Application of RMP/AWMP-lite to North Atlantic fin Whales

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ABSTRACT
RMP/AWMP-lite is a platform written in R which implements an MSE framework for evaluating the performance of catch and strike limit algorithms. This framework can be used to evaluate management schemes where multiple stocks of whales are exploited by a combination of commercial and aboriginal whaling operations. The operating models can be conditioned to the actual data to allow an evaluation of whether stock structure assumptions and other hypotheses are comparable with the available data. The framework is applied for illustrative purposes to fin whales in the North Atlantic.

KEYWORDS: COMMERICAL WHALING; ABORIGINAL WHALING; MANAGEMENT STARTEGY EVALUATION; NORTH ATLANTIC; FIN WHALES

INTRODUCTION

The management strategies (or management procedures) applied by the International Whaling Commission to set catch (or strike) limits for commercial and aboriginal whaling have been selected by means of simulation (the management strategy evaluation approach). This process involves a number of steps (Punt and Donovan, 2007):

- Identification of management goals (and performance measures to quantify the extent to which those goals have been achieved).
- Selection of hypotheses which pertain to the situation at hand, and development of operating models which represent those hypotheses. The set of operating models form the 'trials structure'.
- Conditioning of the operating models on the available data (and possible rejection of hypotheses [or combinations of hypotheses] which are not compatible with the data).
- Identification of candidate management strategies.
- Simulation of the performance of the management strategies by projecting the operating model forward in which catch limits are set using the management strategy.

The step in the process which can (and usually does) take the longest is the development and conditioning of operating models because the operating models are generally age-, sex- and spatially-structured, which complicates coding and adds to run times. The RMP/AWMP-lite framework (Punt, 2007, 2012) involves developing operating models using a general modelling structure (in this paper written in the freely accessible statistical environment R) to allow rapid evaluation of whether hypotheses are likely comparable with the data and the likely performance of candidate management strategies.

This paper outlines the most recent (May 2013) version of RMP/AWMP-lite which extends previous versions by (a) allowing for a more general production function, (b) allowing MSYR to be estimated, (c) using tagging data for parameter estimation, and (d) allowing the population to be initialized a year inother than the first year with catches.

MODEL DESCRIPTION

Basic Population Dynamics

The population dynamics are based on the Pella-Tomlinson model, i.e.:

$$N_{t+1}^{i} = N_{t}^{i} + r^{i} N_{t}^{i} (1 - [N_{t}^{i} / K^{i}]^{z^{i}}) - C_{t}^{i} \tag{1}$$

where N_t^i is the number of stock i animals at the start of year t;
K^i is the carrying capacity of stock i;

r^i is the intrinsic rate of growth for stock *i*;

z^i is the degree of compensation (selected so that $MSYL^i$ equals a pre-specified value); and

C_t^i is the catch during year *t* from stock *i*.

The number of animals in stock *i* at the start of the first year of the model forecast (y_{init}) is $N^i_{y_{\text{init}}} = \delta^i K^i$.

The catch by stock is determined by apportioning the catches by spatio-temporal stratum, taking account of mixing (i.e. exposure to harvesting) matrices, according to:

$$C_t^i = \sum_s \sum_A C_t^{A,s} \frac{X^{A,s,i} N_t^i}{\sum_j X^{A,s,j} N_t^j} \tag{2}$$

where $C_t^{A,s}$ is the catch in spatial stratum *A* during season *s* of year *t*; and

$X^{A,s,i}$ is the relative exposure of stock *i* to harvesting in area *A* during season *s* (i.e., the proportion of stock *i* animals in area *A* during season *s*).

Note that Equation 2 implies that the harvest during the year is sufficiently small that there is no need to remove catches in seasons 1, 2, ..,*s*-1 before determining the split among stocks of the catch during season *s*. The $X^{A,s,i}$ (over all *A*, *s*, and *i*) constitute the elements of a mixing matrix.

Permanent movement among stocks (i.e., "dispersal") can be modelled under the assumption of no net dispersal at carrying capacity, i.e.:

$$N_{t+1}^i \leftarrow N_{t+1}^i (1-\lambda) + \lambda \frac{K^i}{K^j} N_{t+1}^j \tag{3}$$

where λ is the dispersal rate between stocks *i* and *j*.

Parameter estimation

The values for the parameters of the population dynamics model are: a) the intrinsic rate of growth by stock, b) the stock-specific carrying capacities, c) the ratio of the number of animals at the start of the modelled period to carrying capacity (if treated as estimable), d) the dispersal rates, e) the reporting rate for tagged animals, and e) the values for the entries of the mixing matrices. The fourth of these quantities must be pre-specified by the user while the values for the remaining parameters can either be pre-specified or estimated by minimizing an objective function.

The abundance estimates can either be "best estimates" or minima. The contribution of the "best" estimates of abundance to the objective function is:

$$L_1 = \sum_A \sum_t \sum_s \frac{\left(\ell n \hat{B}_t^{A,s} - \ell n B_t^{A,s,\text{obs}}\right)^2}{2\sigma_t^{A,s}} \tag{4}$$

where $B_t^{A,s,\text{obs}}$ is the abundance estimate for spatial stratum *A* during season *s* and year *t*[1];

$\hat{B}_t^{A,s}$ is the model-estimate of the abundance corresponding to $B_t^{A,s,\text{obs}}$:

$$\hat{B}_t^{A,s} = \sum_i X^{A,s,i} N_t^i \tag{5}$$

$\sigma_t^{A,s}$ is the standard error of the logarithm of $B_t^{A,s,\text{obs}}$.

The "minimum" estimates act as a penalty term. If a model-estimate is smaller than a "minimum" estimate, a large penalty (100 log-likelihood units) is added to the objective function.

The contribution of the mixing proportions to the objective function is based on the assumption that the mixing proportions are normally distributed, i.e.:

[1] Abundance estimates can pertain to the average over seasons – the model prediction is then the corresponding average.

$$L_2 = \sum_A \sum_t \sum_s \frac{(\hat{p}_t^{A,s} - p_t^{A,s,\mathrm{obs}})^2}{2\tau_t^{A,s}} \tag{6}$$

where $p_t^{A,s,\mathrm{obs}}$ is the mixing proportion (proportion of stock 1) for spatial stratum *A* during season *s* of year *t*;

$\hat{p}_t^{A,s}$ is the model-estimate corresponding to $p_t^{A,s,\mathrm{obs}}$:

$$\hat{p}_t^{A,s} = \frac{X^{A,s,1} N_t^1}{\sum_j X^{A,s,j} N_t^j} \tag{7}$$

$\tau_t^{A,s}$ is the standard error of $p_t^{A,s,\mathrm{obs}}$.

The contribution of the depletion estimates to the objective function is based on the assumption that these estimates are normally distributed with weight[2] (*w*) which is reduced as the minimization proceeds (so the best estimates of the observed and model-predicted depletions match exactly):

$$L_3 = w \sum_A \sum_t (\hat{d}_t^{A,1} - d_t^{A,\mathrm{obs}})^2 \tag{8}$$

where $d_t^{A,\mathrm{obs}}$ is the pre-specified depletion for spatial stratum *A* at the start of year *t*;

$\hat{d}_t^A$ is the model-estimate corresponding to $d_t^{A,\mathrm{obs}}$:

$$\hat{d}_t^A = \frac{\sum_i X^{A,1,i} N_t^i}{\sum_j X^{A,1,j} N_{y_{\mathrm{init}}}^j} \tag{9}$$

The predicted number of tags recaptured is determined by modelling the tagged population separately from the total population. The number of tagged animals of a given stock in a given area at the start of each year is given by:

$$T_t^{A,A',i} = \sum_B X^{B,1,i} \left(T_t^{B,A',i} - R_t^{B,A',i} + \tilde{T}_t^{A'} \frac{X^{A',s,i} N_t^i}{\sum_j X^{A',s,j} N_t^j} \right) \tag{10}$$

where $T_t^{A,A',i}$ is the number of tagged animals of stock *i* originally tagged in spatial stratum *A’* in spatial stratum *A* at the start of year *i*; and

$R_t^{A,A',i}$ is the number of tagged animals of stock *i* originally tagged in spatial stratum *A’* recaptured in spatial stratum *A* during year *i*:

$$R_t^{A,A',i} = T_t^{A,A',i} \frac{\sum_s C_t^{A,s}}{\sum_j X^{A,1,j} N_t^j} \tag{11}$$

The tagging data are included in the likelihood under the assumption that the recapture process is a Poisson process[3] when expected number of tag-returns is the value from Equation 11 multiplied by a tag-reporting rate parameter (Ψ).

Projection

[2] Which could be considered to be inverse to the square of the standard error.

[3] In principle, the likelihood could be negative binomial but this would add yet another parameter which would need to estimated. Allowance is made to multiply the tagging likelihood by a weighting factor to mimic allowing for overdispersal.

The projections are deterministic (no observation error) and based the assumption that survey estimates of abundance become available on a pre-specified frequency. A removal limit for each area is set as either a catch limit from the CLA or a strike limit from a strike limit algorithm.

APPLICATION TO NA FIN WHALES

Specifications

The example application is based on the six base-case stock structure hypotheses[4] on which the *Implementation* was based (IWC, 2010a,b; Figures 1 and 2):

(I) *Four stocks with separate feeding areas*. There are four stocks with the central 'C' stock divided into 3 sub-stocks. The 'W' stock feeds in the EC and WG sub-areas, sub-stock 'C1' in the EG sub-area, sub-stock 'C2' in the WI sub-area, sub-stock 'C3' in the EI/F sub-area, the stock 'E' in the N sub-area, and stock 'S' in the Sp sub-area.

(II) *Four stocks with 'W' and 'E' feeding in the central sub-areas.* There are four stocks with the central stock divided into 3 sub-stocks. The 'W' stock feeds in sub-areas EC, WG, EG and WI, sub-stock 'C1' in sub-area EG, sub-stock 'C2' in sub-area WI, sub-stock 'C3' in sub-areas EI/F, stock 'E' in sub-areas WI, EI/F and N, and stock 'S' in sub-area Sp.

(III) *Four stocks with 'C' feeding in adjacent sub-areas*. There are four stocks with the central stock divided into 3 sub-stocks. The 'W' stock feeds in sub-areas EC and WG, sub-stock 'C1' in sub-areas EC, WG and EG, sub-stock 'C2' in sub-area WI, sub-stock 'C3' in sub-areas EI/F and N, stock 'E' stock in sub-area N, and stock 'S' in sub-area Sp.

(IV) *Four stocks without sub-stock interchange*. There are four stocks with the central stock divided into 3 sub-stocks, but there is no interchange between the sub-stocks. The 'W' stock feeds in sub-areas EC and WG; sub-stock 'C1' feeds in sub-areas EC, WG, EG and WI, sub-stock 'C2' in sub-areas EG, WI and EI/F, sub-stock 'C3' in sub-areas WI, EI/F and N, stock 'E' in sub-area N, and stock 'S' in sub-area Sp.

(V) *Four stocks with 'S' feeding in adjacent sub-areas*. There are four stocks with the central 'C' stock divided into 3 sub-stocks. The stocks/sub-stocks feed as in hypothesis I except that stock 'S' feeds in sub-areas N and EI/F in addition to sub-area Sp.

(VI) *Three stocks*. There are three stocks with the central 'C' stock divided into 3 sub-stocks. The 'W', 'C1', 'C2' and 'S' stock/sub-stocks feed as in hypothesis II. Sub-stock 'C3' feeds in sub-areas EI/F and N.

The stocks are assumed to have been at their unfished levels at the start of 1885 (i.e. $y_{\rm init}$=1885; $\delta^i = 1$) and three scenarios related to MSYR are considered (MSYR=1%, 2.5% and 4%). Dispersal between the C1, C2 and C3 stocks is estimated for stock structure hypotheses I, II, III, V, and VI. Table 1 lists the specifications for the mixing matrices. Following IWC (2010b), the tag-reporting rate is assumed to depend on MSYR (0.8 for MSYR=1%, 0.6 for MSYR=2.5%, and 0.5 for MSYR=4%). The operating model for North Atlantic fin whales has an annual time-step.

The data used to estimate the parameters of the operating model are the estimates of abundance (Table 2) and the tagging data. The contribution of the tagging data to the likelihood function is downweighted by 25% relative to the Poisson distribution to account (to some extent) for overdispersion.

Results

Figure 3 shows the fit of the operating model to the abundance estimates. As expected from the fits of the operating model to these data in the actual *Implementation*, the results are not markedly sensitive to the form of stock structure hypothesis underlying the trial. Eastern Canada is the only case where there is a noteworthy lack of fit to the abundance estimates. Trials in which the tagging data are excluded (results not shown) are able to mimic this abundance estimate, suggesting a conflict between the tagging and abundance data. The example application uses all of the tagging data whereas the *Implementation* trials accounted for "early" recapture which may explain the lack of fit in this case. Trials with MSYR=1% generally lead to higher initial population sizes.

Even though they are downweighted, the tagging data nevertheless make a large contribution to the objective function than the abundance data.

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[4] A seventh stock structure hypothesis was identified during the *Implementation*, but it was assigned "low plausibility" by the Scientific Committee and was not considered further.

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Table 1. The mixing matrices. The γs indicate that the entry concerned is to be estimated during the conditioning process.

	Feeding Area	Stock W	Sub -stock C1	Sub-stock C2	Sub-stock C3	Stock E	Stock S
HYPOTHESIS I	EC	γ_1	-	-	-	-	-
	WG	$1-\gamma_1$	-	-	-	-	-
	EG	-	1	-	-	-	-
	WI	-	-	1	-	-	-
	EI,F	-	-	-	1	-	-
	N	-	-	-	-	1	-
	SP	-	-	-	-	-	1
HYPOTHESIS II	EC	$0.88\gamma_1$	-	-	-	-	-
	WG	$0.88(1-\gamma_1)$	-	-	-	-	-
	EG	0.10	1	-	-	-	-
	WI	0.02	-	1	-	0.02	-
	EI,F	-	-	-	1	0.10	-
	N	-	-	-	-	0.88	-
	SP	-	-	-	-	-	1
HYPOTHESIS III	EC	γ_1	$0.10\gamma_1$	-	-	-	-
	WG	$1-\gamma_1$	$0.10(1-\gamma_1)$	-	-	-	-
	EG	-	0.90	-	-	-	-
	WI	-	-	1	-	-	-
	EI,F	-	-	-	0.90	-	-
	N	-	-	-	0.10	1	-
	SP	-	-	-	-	-	1
HYPOTHESIS IV	EC	γ_1	$0.05\gamma_1$	-	-	-	-
	WG	$1-\gamma_1$	$0.05(1-\gamma_1)$	-	-	-	-
	EG	-	0.90	0.05	-	-	-
	WI	-	0.05	0.90	0.05	-	-
	EI,F	-	-	0.05	0.90	-	-
	N	-	-	-	0.05	1	-
	SP	-	-	-	-	-	1
HYPOTHESIS V	EC	γ_1	-	-	-	-	-
	WG	$1-\gamma_1$	-	-	-	-	-
	EG	-	1	-	-	-	-
	WI	-	-	1	-	-	-
	EI,F	-	-	-	1	-	0.02
	N	-	-	-	-	1	0.10
	SP	-	-	-	-	-	0.88
HYPOTHESIS VI	EC	$0.88\gamma_1$	-	-	-	n/a	-
	WG	$0.88(1-\gamma_1)$	-	-	-	n/a	-
	EG	0.10	1	-	-	n/a	-
	WI	0.02	-	1	-	n/a	-
	EI,F	-	-	-	γ_2	n/a	-
	N	-	-	-	$1-\gamma_2$	n/a	-
	SP	-	-	-	-	n/a	1

Table 2. The abundance estimates used in the example application

Sub-Area / stratum	Year	Estimate	CV
1 (EC)	2007	10105	0.4
2 (WG)	1987	1100	0.566
2 (WG)	2005	3218	0.587
2 (WG)	2007	4656	0.61
3 (EG)	1988	5269	0.334
3 (EG)	1995	8412	0.381
3 (EG)	2001	11706	0.316
3 (EG)	2007	12215	0.32
4 (WI)	1988	4243	0.229
4 (WI)	1995	6800	0.218
4 (WI)	2001	6565	0.194
4 (WI)	2007	8118	0.26
5 (EI+F)	1987	5261	0.707
5 (EI+F)	1995	6647	0.711
5 (EI+F)	2001	7490	0.698
5 (EI+F)	2007	1613	0.7
6 (N)	1995	3964	0.21
6 (N)	1999	3749	0.24
7 (SP)	1989	17355	0.265

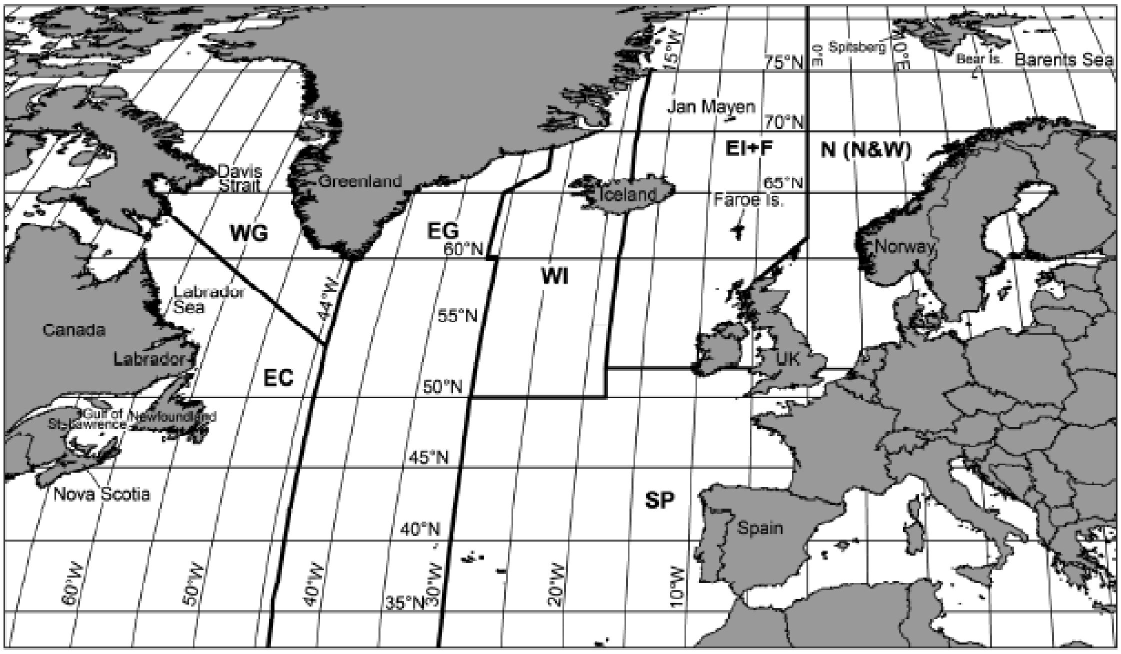


Figure 1. Map of the North Atlantic showing the sub-areas (spatial strata) defined for the North Atlantic fin whales. Reproduced from IWC (2010a).

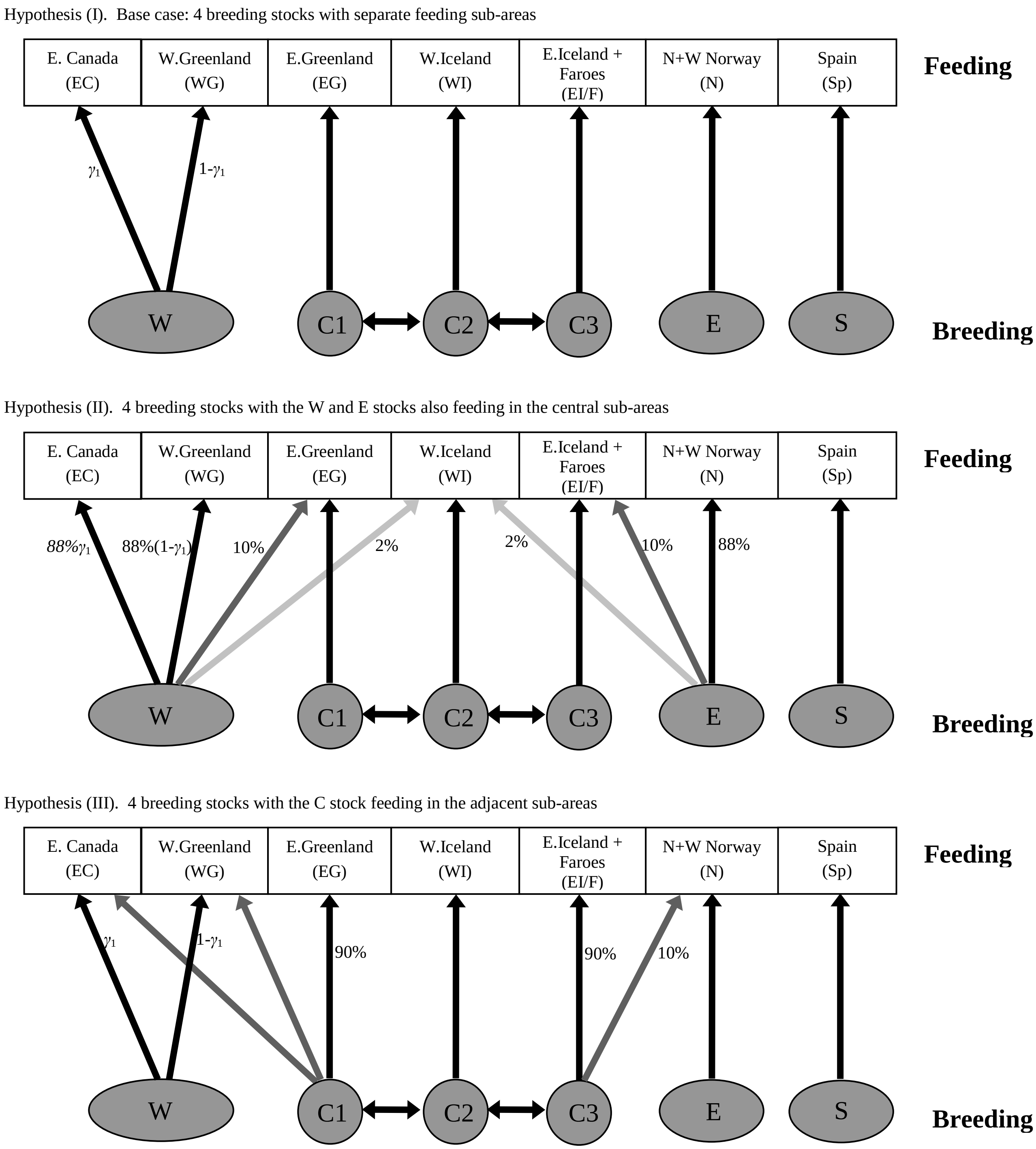
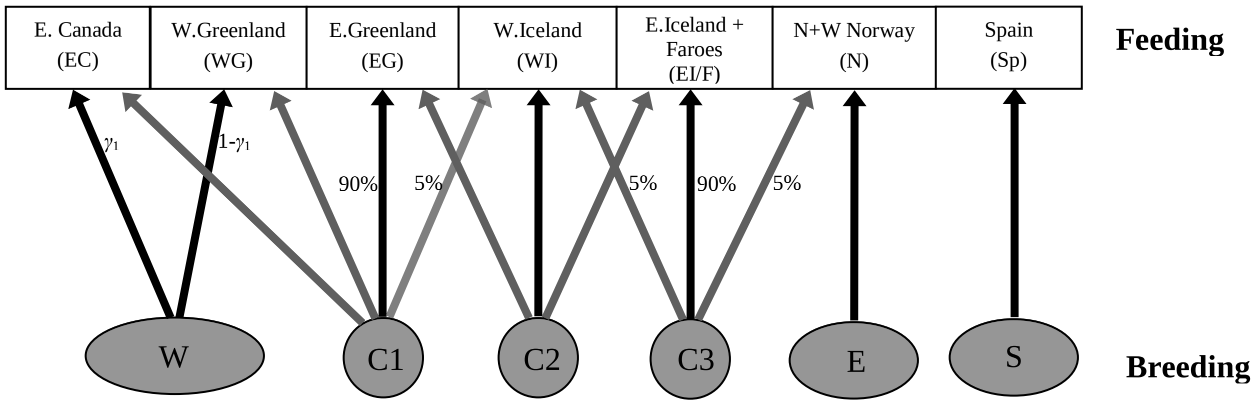
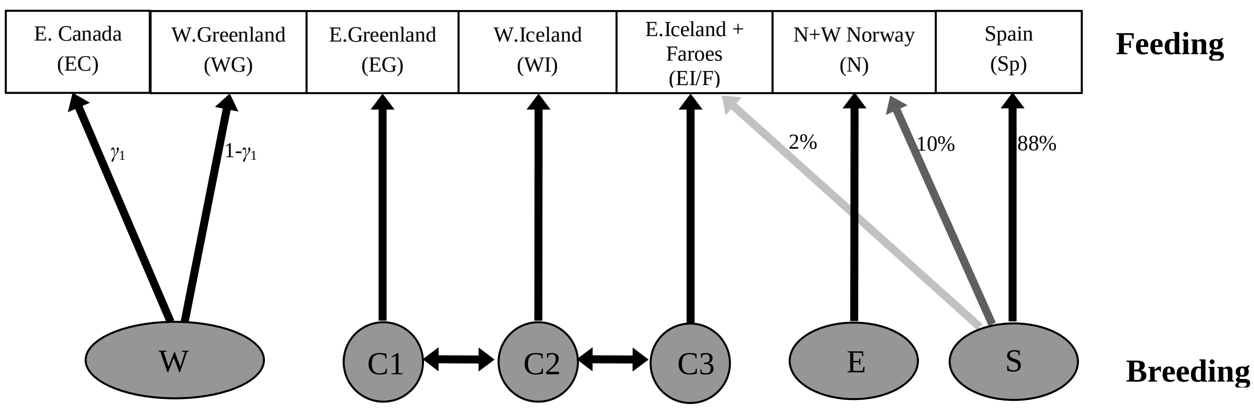


Figure 2. Stock structure hypotheses for North Atlantic Fin whales. Reproduced from IWC (2010a).

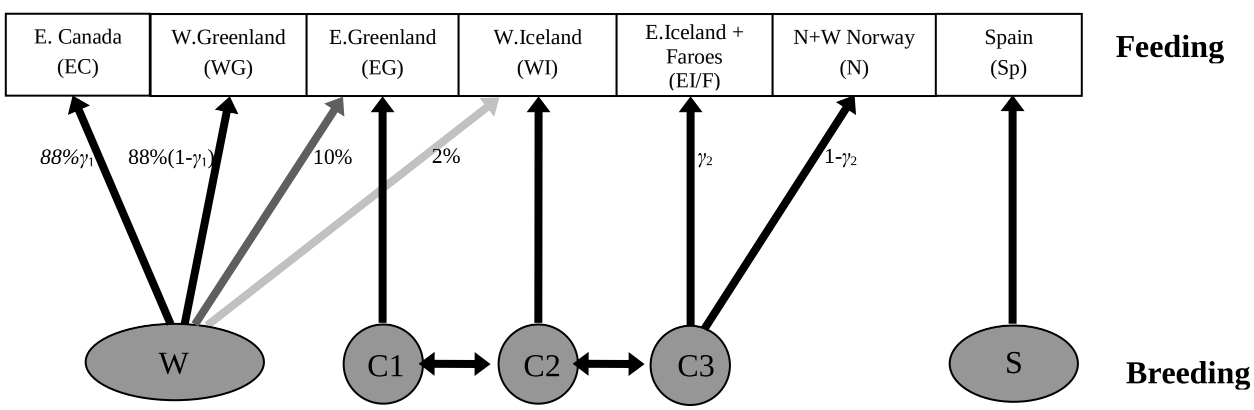
Hypothesis (IV). 4 breeding stocks but without interchange between the C sub-stocks



Hypothesis (V). 4 breeding stocks with the S stock feeding in the two adjacent sub-areas



Hypothesis (VI). 3 breeding stocks



(Figure 2 Continued)

Stock Structure Hypothesis I

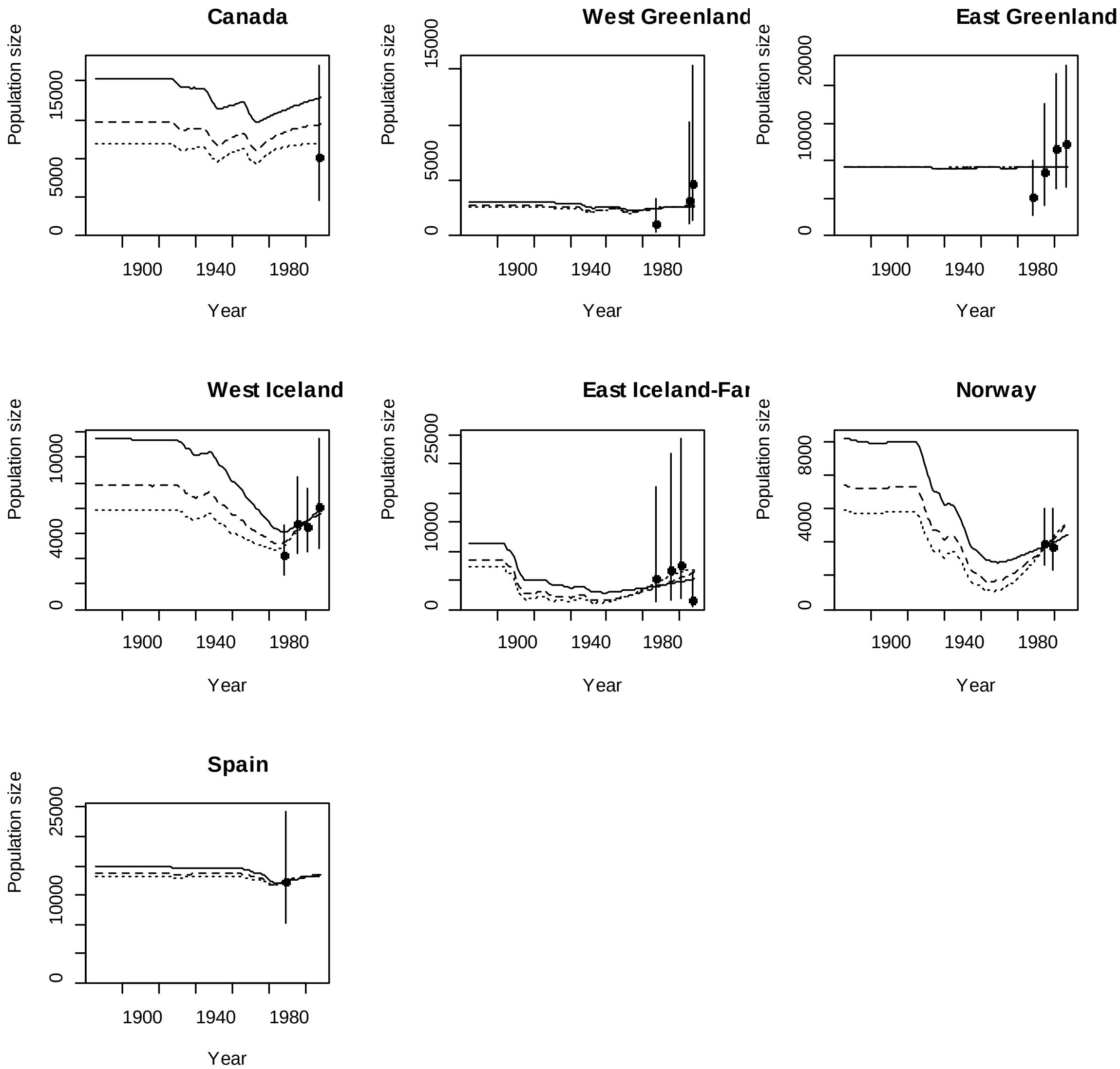
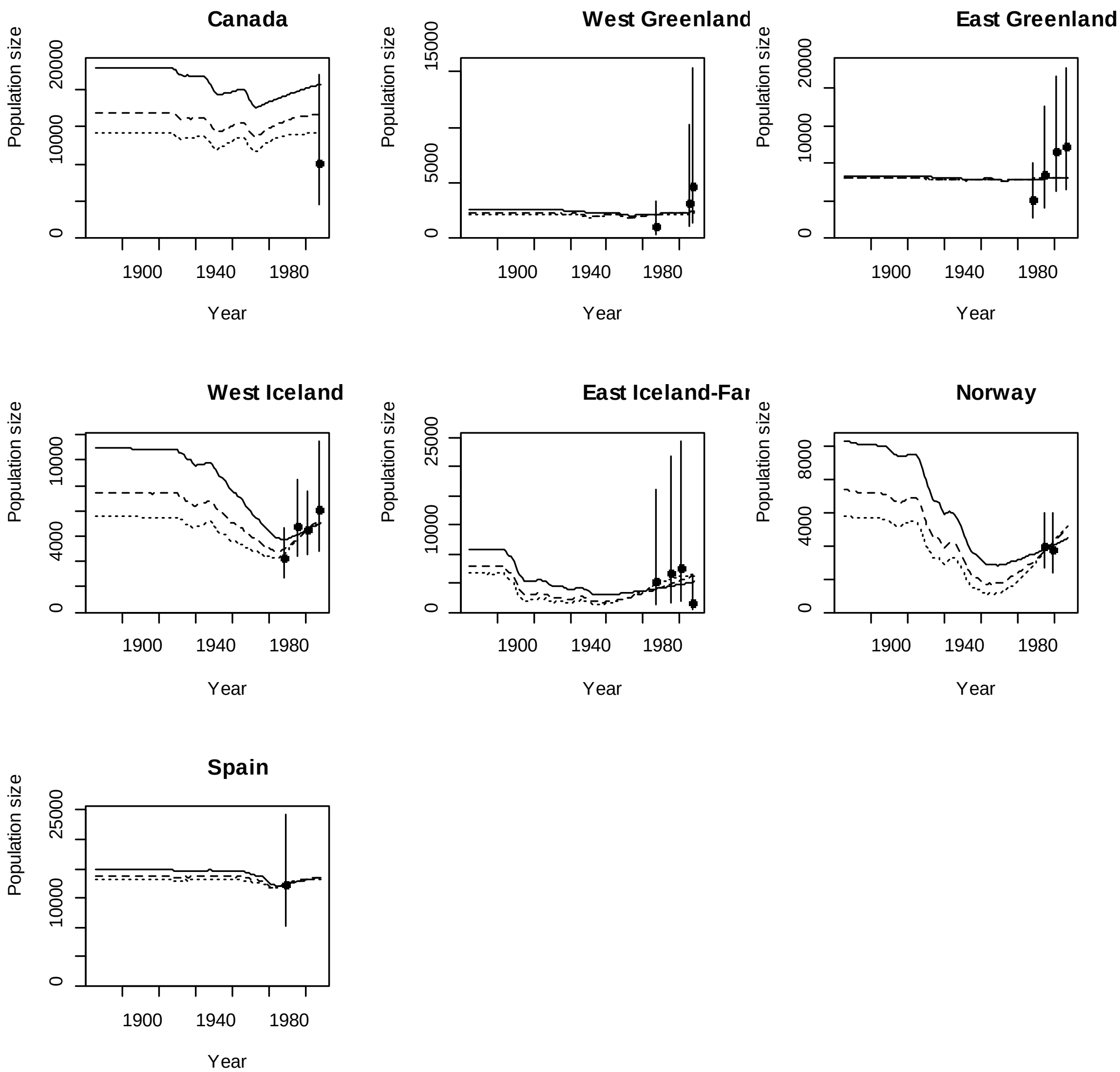


Figure 3. Abundance estimates and the associated model fits from RMP/AWMP-lite. The solid, dashed and dotted lines show results shown for MSYR 1=%, 2.5% and 4%.

Stock Structure Hypothesis II



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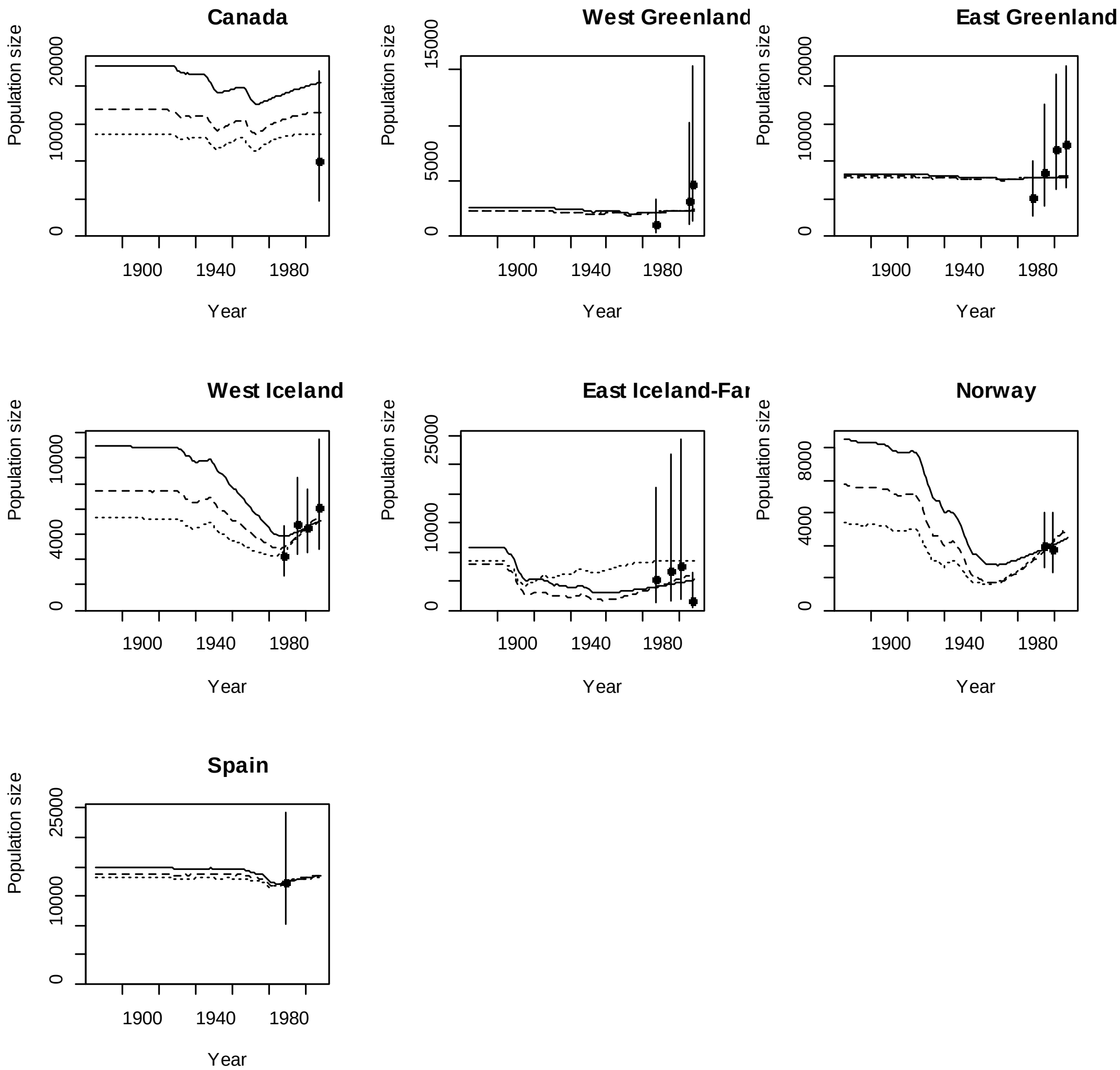
Stock Structure Hypothesis III



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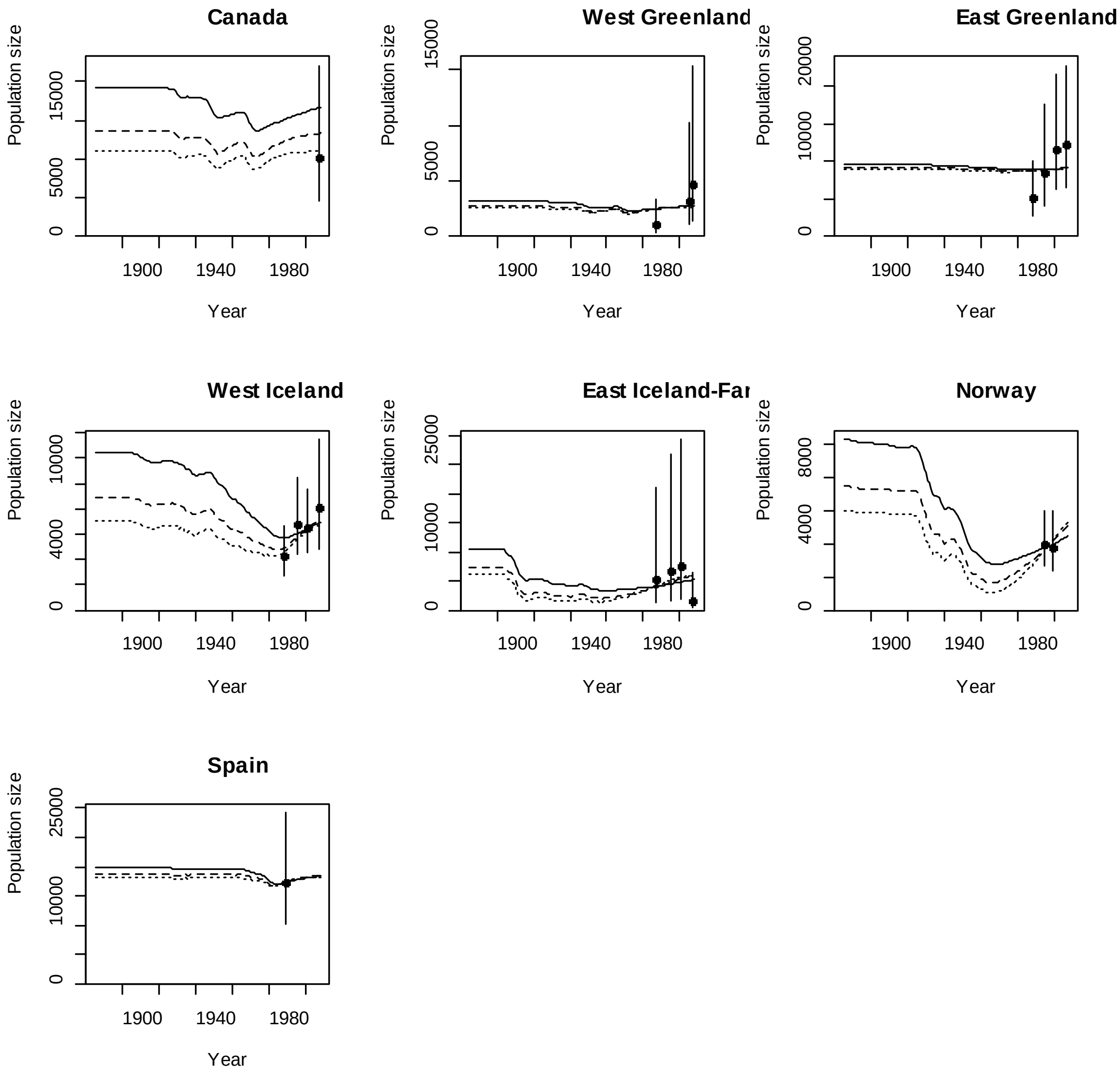
Stock Structure Hypothesis IV



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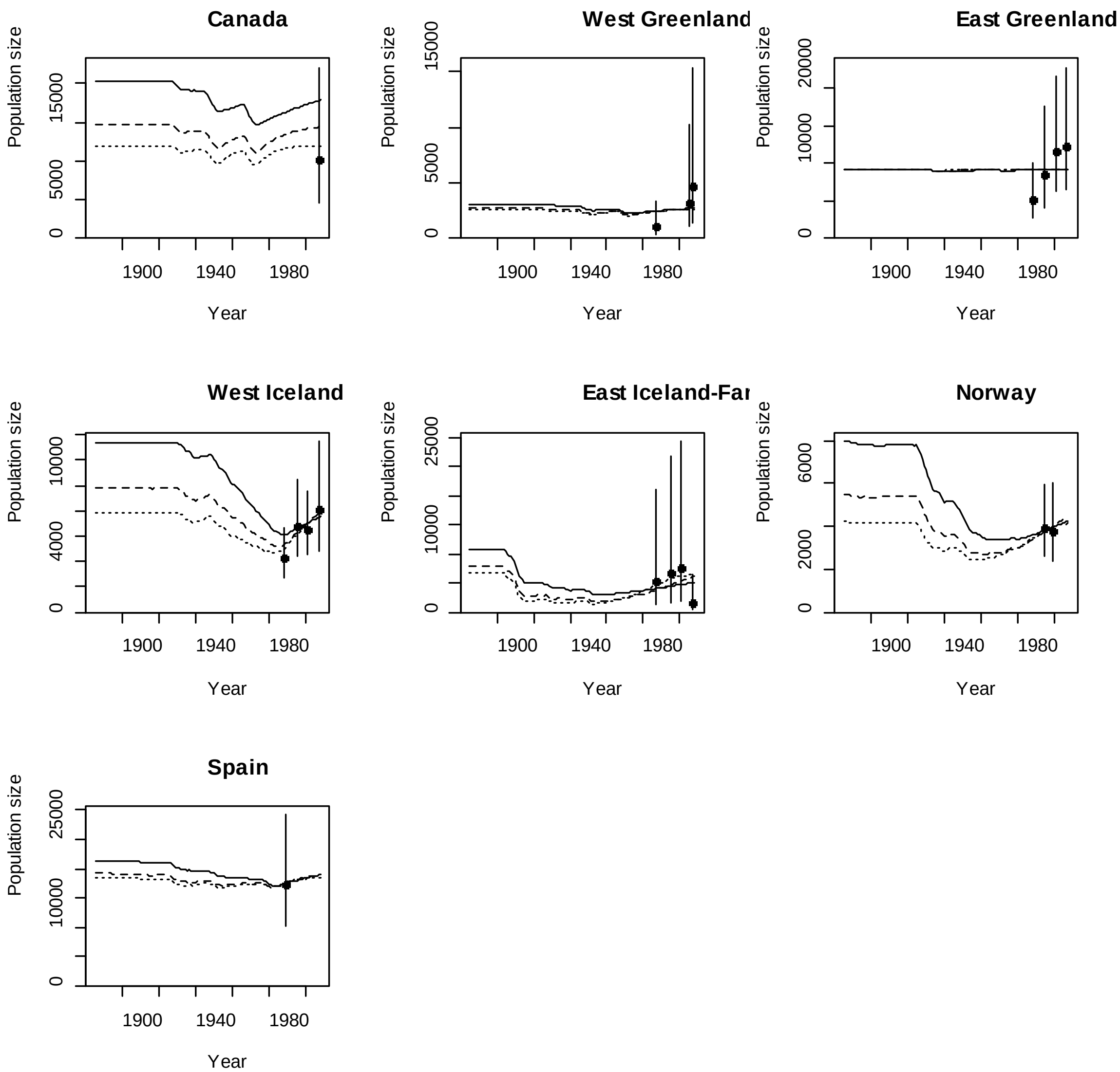
Stock Structure Hypothesis V



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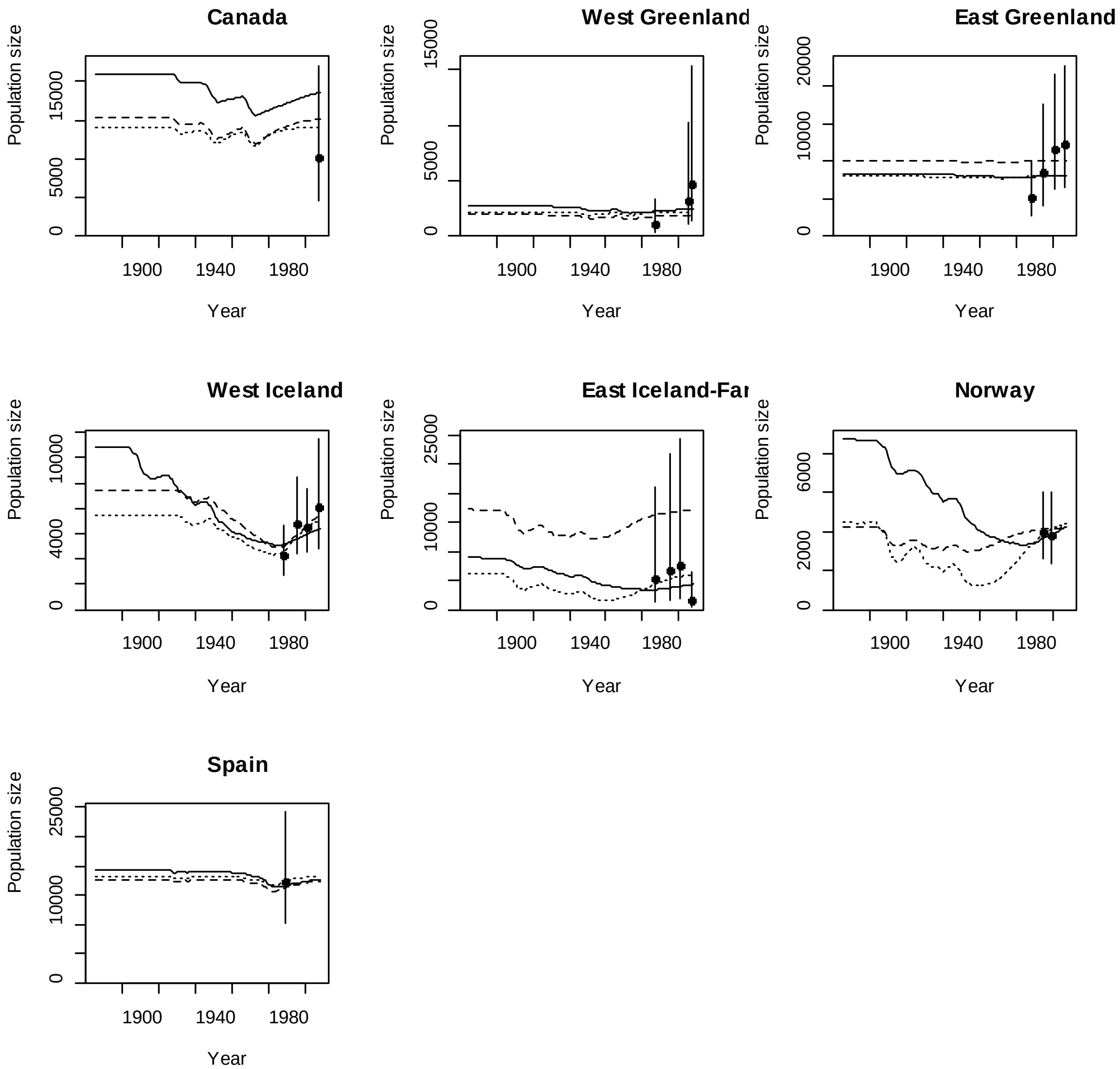
Stock Structure Hypothesis VI



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