{t}) + \\ \qquad (\chi^{\text{s,m/f,i},A'}_{t',\text{x}}(S_x)^{1/2} + \chi^{\text{s,m/f,i},A'}_{t',x-1}(S_{x-1})^{1/2})T^{\text{s},A'}_{t',h}e^{-F^{\text{s,m/f},A'}_{t'}} \end{cases} \tag{5.5a}$$

$$\tilde{N}^{\text{s,m/f},i,s',A'}_{t,a,t',h} = \tilde{N}^{\text{w,m/f},i,s',A'}_{t,a,t',h}(S_a)^{1/2} + \chi^{\text{w,m/f},A'}_{t',a}T^{\text{w},A'}_{t',h}(S_a)^{1/2} \tag{5.5b}$$

where $\tilde{N}^{s,\text{m/f},i,s',A'}_{t,a,t',h}$ is the number of marked males / females of age *a* in breeding stock *i* at the start season *s* of year *t* that were marked with *h* hits during seasons *s*' of year *t*' in sub-area *A*'; $T^{s,A}_{t,h}$ is the number of animals that were marked with *h* hits in sub-area *A* during season *s* of year *t*; $\chi^{s,\text{m/f},i,A}_{t,a}$ is the proportion of animals in sub-area *A* at the start of season *s* of year *t* that are males/females of age *a* from breeding stock *i*, i.e.:

$$\chi^{s,\text{m/f},i,A}_{t,a} = \frac{X^{A,s,i}N^{s,\text{m/f},i}_{t,a}}{\sum_{a'>0}\sum_{\text{m/f}}\sum_{i'} X^{A,s,i'}N^{s,\text{m/f},i'}_{t,a'}} \tag{5.6}$$

The model estimate of the number of recaptures of animals originally marked with *h* hits on feeding ground *A*' during season *s*' of year *t*' that were recaptured in feeding ground *A* during season *s* of year *t* (excluding within-season recaptures), $\hat{R}^{s,s',A,A'}_{t,t',h}$, is given by:

$$\hat{R}^{s,s',A,A'}_{t,t',h} = \omega_h \frac{\tilde{C}^{\text{s,m/f},A}_{t}}{C^{\text{s,m/f},A}_{t}} \sum_{i}\sum_{m/f}\sum_{a} X^{A,s,i}\tilde{N}^{s,\text{m/f},i,s'A'}_{t,a,t',h}E^{\text{s,m/f},A}_{t} \tag{5.7}$$

where ω_h is the recapture probability for animals marked with *h* hits, and $\tilde{C}^{\text{s,m/f},A}_{t}$ is the catch of males/females in sub-area *A* during year *t* that could have reported a recapture (Figs 2 and 3).

The log-likelihood for the marking data, under the assumption of a Poisson recapture process, is given by:

$$\ell nL_2 = \sum_{h}\sum_{s}\sum_{s'}\sum_{t'}\sum_{t>t'}\sum_{A'}\sum_{A} \ell n\left\{(\hat{R}^{s,s',A,A'}_{t,t',h})^{R^{s,s',A,A'}_{t,t',h}} e^{-\hat{R}^{s,s',A,A'}_{t,t',h}}\right\} \tag{5.8}$$

where $R^{s,s',A,A'}_{t,t',h}$ is observed the number of recaptures of animals originally marked with *h* hits on feeding ground *A*' during season *s*' of year *t*' that were recaptured in feeding ground *A* during season *s* of year *t*.

Example application

Model structure assumptions

Three scenarios are explored:

A. there is a single-stock of sei whales across the North Pacific (see Table 1a for the mixing matrices); the reporting rates are 0.36, 0.495 and 0.63[2],
B. there are three stocks of sei whales across the North Pacific (see Table 1b for the mixing matrices); the reporting rates are 0.36, 0.495 and 0.63;
C. there are five stocks of sei whales across the North Pacific (see Table 1c for the mixing matrices); the reporting rates are 0.36, 0.495 and 0.63; and

The estimated parameters are: (a) the carrying capacity of each breeding stock (equivalent to the number of animals by breeding stock at the start of 1906) parameterized as a constant (500) plus an estimated constant multiplied by estimated proportions for each breeding stock (normalized to sum to 1), (b) the entries of the catch mixing matrix, (c)

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[2] The values of 0.36 and 0.63 were provided by Justin Cooke (Pers commn). 0.495 is the average of 0.36 and 0.63.

the catchability coefficient for the relative abundance indices. The pre-specified parameters of the base-case model are:

- Age-at-maturity: 5 years.
- Natural mortality rate: 0.05yr^{-1} (equivalent to S=0.951)
- Density-dependence parameters (A=0.7614; z=2.1466) chosen so that MSYR_{mat}=2% and MSYL_{mat}=0.6

Table 2 lists proposed sensitivity tests that explore the sensitivity of results to assumptions regarding reporting rates (equivalent to rates of initial tag loss), productivity, the weight assigned to each data source, and how to deal with spatial structure.

RESULTS

Fit diagnostics – base-case model

The models for the single-stock and 3-stock scenarios converged (positive definitive Hessian matrices, and low maximum gradients). However, the model based on the 5-stock scenario could not converge, with the estimates of initial abundance for stocks C and D hitting the minimum value of 500 animals and a very large final gradient. This suggests that the currently-available data are not able distinguish among five stocks (if there are five stocks). Consequently, the 5-stock model is not considered further in this paper. However, it may be that a different 5-stock hypothesis (or setting rather than estimating the proportions of stocks C and D spatially) would converge. The basis for setting such proportions is unclear and would be desirably established as data.

The negative log-likelihood for the 3-stock base-case model (B0) is over 60 log-likelihood units lower than that of the single-stock model (A0) [Table 3]. The 3-stock model fits the data for the Western Coastal sub-area much better than the single-stock model (the single-stock model fits the relative abundance estimates for the Eastern Coastal sub-area better than the 3-stock model, but not substantially so) (Figs 4 and 6). Neither model fits the estimate of absolute abundance for the Pelagic sub-area well (Figs 4 and 6, upper right panels). Both base-case models predict a rapid increase in abundance following the cessation of commercial whaling, which is consistent with the abundance estimates for the Pelagic sub-area but not the Aleutian and Eastern Coastal sub-areas.

The two base-case models under-predict the number of recaptures for all sub-areas except the Eastern North Pacific sub-area. Sensitivity test 1, based on a higher reporting rate, suggests that this is due to many potential recaptures not being reported (or the tags assumed lost). The numbers of recaptures of animals marked by sub-area are broadly correct, although there are some noteworthy misfits (focusing on regions with at least 8 recaptures), in particular the low fraction of predicted relative to observed recaptures of animals marked in the Aleutian sub-area.

Stock trajectories – base-case model

Figure 8 plots the time-trajectories of 1+ numbers by stock. The trajectories for the two base-case models are quite similar, particularly in recent years, although the 3-stock hypothesis infers a larger initial size. The right panel of Figure 8 shows time-trajectories of 1+numbers by breeding stock for the 3-stock hypothesis, which implies a rapid decline in abundance for the stock found only in the Western Coastal sub-area (essentially extirpated by the end of the time-series), while that found only in the Eastern Coastal sub-area is at a relatively high abundance. The trend in 1+ abundance for third stock (Stock A) matches that for the total because this stock is the largest.

Sensitivity tests

Figures 9 and 10 summarize the results of the sensitivity tests in terms of time-trajectories of total over all stocks 1+ population size. Table 4 contrasts the negative log-likelihoods for the base-case and the sensitivity tests that can be compared with the base-case model in terms of likelihood.

A higher reporting rate leads to higher abundance. This likely occurs because with a higher reporting rate, the exploitation rate can be lower to achieve same number of recaptures. However, setting the reporting rate to 1 irrespective of the number of hits leads to poorer fits to the data (Table 4). Unexpectedly, increasing MSYR reduces historical abundance while the opposite is the case for decreasing MSYR_{1+} (sensitivity tests 2 and 3). As expected, a higher MSYR leads to greater current abundance and vice versa. A lower MSYR leads to better fits for the single-stock model, but the negative log-likelihood is quite insensitive to MSYR for the 3-stock model.

Increasing the weight on the absolute abundance data (sensitivity test 4) leads to greater current abundance, while the results (for the single-stock hypothesis) are not very sensitive to changing the weight assigned to the relative abundance data (sensitivity test 5). The results for sensitivity test 5 for the 3-stock model appear anomalous. Increasing the weight assigned to the mark-recapture data or halving the 2011 abundance estimate (sensitivity tests 6 and 7) for the Pelagic sub-area lead to lower current abundance. These results suggest that there is a conflict between the information provided by the mark-recapture data and the estimates of absolute abundance (particularly for the Pelagic sub-area).

Ignoring the winter marks (sensitivity test 8) has little effect on 1906 abundance but to a less depleted stock at present for the single-stock model, but to higher 1906 and current abundance for the 3-stock model.

DISCUSSION

The results in the paper are much more plausible than those shown by Punt (2018). This is attributable to way catches in the Mixed sub-area are treated and the revised data. However, the inability to mimic the abundance estimates for the Pelagic region is a concern and suggests a conflict between the mark-recapture and the absolute abundance estimates for this sub-area.

The next (and perhaps final) step is to review the data and identify additional sensitivity analyses. In addition, and at present the zero abundance estimates are not used and the IA sub-committee may wish to specify how these estimates can be used. Finally the 5-stock hypothesis appears to be over-parameterized and the IA sub-committee may wish to specify some simpler variants of the hypothesis.

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Table 1. The catch mixing matrices. The γ-values are the estimated parameters, whereas the remaining values are pre-specified.

	West Coastal	Aleutians	Pelagic	Mixed	ENP	East Coastal
(a) Single stock						
	γ_1	γ_2	1	γ_3	γ_4	γ_5
(b) Three stocks						
Stock A	1	0	0	0	0	0
Stock B	γ_1	γ_2	1	γ_3	γ_4	γ_5
Stock C	0	0	0	0	0	1
(c) Five stocks						
Stock A	γ_1	γ_2	1	γ_3	γ_4	γ_5
Stock B	1	0	0	0	0	0
Stock C	γ_6	1	0	γ_7	0	0
Stock D	0	0	0	γ_8	0	γ_9
Stock E	0	0	0	0	0	1

Table 2. The sensitivity factors on which the alternative model runs are/will be based. Analyses are conducted for stock structure hypotheses A and B (single stock and 3-stock).

Run number	Description
0	Base model
1	The reporting rates by hit number is 1
2	Lower MSYR (1% on total abundance)
3	Higher MSYR (3% on total abundance)
4	10x weight on the absolute abundance estimates
5	10x weight on the marking data
6	10x weighting on the relative abundance estimates
7	Halve the 2011 estimate of abundance for the Pelagic sub-area
8	Ignore the winter marks
9	Alternative way to treat the winter marks&
10	Use of zero observations&

&: To be specified by the IA sub-committee in May 2019.

Table 3. Number of parameters and the negative log-likelihood for the three base-case models

Model	Number of parameters	Negative log-likelihood
A0	7	312.70
B0	9	249.92
C0	15	Did not converge

Table 4. Negative log-likelihoods for the base-case models and the sensitivity tests for which the likelihood function is comparable with that of the base-case model.

Scenario	**Single-stock (A models)**	**3-stocks (B models)**
Base model	312.70	249.92
The reporting rates by hit number is 1	324.94	262.01
Lower MSYR (1% on total abundance)	301.81	249.82
Higher MSYR (3% on total abundance)	334.76	250.35

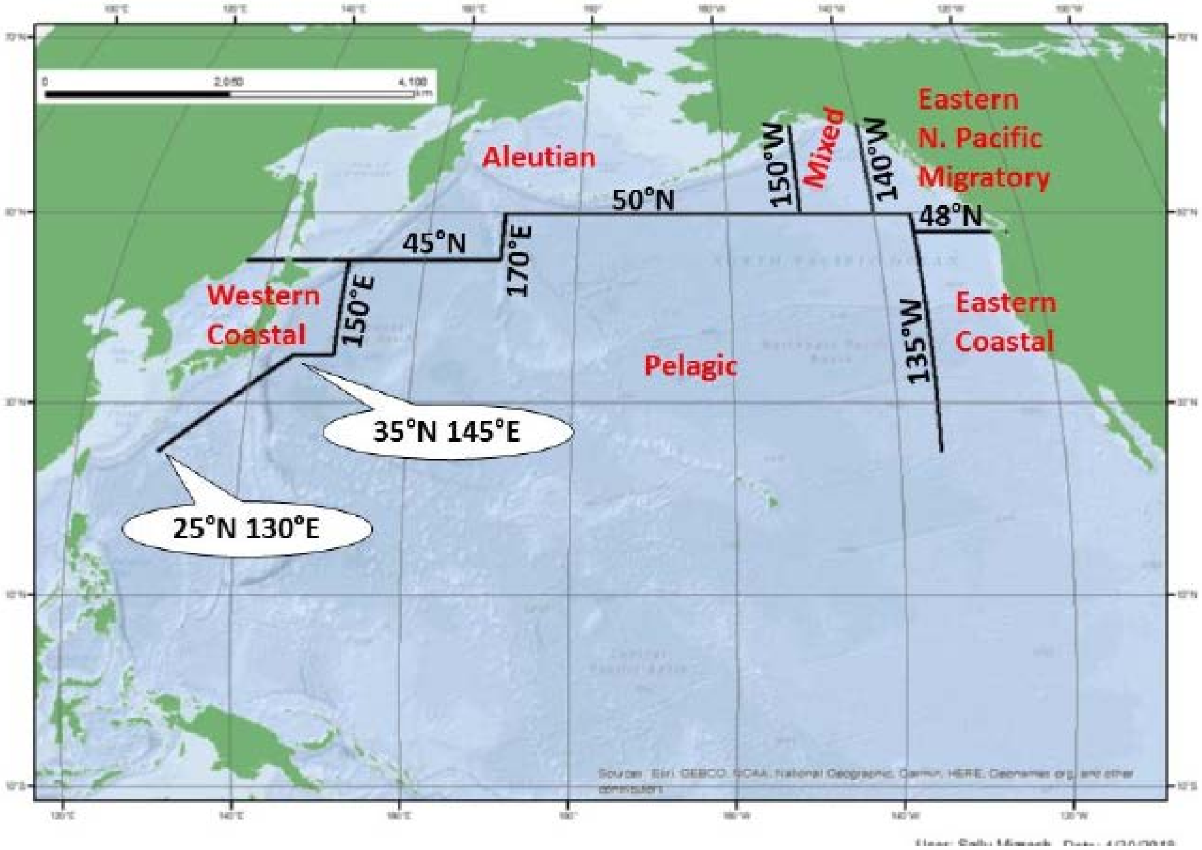
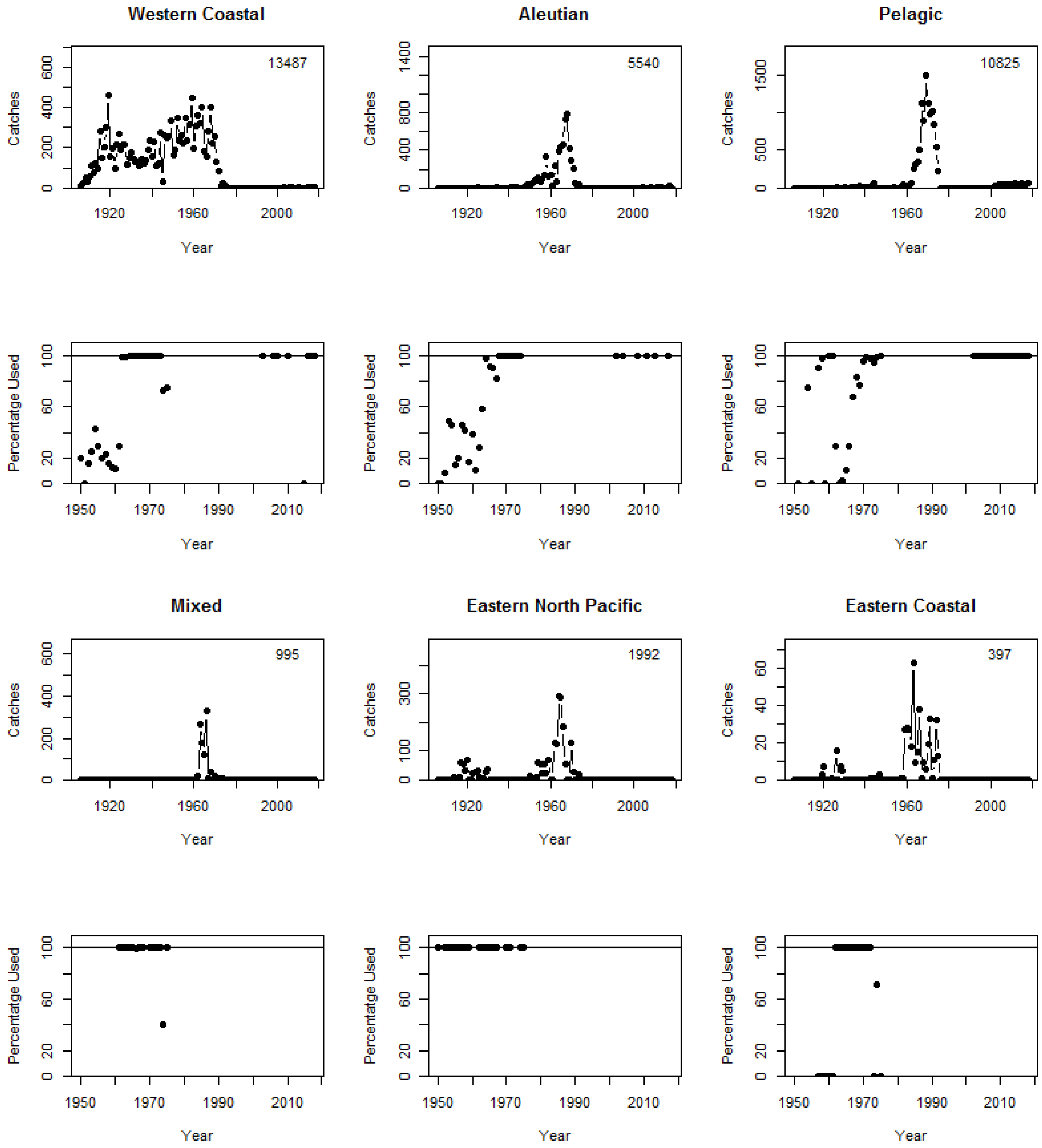


Figure 1. Lines (black lines) for dividing data into sub-areas for the in-depth assessment of North Pacific sei whales. Red words indicate name of the sub-areas. Numbers indicate locations of the lines (Figure 1; IWC 2019).



Western Coastal

Aleutian

Pelagic

Mixed

Eastern North Pacific

Eastern Coastal

Figure 2, Catches by sub-area and year for females. The upper panels show the time-series of catches aggregated over fleet, while the lower panels show the percentage of the annual catches considered to be capable of reporting the recapture of a marked animal. Missing values in the lower panels for each sub-area are years for which the catch is zero. Source: J.G. Cooke (pers. commn).

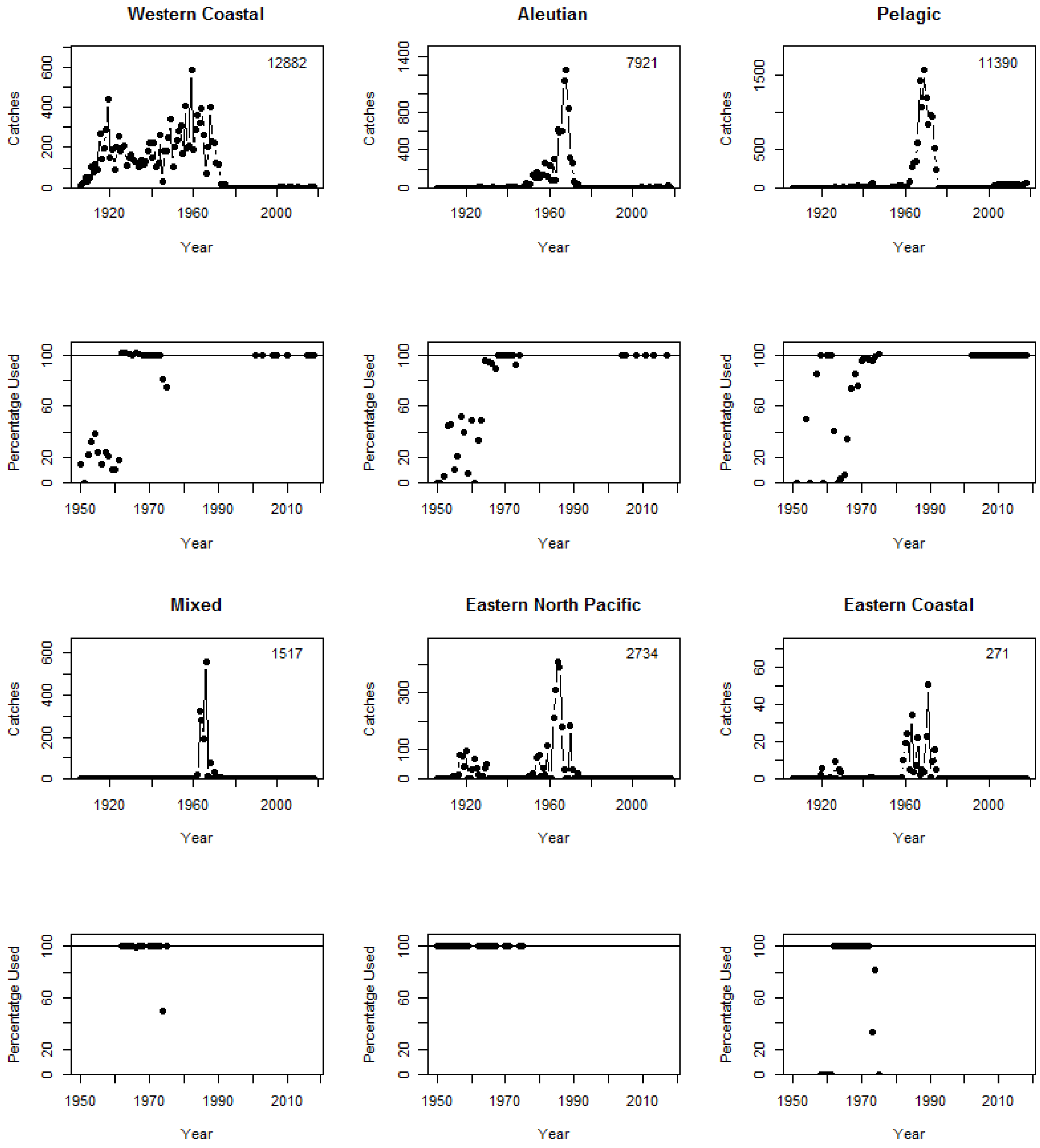


Figure 3, Catches by sub-area and year for males. The upper panels show the time-series of catches aggregated over fleet, while the lower panels show the percentage of the annual catches considered to be capable of reporting the recapture of a marked animal. Missing values in the lower panels for each sub-area are years for which the catch is zero. Source: J.G. Cooke (pers. commn).

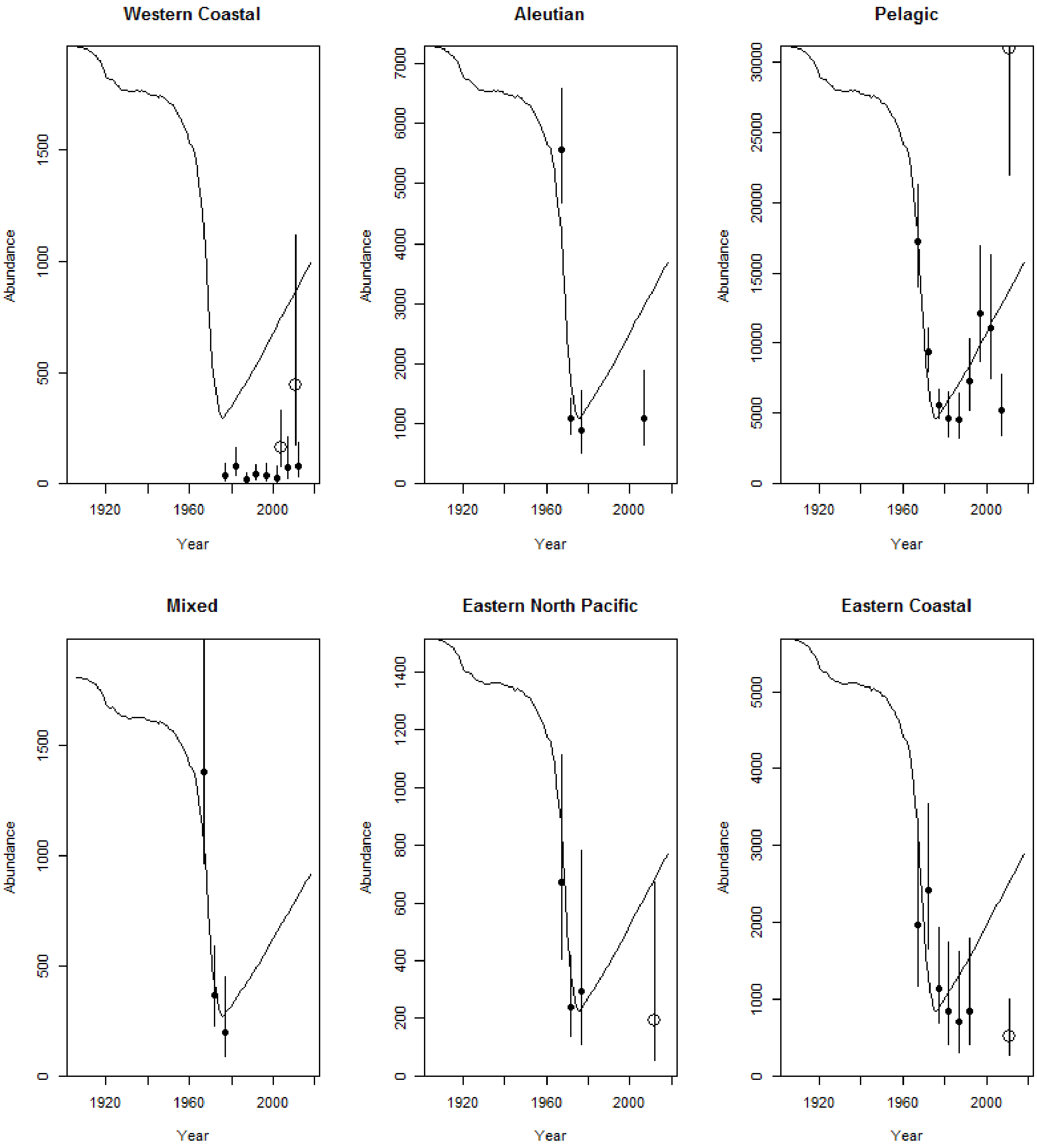


Figure 4. Time-trajectories of summer 1+ abundance by sub-area with the estimates of absolute (open circles) and relative (closed circles) abundance. The vertical lines denote 95% confidence intervals based on the sampling CVs. The lines are the model predictions from the single-stock model where the reporting rates are set to the default values (Model A0).

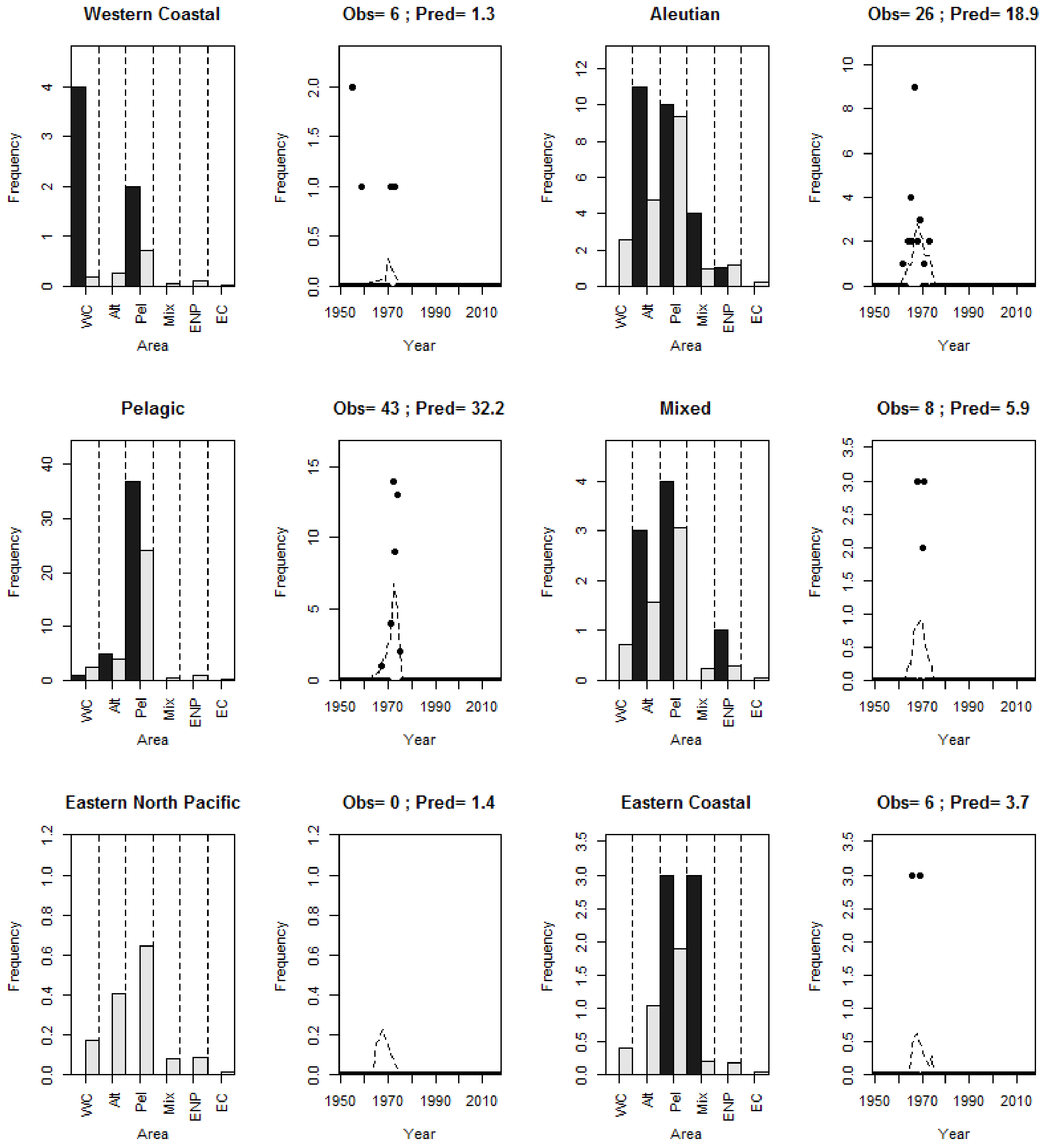


Figure 5. Observed (black bars) and model-predicted (gray bars) numbers of recaptures by recapture sub-area by sub-area of marking and the time-trajectories of observed and model-predicted recaptures by sub-area of marking. The model predictions are based on the single-stock model where the reporting rates are set to the default values (Model A0).

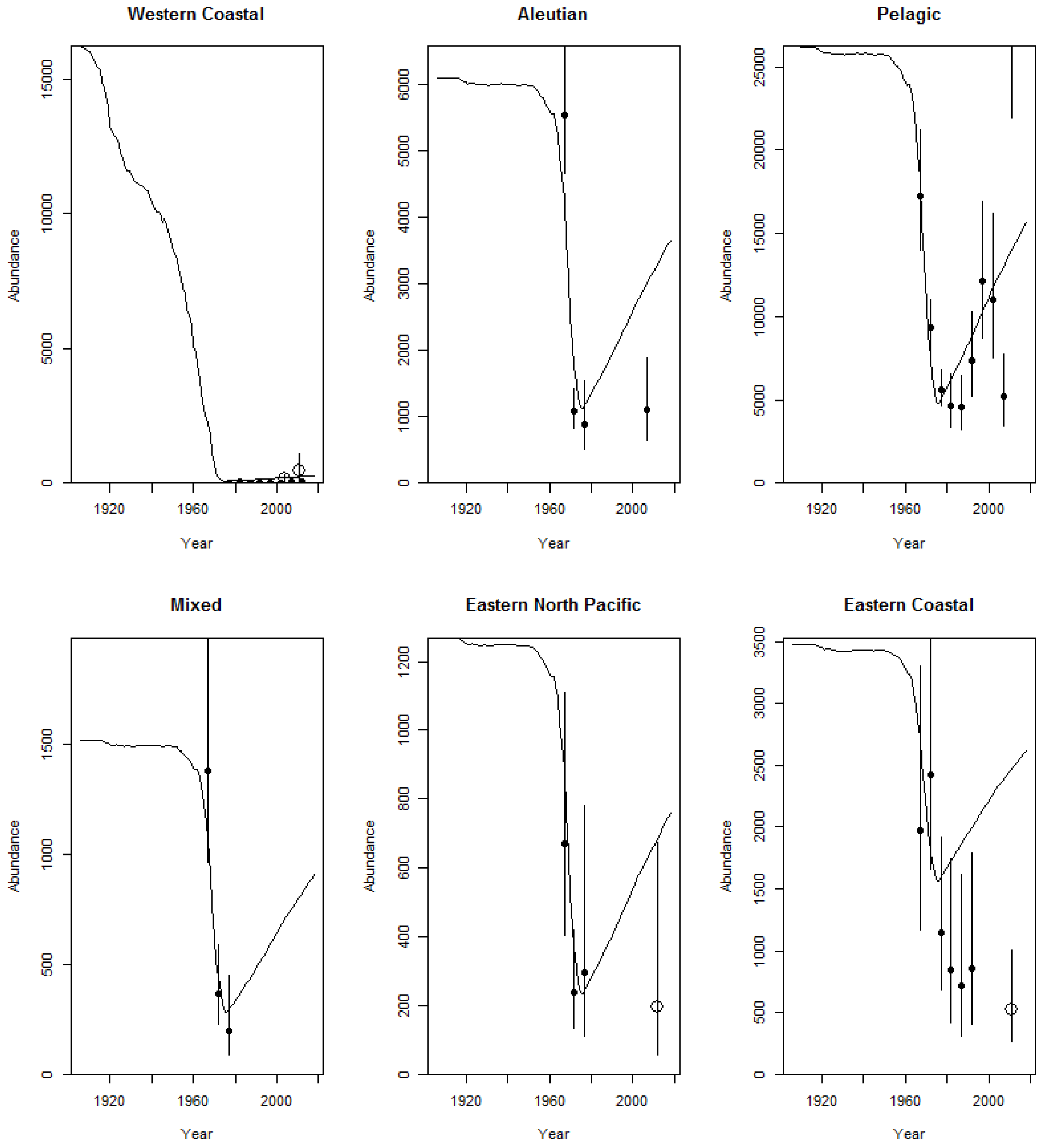


Figure 6. Time-trajectories of summer 1+ abundance by sub-area with the estimates of absolute (open circles) and relative (closed circles) abundance. The vertical lines denote 95% confidence intervals based on the sampling CVs. The lines are the model predictions from the 3-stock model where the reporting rates are set to the default values (Model B0).

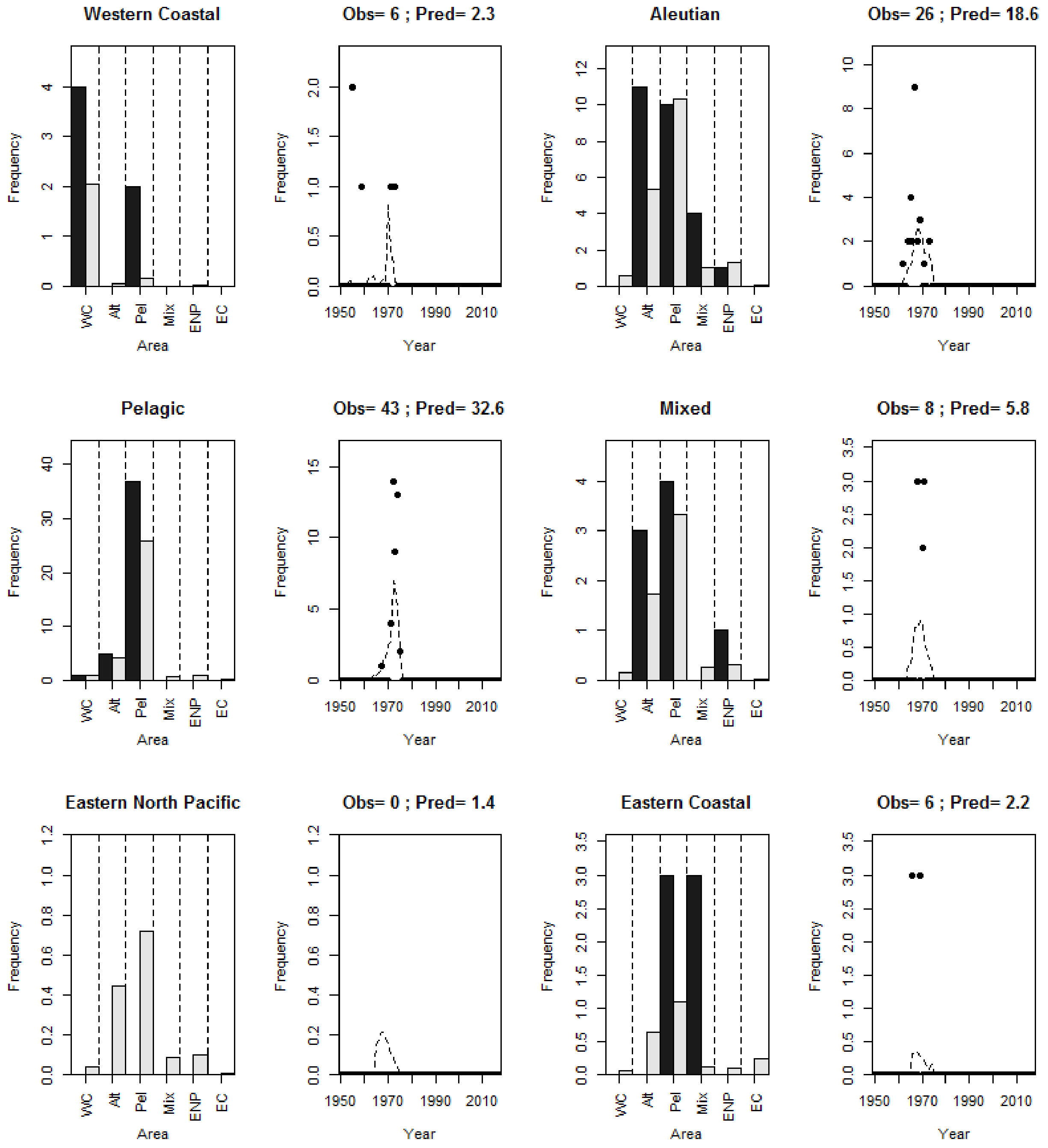


Figure 7. Observed (black bars) and model-predicted (gray bars) numbers of recaptures by recapture sub-area by sub-area of marking and the time-trajectories of observed and model-predicted recaptures by sub-area of marking. The model predictions are based on the 3-stock model where the reporting rates are set to the default values (Model B0).

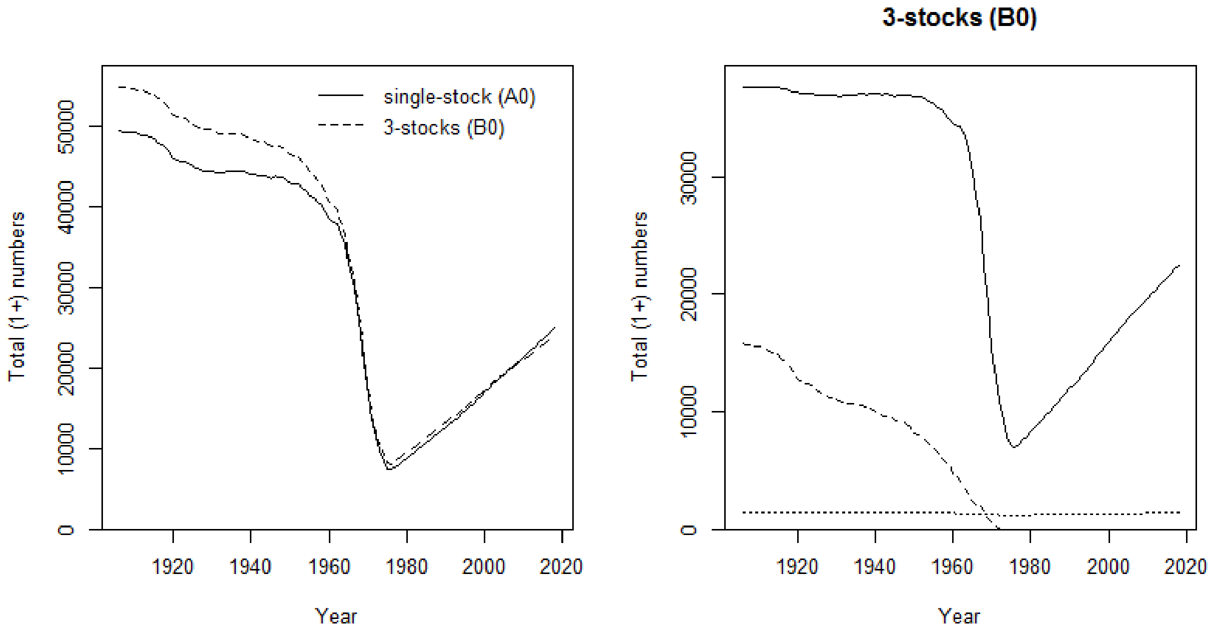


Figure 8. Time-trajectories of total (1+) numbers. The left panel shows the total (over stock) abundance and the right panel the time-trajectories of 1+ numbers by stock for model B0.

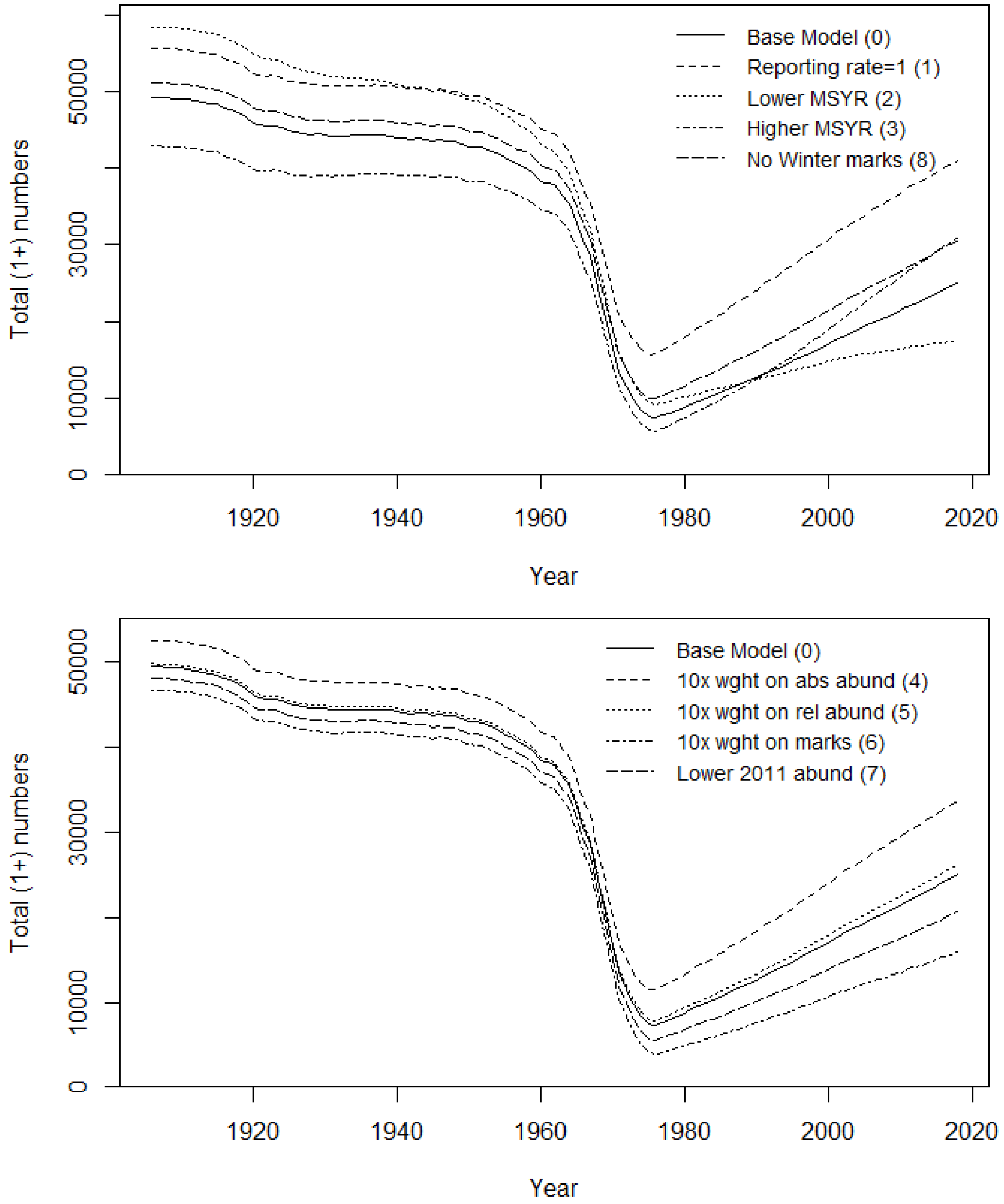


Figure 9. Time-trajectories of total (1+) numbers for the single-stock model. Results are shown for the base-case model and sensitivity tests 1-8.

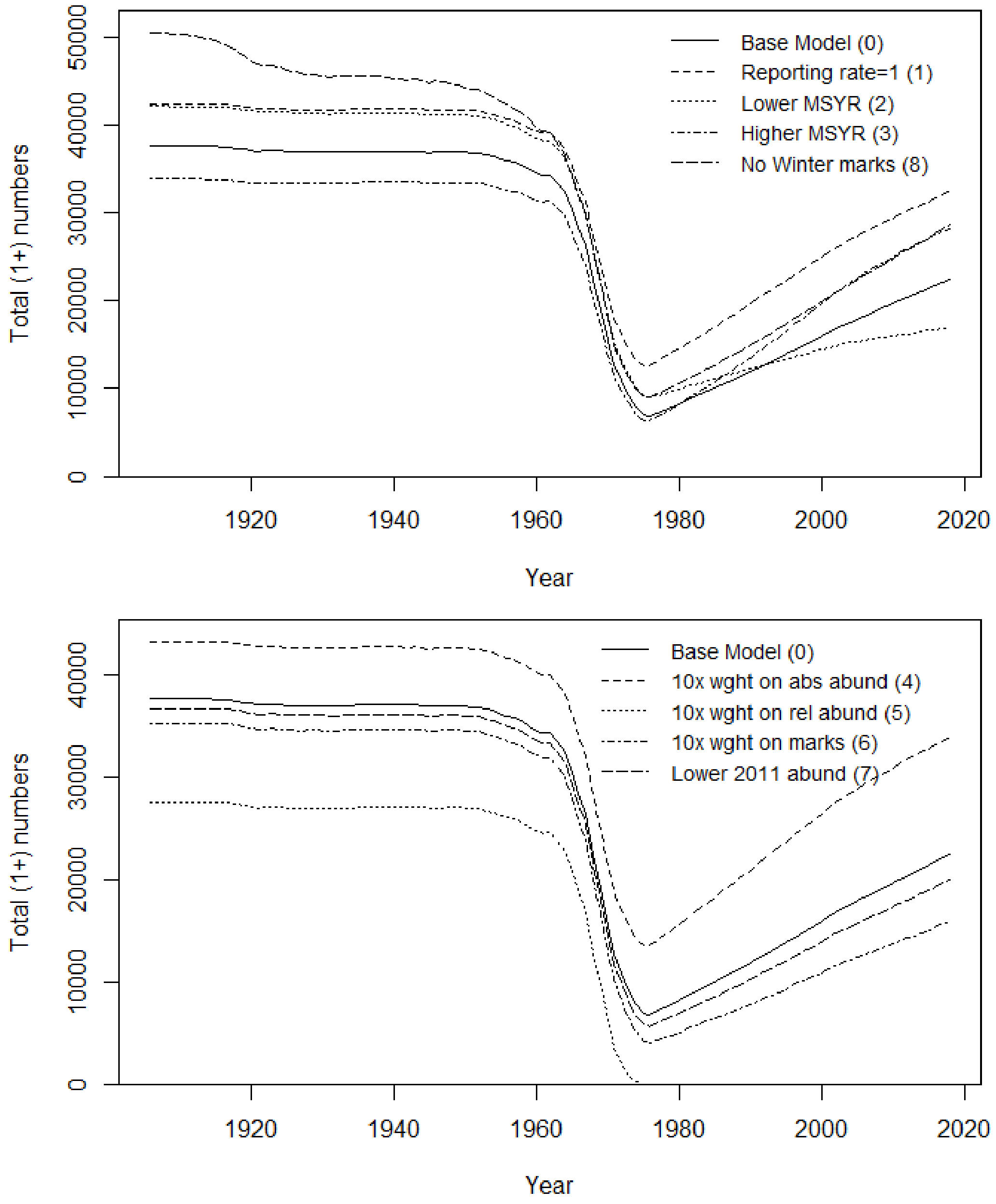


Figure 10. Time-trajectories of total (1+) numbers for the 3-stock model. Results are shown for the base-case model and sensitivity tests 1-8.