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Grym assessment for Subarea 48.1 Euphausia superba populations

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Introduction

WG-SAM-2021 and WG-EMM-2021 reviewed available information for krill assessment simulations in Subarea 48.1 using the Grym. Whilst no agreement on parameters was achieved at WG-SAM-2021, the Working Group agreed that an ensemble approach using multiple parameter value combinations could be used (WG-SAM-2021, paras 3.21-3.22.)

WG-EMM-2021 provided initial parameters for the assessment simulations noting that alternate parameters could be tested to compare (WG-EMM-2021, paras 2.32-2.33 and Table 1).

Here we present the results of model ensembles for values either provided directly to the CCAMLR e-group on 'GYM/Grym assessment model development', or calculated based upon data submitted to the e-group. Code and outputs of the models are available on github (https://github.com/ccamlr/Grym_Base_Case /tree/Simulations).

Parameters

Following on from the model parameters for the GYM assessment discussed by WG-EMM-2021 (Table 1, replicated here in Appendix 1), alternate values for three groups of parameters were proposed by the e-group members: namely the parameters for the proportional recruitment, weight-at-length relationship, and size at maturity.

Proportional Recruitment

Six scenarios of proportional recruitment were tested (Table 1). These consist of the initial values discussed by WG-EMM-2021 (Appendix 1), and three estimates using catch-weighted, strata-scaled survey proportions based on 1) the US-AMLR time series data, 2) the Atlántida 2020 survey, and 3) both datasets combined. Two other estimates were provided which use catch-weighted haul-by-haul proportions with cutoffs at either 36mm or 40mm based on the US-AMLR time series.

For each of these scenarios, recruitment series were calculated following the method described in Pavez et al., (2021). Estimates for the Atlántida 2020 survey were treated slightly differently in that the number of surveys was set to 3, corresponding to the number of strata in the survey, as the proportional recruitment model is unable to generate recruitment series from a single survey.

Sensitivity runs exploring the impact of varying recruitment SD (0.1 to 0.4) were also conducted for three values of mean recruitment (0.35, 0.4 and 0.5), with all other parameter values fixed (Appendix 2).

Size at maturity

Two alternative estimates for size at maturity were tested in simulations. Initial values from WG-EMM-2021 (Appendix 1), and those estimated by fitting a Bayesian model to estimate the width and slope of a ramp-shaped maturity ogive as required by the Grym based on US-AMLR data provided to the CCAMLR E-group (Appendix 3). This maturity ogive showed little overlap with the ogive used in previous assessments, and indicated that krill in 48.1 mature at a larger size than previously assumed (Figure 1, Table, 2)

Weight-at-Length

Three weight-at-length estimates were evaluated, the initial value based on the CCAMLR 2000 synoptic survey (SC-CAMLR, 2000) and two estimates from the Atlántida survey conducted in 2020. For the latter data, weight-at-length was estimated from the entire survey (2021a) and restricted to krill caught within Subarea 48.1 (2021b, Figure 2, Table 3).

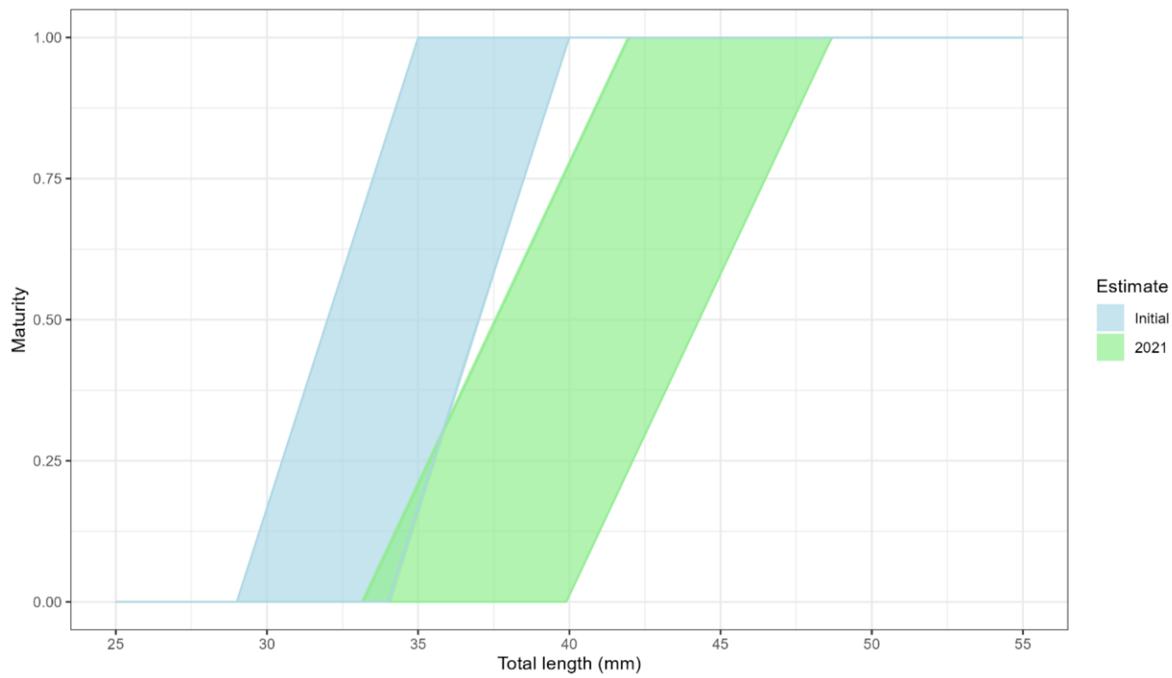

Figure 1: Size at maturity estimates used in the Grym assessments for *Euphausia superba* in CCAMLR Subarea 48.1. 'Initial' ogive is based on WG-EMM-2010 (Appendix 1), '2021' is the re-estimated ogive based on US-AMLR data.

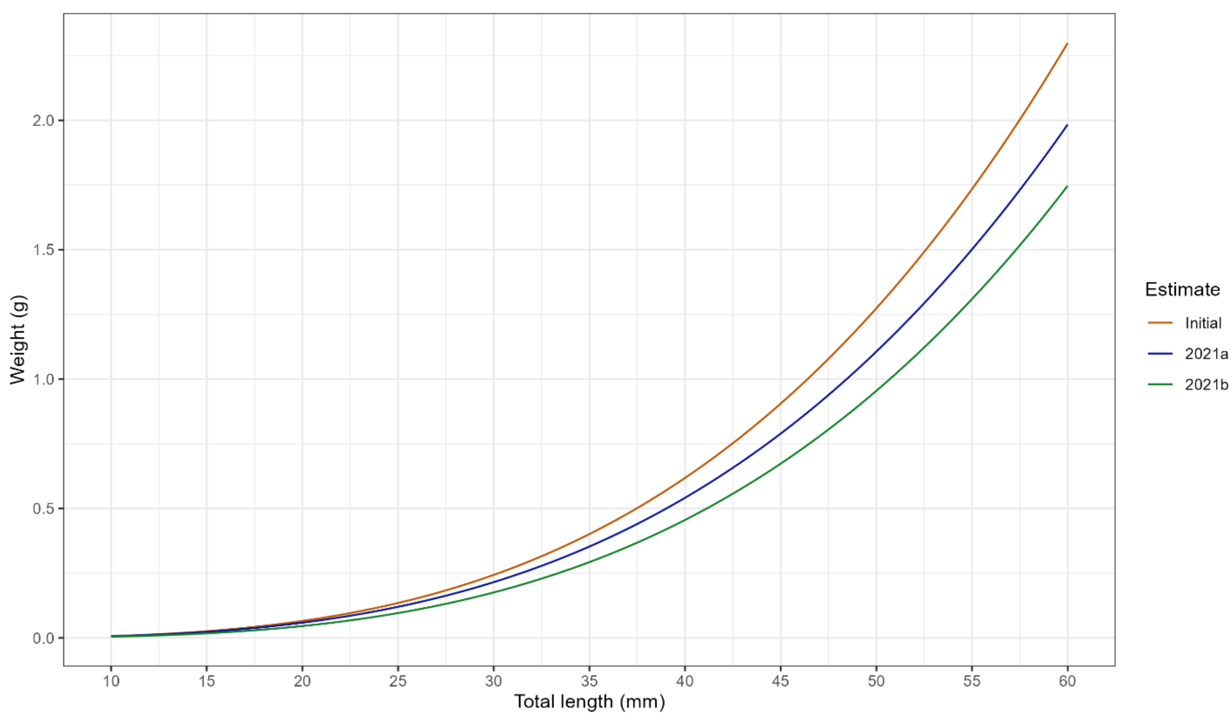

Figure 2: Weight-at-length relationship estimates used in the Grym assessment for *Euphausia superba* within CCAMLR Subarea 48.1. Estimates calculated based on CCAMLR 2000 synoptic survey (Initial), the entire Atlántida survey (2021a) and Atlántida survey restricted to 48.1 (2021b).

Table 1: Proportional recruitment estimates used for different scenarios within the *Euphausia superba* assessment simulations. *R2 indicates recruitment calculated based on a mixture model fitted to length frequencies rather than a fixed length cutoff.

Recruitment scenario	Years of data	Length cutoff (mm)	R. mean	R. sd	N. surveys	Independent Unit	Time period
(1) Initial values	1977-1993	R2*	0.5570	0.126	17	Survey	Unknown
(2) US-AMLR summer	1992-2011	36	0.4079	0.3118	20	Survey	Day only
(3) US-AMLR summer with Atlántida survey	1992-2011, 2020	36	0.4089	0.3040	21	Survey	Day only
(4) Atlántida survey	2020	36	0.4281	0.1112	3	Survey	Day only
(5) US-AMLR summer haul-by-haul	1991-2011	36	0.2520	0.3380	21	Haul	Day and night
(6) US-AMLR summer haul-by-haul	1991-2011	40	0.3630	0.3700	21	Haul	Day and night

Table 2: Size at maturity parameter values used in the Grym assessment for *Euphausia superba* within CCAMLR Subarea 48.1. 'Initial' ogive is based on WG-EMM-2010 (Appendix 1), '2021' is the re-estimated ogive based on US-AMLR data.

Source	Min length 50% mature (mm)	Max length 50% mature (mm)	Range over which maturity occurs (mm)
Initial	32.0	37.0	6.0
2021	37.6	44.3	8.8

Table 3: Weight-at-length parameter values used in the Grym assessment for *Euphausia superba* within CCAMLR Subarea 48.1.

Parameter	CCAMLR 2000 synoptic survey	Atlántida survey (all)	Atlántida survey restricted to 48.1
Weight-length parameter - A	2.236E-06	4.0E-06	4.0E-06
Weight-length parameter - B	3.314	3.239	3.203

Natural mortality and recruitment

The model outlined in de la Mare (1994a) presupposes that surveys will be treated as independent units. Comparing the sets of the recruitment parameters (Table 4, Figures 3 & 4), the four recruitment estimates which considered surveys as the independent unit contained >62.9% overlap with the expected natural mortality range (0.5-1.1, Appendix 1). Of these, the initial proportional recruitment estimates (R. mean=0.552, R.sd=0.126) had the largest overlap with 99.3% of mortality estimates within the expected range. Conversely, the two recruitment estimates which used haul-by-haul as the independent unit had 2.4%, and 0% overlap with the expected mortality range.

Table 4: Summary statistics of natural mortality for six combinations of mean and standard deviation for proportional recruitment using an inverse-beta distribution.

Recruitment scenario	R.mean	R.sd	M mean	M min	M max	M prop in range
(1) Initial values	0.5570	0.1260	0.854	0.514	1.355	0.993
(2) US-AMLR summer	0.4080	0.3118	0.544	0.001	0.992	0.629
(3) US-AMLR summer with Atlántida survey	0.4089	0.3040	0.564	0.039	1.169	0.684
(4) Atlántida survey	0.4281	0.1112	0.574	0.000	1.830	0.645
(5) US-AMLR summer haul-by-haul	0.2520	0.3380	0.099	0.000	0.544	0.000
(6) US-AMLR summer haul-by-haul	0.3630	0.3700	0.215	0.000	0.820	0.024

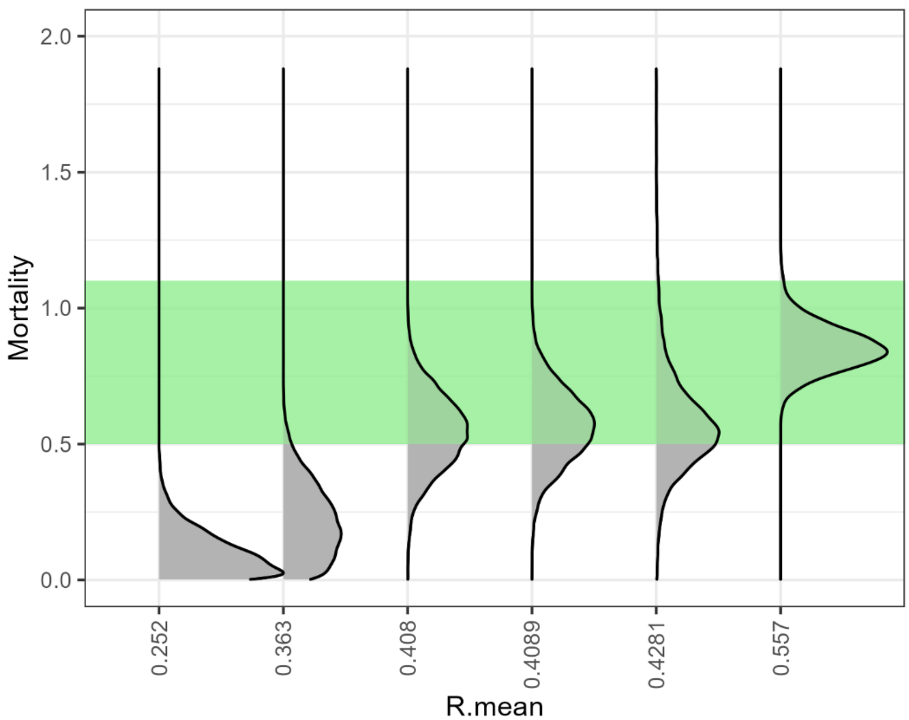

Figure 3: Distribution of natural mortality estimates for six combinations of mean and standard deviation for proportional recruitment using an inverse-beta distribution. The expected mortality range 0.5-1.1 (Appendix 1) is marked in green.

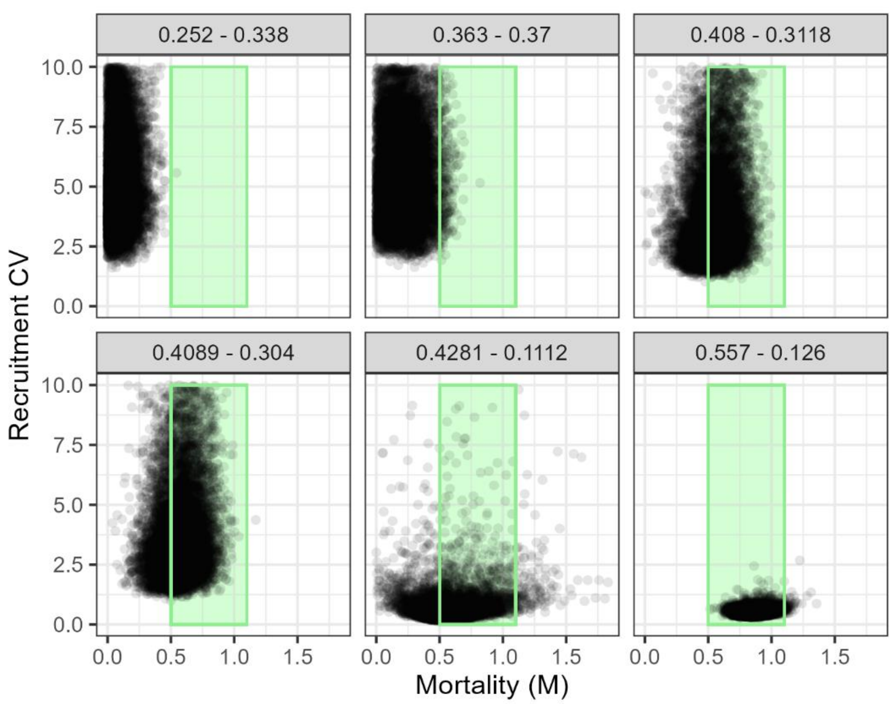

Figure 4: Estimated natural mortality values and recruitment CV for six combinations of mean and standard deviation for proportional recruitment using an inverse-beta distribution. The expected mortality range 0.5-1.1 (Appendix 1) is marked in green.

Assessment simulation outputs

Outputs from the 36 assessment simulations are presented in Table 4. Recruitment parameters were most influential in determining gamma estimates. All evaluated parameter combinations using the two recruitment scenarios with an R.sd smaller than 0.13 (i.e. (1) Initial values and (4) Atlántida survey) resulted in gamma values between 7.0% - 11.4% selecting the 75% escapement rule as the lower of the two decision rules (Table 5, Appendix 4, Figures 3-8). The recruitment scenarios (2) US-AMLR and (3) US-AMLR and Atlántida, with R.mean of around 0.41 and R.sd of around 0.31, resulted in gamma estimates <1.4%, determined by the smaller gamma satisfying the depletion rule.

Both recruitment scenarios (5) and (6) based on haul-by-haul US-AMLR data with a length cutoff of 36 mm and 40mm with R.mean between 0.25 - 0.36 and R.sd of over 0.33 resulted in gammas of 0, again determined by the gamma satisfying the depletion rule. This results was supported by the conducted sensitivity runs with variable combinations of R.mean and R.sd (Appendix 2). The combination of R.mean and R.sd was important in determining the likelihood that the depletion rule was triggered, with e.g. an R.sd of 0.37 or greater resulting in gammas of 0 even when R.mean was as large as 0.5.

Within a recruitment group, scenarios using the 2021 estimated maturity curve estimated a slightly lower value for gamma that satisfied the CCAMLR decision rules than scenarios using the original maturity estimate. The choice of weight-at-length relationship had little impact on the estimated gamma values.

Table 5: Projected gammas for CCAMLR decision rules under various scenarios. Gamma 1 is the value which satisfies the depletion rule, Gamma 2 is the value which satisfies the 75% escapement rule. Lowest gamma is bold.

Scenarios	Recruitment	Maturity	Length-weight	Mean proportional recruitment	SD of proportional recruitment	N. surveys	Min length, 50% mature (mm)	Max length, 50% mature (mm)	Range over which maturity occurs	Weight-length parameter - A (g)	Weight-length parameter - B	Gamma 1	Gamma 2	Gamma to use
1	1: Initial values	Initial	2000 Synoptic	0.5570	0.126	17	32.0	37.0	6.0	2.236E-06	3.314	0.1286	**0.1110**	2
2	1: Initial values	Initial	Atlántida all	0.5570	0.126	17	32.0	37.0	6.0	4.0E-06	3.239	0.1291	**0.1139**	2
3	1: Initial values	Initial	Atlántida 48.1	0.5570	0.126	17	32.0	37.0	6.0	4.0E-06	3.203	0.1310	**0.1097**	2
4	1: Initial values	US-AMLR-Data	2000 Synoptic	0.5570	0.126	17	37.6	44.3	8.8	2.236E-06	3.314	0.1034	**0.0888**	2
5	1: Initial values	US-AMLR-Data	Atlántida all	0.5570	0.126	17	37.6	44.3	8.8	4.0E-06	3.239	0.1044	**0.0882**	2
6	1: Initial values	US-AMLR-Data	Atlántida 48.1	0.5570	0.126	17	37.6	44.3	8.8	4.0E-06	3.203	0.1030	**0.0899**	2
7	2: US-AMLR	Initial	2000 Synoptic	0.4080	0.3118	20	32.0	37.0	6.0	2.236E-06	3.314	**0.0088**	0.0485	1
8	2: US-AMLR	Initial	Atlántida all	0.4080	0.3118	20	32.0	37.0	6.0	4.0E-06	3.239	**0.0085**	0.0514	1
9	2: US-AMLR	Initial	Atlántida 48.1	0.4080	0.3118	20	32.0	37.0	6.0	4.0E-06	3.203	**0.0089**	0.0511	1
10	2: US-AMLR	US-AMLR-Data	2000 Synoptic	0.4080	0.3118	20	37.6	44.3	8.8	2.236E-06	3.314	**0.0009**	0.0421	1
11	2: US-AMLR	US-AMLR-Data	Atlántida all	0.4080	0.3118	20	37.6	44.3	8.8	4.0E-06	3.239	**0.0000**	0.0414	1
12	2: US-AMLR	US-AMLR-Data	Atlántida 48.1	0.4080	0.3118	20	37.6	44.3	8.8	4.0E-06	3.203	**0.0000**	0.0433	1

Scenarios	Recruitment	Maturity	Length-weight	Mean proportional recruitment	SD of proportional recruitment	N. surveys	Min length, 50% mature (mm)	Max length, 50% mature (mm)	Range over which maturity occurs	Weight-length parameter - A (g)	Weight-length parameter - B	Gamma 1	Gamma 2	Gamma to use
13	3: US-AMLR & Atlántida	Initial	2000 Synoptic	0.4089	0.3040	21	32.0	37.0	6.0	2.236E-06	3.314	**0.0125**	0.0492	1
14	3: US-AMLR & Atlántida	Initial	Atlántida all	0.4089	0. 3040	21	32.0	37.0	6.0	4.0E-06	3.239	**0.0115**	0.0544	1
15	3: US-AMLR & Atlántida	Initial	Atlántida 48.1	0.4089	0. 3040	21	32.0	37.0	6.0	4.0E-06	3.203	**0.0110**	0.0528	1
16	3: US-AMLR & Atlántida	US-AMLR-Data	2000 Synoptic	0.4089	0. 3040	21	37.6	44.3	8.8	2.236E-06	3.314	**0.0021**	0.0431	1
17	3: US-AMLR & Atlántida	US-AMLR-Data	Atlántida all	0.4089	0. 3040	21	37.6	44.3	8.8	4.0E-06	3.239	**0.0023**	0.0447	1
18	3: US-AMLR & Atlántida	US-AMLR-Data	Atlántida 48.1	0.4089	0. 3040	21	37.6	44.3	8.8	4.0E-06	3.203	**0.0018**	0.0445	1
19	4: Atlántida	Initial	2000 Synoptic	0. 4281	0.1112	3	32.0	37.0	6.0	2.236E-06	3.314	0.0939	**0.0796**	2
20	4: Atlántida	Initial	Atlántida all	0. 4281	0.1112	3	32.0	37.0	6.0	4.0E-06	3.239	0.0932	**0.0796**	2
21	4: Atlántida	Initial	Atlántida 48.1	0. 4281	0.1112	3	32.0	37.0	6.0	4.0E-06	3.203	0.0942	**0.0810**	2
22	4: Atlántida	US-AMLR-Data	2000 Synoptic	0.4281	0.1112	3	37.6	44.3	8.8	2.236E-06	3.314	0.0820	**0.0685**	2
23	4: Atlántida	US-AMLR-Data	Atlántida all	0.4281	0.1112	3	37.6	44.3	8.8	4.0E-06	3.239	0.0821	**0.0706**	2
24	4: Atlántida	US-AMLR-Data	Atlántida 48.1	0.4281	0.1112	3	37.6	44.3	8.8	4.0E-06	3.203	0.0820	**0.0702**	2

Scenarios	Recruitment	Maturity	Length-weight	Mean proportional recruitment	SD of proportional recruitment	N. surveys	Min length, 50% mature (mm)	Max length, 50% mature (mm)	Range over which maturity occurs	Weight-length parameter - A (g)	Weight-length parameter - B	Gamma 1	Gamma 2	Gamma to use
25	5: US-AMLR haul-by-haul @36mm	Initial	2000 Synoptic	0.2520	0.3380	21	32.0	37.0	6.0	2.236E-06	3.314	**0.0000**	0.0117	1
26	5: US-AMLR haul-by-haul @36mm	Initial	Atlántida all	0.2520	0.3380	21	32.0	37.0	6.0	4.0E-06	3.239	**0.0000**	0.0115	1
27	5: US-AMLR haul-by-haul @36mm	Initial	Atlántida 48.1	0.2520	0.3380	21	32.0	37.0	6.0	4.0E-06	3.203	**0.0000**	0.0106	1
28	5: US-AMLR haul-by-haul @36mm	US-AMLR-Data	2000 Synoptic	0.2520	0.3380	21	37.6	44.3	8.8	2.236E-06	3.314	**0.0000**	0.0102	1
29	5: US-AMLR haul-by-haul @36mm	US-AMLR-Data	Atlántida all	0.2520	0.3380	21	37.6	44.3	8.8	4.0E-06	3.239	**0.0000**	0.0104	1
30	5: US-AMLR haul-by-haul @36mm	US-AMLR-Data	Atlántida 48.1	0.2520	0.3380	21	37.6	44.3	8.8	4.0E-06	3.203	**0.0000**	0.0104	1
31	6: US-AMLR haul-by-haul @40mm	Initial	2000 Synoptic	0.3630	0.3700	21	32.0	37.0	6.0	2.236E-06	3.314	**0.0000**	0.0146	1
32	6: US-AMLR haul-by-haul @40mm	Initial	Atlántida all	0.3630	0.3700	21	32.0	37.0	6.0	4.0E-06	3.239	**0.0000**	0.0167	1
33	6: US-AMLR haul-by-haul @40mm	Initial	Atlántida 48.1	0.3630	0.3700	21	32.0	37.0	6.0	4.0E-06	3.203	**0.0000**	0.0157	1
34	6: US-AMLR haul-by-haul @40mm	US-AMLR-Data	2000 Synoptic	0.3630	0.3700	21	37.6	44.3	8.8	2.236E-06	3.314	**0.0000**	0.0131	1
35	6: US-AMLR haul-by-haul @40mm	US-AMLR-Data	Atlántida all	0.3630	0.3700	21	37.6	44.3	8.8	4.0E-06	3.239	**0.0000**	0.0130	1
36	6: US-AMLR haul-by-haul @40mm	US-AMLR-Data	Atlántida 48.1	0.3630	0.3700	21	37.6	44.3	8.8	4.0E-06	3.203	**0.0000**	0.0139	1

Discussion

Gamma estimation

Recruitment parameters were most influential in determining gamma estimates. The choice of maturity had only a small impact and the weight-at-length relationship had virtually no impact on the estimated gamma values.

Of the six combinations of recruitment parameters tested, only four resulted in overlaps with the expected mortality range for *E. superba*. These four also generally met the assumptions of the recruitment model using a proportion over a full survey, to calculate mean and standard deviation (SD) across surveys treating each survey as an independent unit (de la Mare, 2994a). Additionally, three of these estimates also scaled to account for uneven sampling effort across survey strata (see Maschette & Wotherspoon, 2021 Appendix 1).

Gamma estimates from these four recruitment scenarios fell into two general categories:

- For recruitment estimates based on (1) Initial values and (4) Atlántida survey, which had variable R.mean estimates (0.58 and 0.43, respectively) but R.sd smaller than 0.13, gamma values ranged from 7.0% - 11.4% selecting the 75% escapement rule as the lower of the two decision rules.

- For recruitment estimates based on (2) US-AMLR and (3) US-AMLR and Atlántida, with R.mean of around 0.41 and R.sd of around 0.31, gamma estimates were <1.4%, determined by the smaller gamma satisfying the depletion rule.

The remaining two proportional recruitment estimates, with R.means between 0.25 - 0.36 and R.sd of over 0.33, resulted in gamma estimates of 0, again determined by the gamma satisfying the depletion rule. Both scenarios estimate mean and SD of recruitment proportions across all hauls and all years combined. This implies that each haul is an independent sampling unit and removes seasonal and spatial variability. Given the known spatial autocorrelation with krill as discussed previously at WG-ASAM and WG-EMM (See Zhu & Liu, 2021) it is unlikely that hauls can be considered independent sampling units, or that an individual haul is representative of the population. Additionally, as surveys vary in both total number of hauls and the number of hauls within each stratum, estimating a mean across all hauls in all years combined may results in surveys with fewer hauls to be out-weighted by surveys with more hauls. Given the above, and the lack of overlap with the expected natural mortality range, we consider that these recruitment scenarios should not be used to provide management advice on suitable gamma values.

With the exception of the initial proportional recruitment values, all other estimates used a hard length cut off to determine proportional recruitment. The original work by de la Mare (1994a) recommended fitting a mixture distribution to length densities in each survey and using the proportion of the 2+ cohort for recruitment. Whilst there was insufficient time to do this in this analysis, estimating these in future may provide a more robust estimate of recruitment mean and SD. Sensitivity analysis indicated that recruitment SD of approximately 0.37 or above results in the population triggering the 20% depletion probability even within no fishing and a recruitment mean of 0.5.

Finally, de la Mare (1994b) estimated recruitment parameters using Taylor series approximations to the variance of a ratio. This approximation performs poorly for larger variances and did not allow for the range of variability observed within the survey time series. The extension by Pavez et al., (2021) correctly accounts for a greater variability in recruitment, implemented within these simulations. The simulations presented here assume inverse Beta distributed recruitment, but

Pavez et al., (2021) also extended the proportional recruitment model to more readily allow for other underlying distributions, such as Log-Normal or Gamma. Each distribution has advantages and disadvantages depending on the level of variability seen within the recruitment series. However, given the impact that proportional recruitment has on the Grym projections further investigation should be conducted to assess which underlying recruitment distribution is the most appropriate.

Of the parameters tested size, the choice of proportional recruitment had the largest impact on the gamma which satisfied the CCAMLR decision rules. The effect of size at maturity had also an impact on gamma as it dictates what proportion of the population is considered to be the spawning stock biomass. Of the two options tested, we recommend using the values estimated in Appendix 3 as they contain the largest time series of data available. Further work should be conducted to explore additional data that could be included, and further explore anomalies in the data.

Of the three weight-at-length relationships tested there was a minimal effect on gamma estimates. It would therefore seem logical to select the parameters estimated from the Atlántida survey for 48.1 as it is both the most recent and an area specific estimate for this parameter.

Data availability

Lack of data availability was the largest obstacle in the calculation of parameters for these assessments. With the expectation that values for gamma will also be estimated for Subareas 48.2, 48.3 and 48.4, ideally each with their own local parameter estimates, consideration needs to be given to how data can be made available in a consistent and timely manner for those undertaking estimates on behalf of the CAMLR Scientific Committee. Whilst fishing vessels collect and report data either with the C1 forms or through the Scheme of International Scientific Observer programs there appears to be no consistent reporting of data collected on research vessel surveys.

For 48.1, data was made available for a summer period between 1991 – 2011 (US-AMLR) and 2020 (Atlántida), however data from surveys outside of these periods were not provided making it difficult to compare previous estimates of parameters using the same methods.

We therefore recommend the Scientific Committee develop a quality controlled, centralized database of krill survey and biological data and that the data from any parameter estimates used to provide management advise for krill be made included in the database.

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Appendix 1: Initial parameters for Grym assessment simulations.

Table 1. Grym parameters and their initial values from WG-EMM-2021 Table 1. Note natural mortality is calculated within the model as a function of proportional recruitment and is included in this table to provide an expected range for comparing to those calculated for different proportional recruitment values.

Parameter	48.1	Reference
First Age Class	1	Thanassekos (2021)
Last Age Class	7	Constable and de la Mare (1996)
t0	0	Constable and de la Mare (1996)
$L\infty$	60mm	Constable and de la Mare (1996)
k	0.48	Thanassekos (2021)
Start growth period (dd/mm)	21/10	Thanassekos (2021)
End growth period (dd/mm)	12/02	Thanassekos (2021)
Weight-length parameter - A (g)	2.236×10^{-6}	SC-CAMLR (2000)
Weight-length parameter - B	3.314	SC-CAMLR (2000)
Min length, 50% mature	32mm	WG-EMM-2010
Max length, 50% mature	37mm	WG-EMM-2010
Range over which maturity occurs	6mm	Thanassekos (2021)
Start of spawning season (dd/mm)	15/12	Kawaguchi (2016)
End of spawning season (dd/mm)	15/02	Kawaguchi (2016)
Monitoring interval (dd/mm)	01/01 to 15/01	Thanassekos (2021)
Recruitment function	*Proportional*	
Mean proportional recruitment	0.557	WG-EMM-2010
SD of proportional recruitment	0.126	WG-EMM-2010
Natural Mortality range	0.5-1.1	Pakhomov (1995)
Min length, 50% Selected	30mm	Thanassekos (2021)
Max length, 50% Selected	35mm	Thanassekos (2021)
Range over which selection occurs	11mm	Thanassekos (2021)
Fishing Season (dd/mm)	01/12 to 30/11	Thanassekos (2021)
Reference Date (dd/mm)	01/10	Thanassekos (2021)
Reasonable upper bound for Annual F	1.5	Constable and de la Mare (1996)
B0logSD	0.361	Kinzley (2021)
Target Escapement	75%	Constable and de la Mare (1996)

References

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Appendix 2: Proportional recruitment sensitivity modelling

Sensitivity runs were conducted to explore the effects of varying proportional recruitment standard deviations (R.sd) across three mean recruitments (R.mean) in order to explore situations when assessment simulations trigger the 20% depletion rule under a no fishing scenario.

Model setup

All model parameters were held constant with only R.mean and R.sd changing. N.surveys was set at 10, size at maturity was set to use those values estimated within Appendix 3, and weight-to-length relationship was set to use the 48.1 specific Atlántida estimate (See Table 5).

Recruitment series were generated 15 values for R.sd for each of three R.mean (0.35, 0.4, 0.5). R.sd values consisted of 0.1, 0.15-0.25 at 0.01 increments, 0.3, 0.35 and 0.4. For each combination of R.mean and R.sd projections were run to determine the probability of depletion under a no fishing scenario. Additionally, for each combination the mean natural mortality, and proportion of mortalities which occurred within the expected range was calculated.

Probability of depletion

Of the combinations tested, the probability of depletion under a no fishing scenario was greater with both increasing R.sd, and decreasing R.mean values (Table A2.1).

Mortality

Of the three mean recruitments tested the average M for the 0.35 R.mean was below the expected range (0.5-1.1) for all values of R.sd tested (Table A2.1). R.means 0.4 and 0.5 had average M within the expected range with the exception of the two largest R.sd values tested. Similarly, R.mean of 0.5 had >85% of M estimates within the expected range with the exception of the two largest R.sd values tested (0.35,0.40). Visual summaries of M distributions, M with recruitment CV, and estimated mean recruitment with recruitment variance are presented in Figures A2.1-A2.3.

Table A2.1: Probability of depletion under no fishing scenarios for varying mean and standard deviations (R.sd) for proportional recruitment given an inverse beta distribution. Values >0.1 which fail the CCAMLR decision rules are highlighted in red.

	Mean proportional recruitment		
R.sd	**0.35**	**0.4**	**0.5**
0.1	0.000	0.000	0.000
0.15	0.003	0.001	0.001
0.16	0.004	0.002	0.001
0.17	0.006	0.003	0.001
0.18	0.007	0.004	0.003
0.19	0.010	0.006	0.003
0.2	0.015	0.008	0.005
0.21	0.022	0.011	0.006
0.22	0.025	0.017	0.009
0.23	0.036	0.020	0.011
0.24	0.043	0.027	0.014
0.25	0.055	0.037	0.016
0.26	0.0657	0.0459	0.0273
0.27	0.0852	0.0475	0.0263
0.28	0.0958	0.0583	0.0316
0.29	0.1107	0.0726	0.0354
0.30	0.1317	0.0842	0.0428
0.31	0.1500	0.0962	0.0513
0.32	0.1681	0.1110	0.0532
0.33	0.2025	0.1347	0.0656
0.34	0.2197	0.1524	0.0751
0.35	0.2480	0.1789	0.0836
0.36	0.2735	0.1988	0.0961
0.37	0.3167	0.2331	0.1176
0.38	0.3566	0.2725	0.1433
0.39	0.3834	0.3081	0.1736
0.40	0.4201	0.3535	0.2081

Table A2.1: Natural mortality summaries (M) for proportional recruitment sensitivity tests. Mean M which occur outside the expected range (0.5-1.1) are highlighted in red.

	Mean M			**Minimum M**			**Maximum M**			**Proportion of M in range (0.5-11)**		
R.mean:	**0.35**	**0.4**	**0.5**	**0.35**	**0.4**	**0.5**	**0.35**	**0.4**	**0.5**	**0.35**	**0.4**	**0.5**
R. Sd 0.1	0.40	0.50	0.70	0.09	0.17	0.36	0.85	1.05	1.20	0.08	0.45	1.00
0.15	0.42	0.52	0.74	0.07	0.12	0.28	1.15	1.31	1.33	0.22	0.56	0.98
0.16	0.43	0.53	0.75	0.03	0.06	0.20	1.15	1.18	1.38	0.25	0.58	0.97
0.17	0.44	0.54	0.76	0.03	0.09	0.23	1.28	1.25	1.56	0.28	0.59	0.96
0.18	0.44	0.55	0.77	0.00	0.09	0.27	1.31	1.34	1.58	0.30	0.61	0.95
0.19	0.45	0.55	0.78	0.00	0.00	0.16	1.15	1.36	1.60	0.32	0.62	0.94
0.2	0.45	0.56	0.78	0.00	0.06	0.16	1.44	1.29	1.67	0.33	0.62	0.93
0.21	0.45	0.56	0.79	0.00	0.00	0.11	1.24	1.38	1.57	0.35	0.64	0.93
0.22	0.45	0.57	0.79	0.00	0.02	0.17	1.13	1.39	1.50	0.37	0.64	0.92
0.23	0.45	0.57	0.80	0.00	0.01	0.16	1.17	1.38	1.71	0.37	0.64	0.91
0.24	0.45	0.57	0.80	0.00	0.02	0.13	1.27	1.28	1.73	0.37	0.64	0.90
0.25	0.45	0.57	0.81	0.00	0.01	0.07	1.24	1.26	1.73	0.37	0.64	0.90
0.3	0.40	0.53	0.78	0.00	0.00	0.02	1.09	1.20	1.60	0.29	0.55	0.86
0.35	0.29	0.42	0.68	0.00	0.00	0.00	0.97	1.14	1.58	0.12	0.34	0.76
0.4	0.17	0.24	0.47	0.00	0.00	0.00	0.83	1.01	1.30	0.02	0.09	0.45

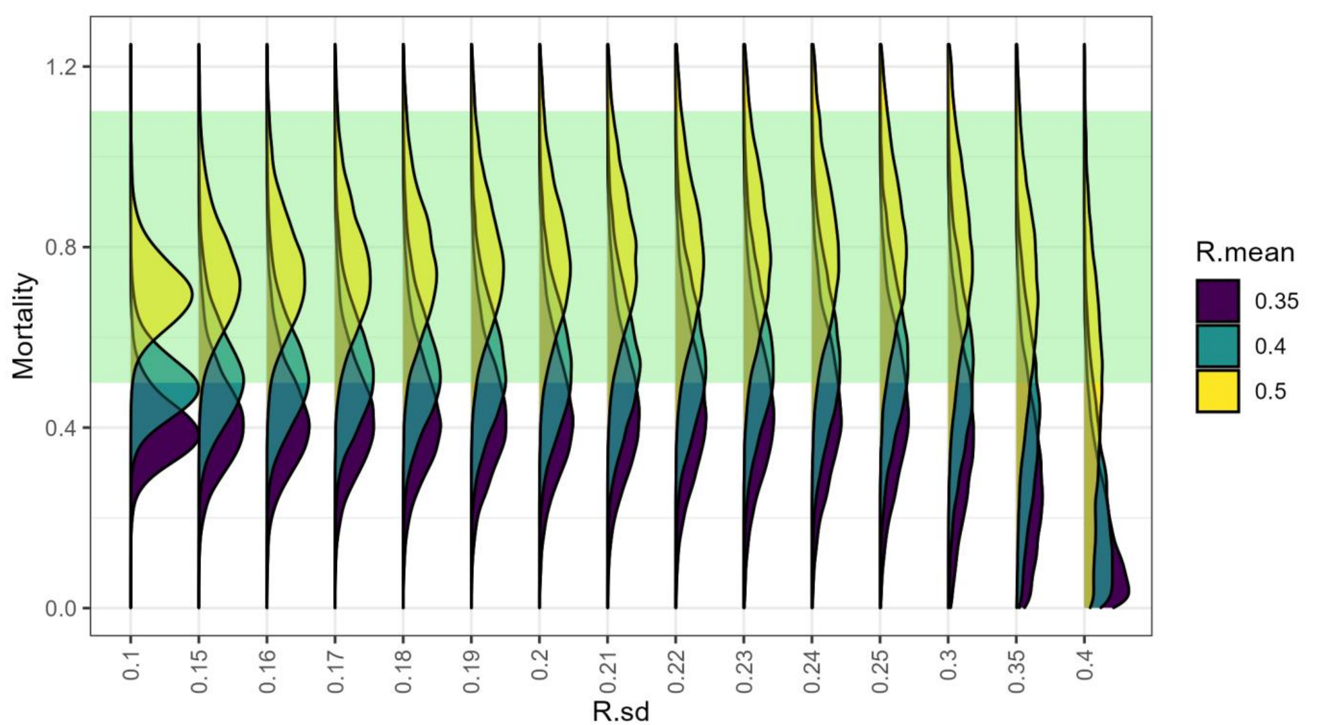

Figure A2.1: Comparison of mortality distribution estimated for a combination of mean (R.mean) and standard deviations (R.sd) for proportional recruitment using an inverse-beta distribution. Green highlights mortality range 0.5-1.1.

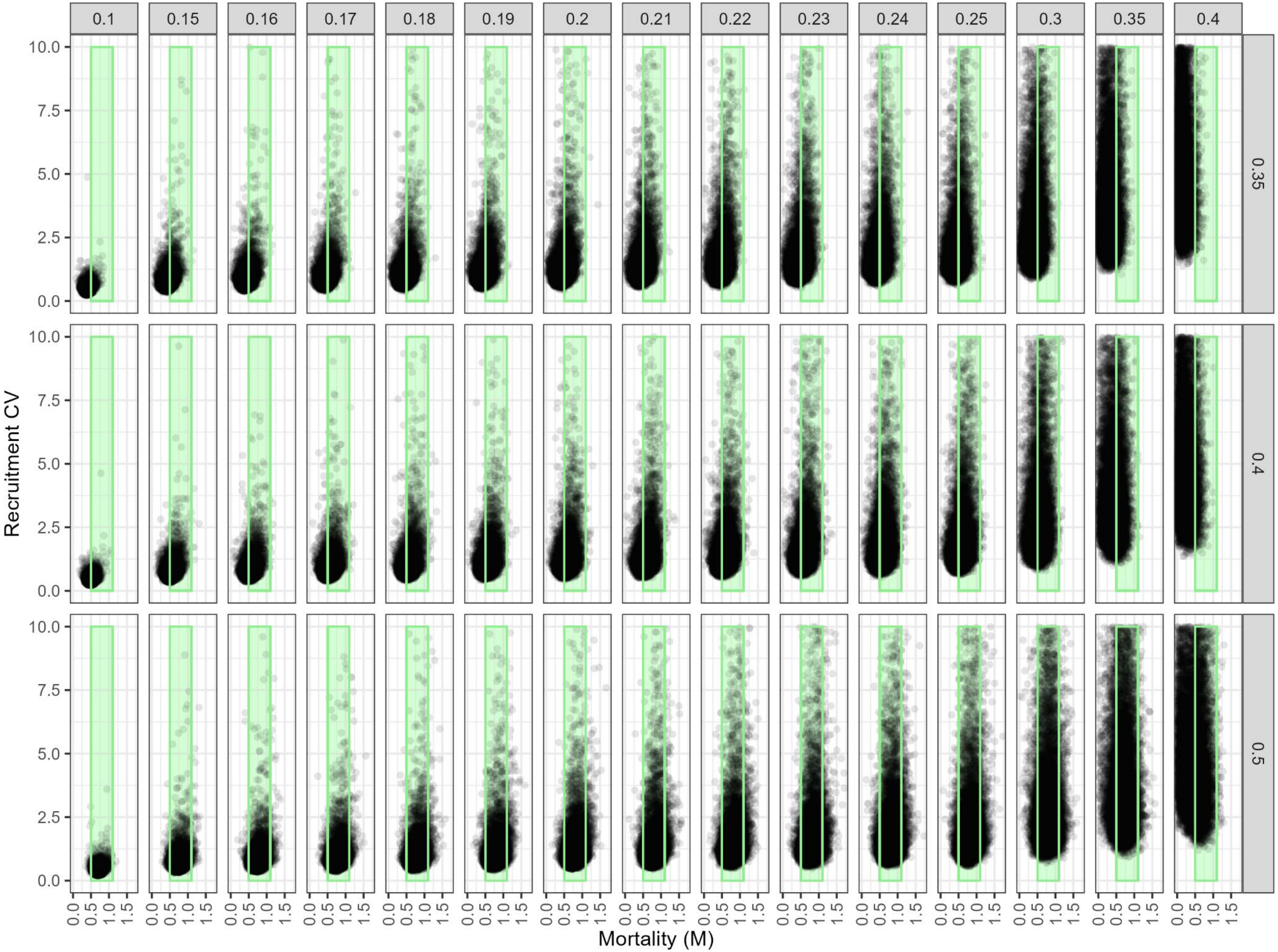

Figure A2.1: Comparison of mortality and recruitment CV estimated for a combination of mean (rows) and standard deviations (columns) for proportional recruitment using an inverse-beta distribution. Green highlights mortality range 0.5-1.1.

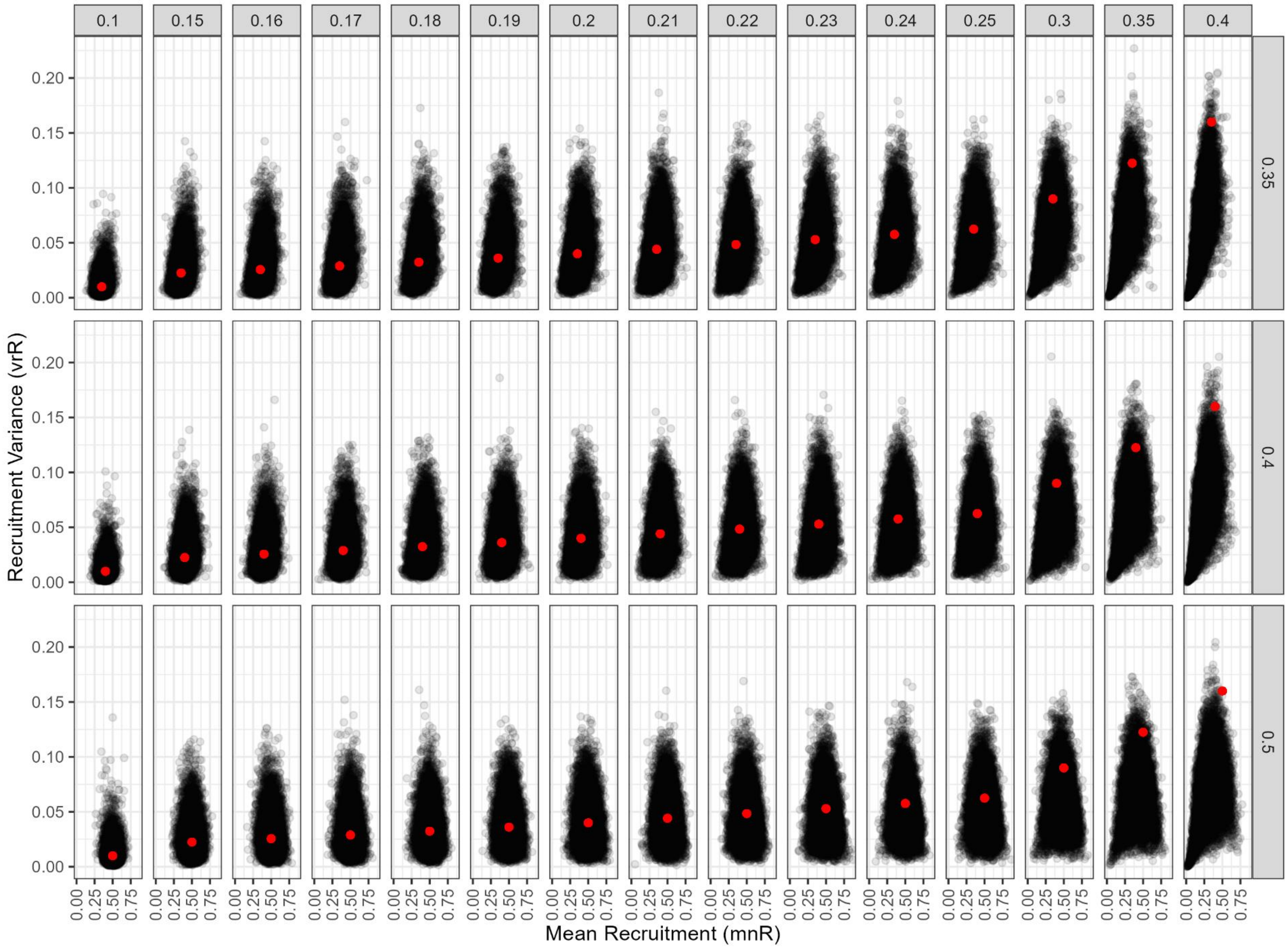

Figure A2.3: Comparison of estimated mean recruitment and recruitment variance for a combination of starting mean (rows) and standard deviation (columns) values for proportional recruitment using an inverse-beta distribution. Starting values for models are indicated in red.

Appendix 3: Maturity-at-length estimation based on US-AMLR survey data

Requirements of the Grym

The Grym models maturity-at-length with a ramp-shaped ogive function

$$p(l) = \begin{cases} 0 & l \leq L - \dfrac{w}{2} \\ \dfrac{l - L}{w} + \dfrac{1}{2} & L - \dfrac{w}{2} < \ l < L + \dfrac{w}{2} \\ 1 & l \geq L + \dfrac{w}{2} \end{cases}$$

where $p(l)$ represents the proportion of individuals of length l that are mature, L is the length at which 50% of individuals are mature, and w is the width of the ramp.

Within each projection L and w are held constant, but for each projection L is drawn from a uniform distribution with limits $L_{\min}$ and $L_{\max}$

$$L \sim \mathrm{U}(L_{\min}, L_{\max}).$$

Available data

US-AMLR summer survey data was available from 1991-2011. Of these, 1991 consisted of only 2 hauls and 59 krill measurements and was removed from the analysis.

Krill within maturity stages F3B-F3E, and M3 were considered mature individuals. Additionally, all krill below 30mm were considered to be immature.

Finally, the 2010 survey showed an abnormally high amount of large immature krill compared to other survey years. As insufficient time was available to investigate the cause of this, the 2010 survey was removed from the analysis (Figure A2.1).

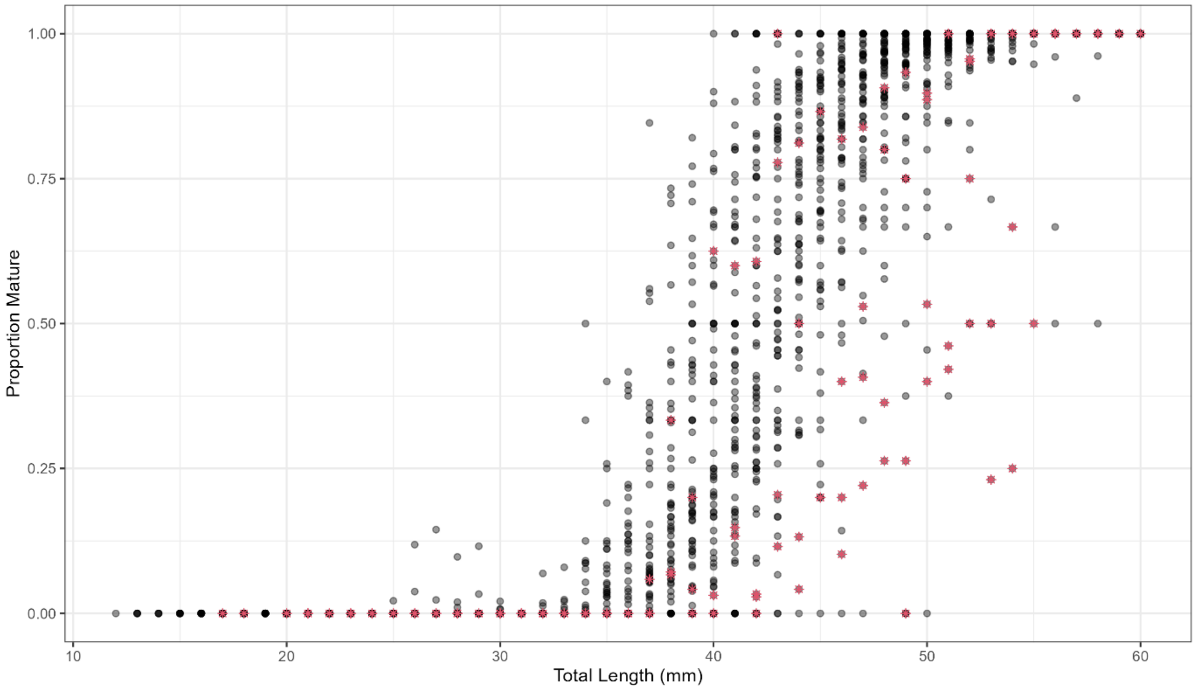

Figure A3.1: US-AMLR maturity data available from 1992-2011. 2010 was removed from subsequent analysis (red stars).

Estimating ogive function

The parameters $L_{\min}$, $L_{\max}$ and w are estimated by fitting a Bayesian nonlinear Binomial random effects model to maturity at length data observed in annual surveys. The model takes the form

$$M_{yi} \sim \mathrm{Bin}(1, \pi_{yi})$$
$$\pi_{yi} = \begin{cases} p_1 & l_{yi} \leq L_y - \dfrac{w_y}{2} \\ p_1 + (p_2 - p_1)\left(\dfrac{l_{yi} - L_y}{w_y} + \dfrac{1}{2}\right) & L_y - \dfrac{w_y}{2} < l_{yi} < L_y + \dfrac{w_y}{2} \\ p_2 & l_{yi} \geq L_y + \dfrac{w_y}{2} \end{cases}$$

where M_{yi} is a binary variable that is 1 if individual i observed in year y is mature and 0 otherwise, l_{yi} is the length of that individual, and π_{yi} is the probability that individual of that length observed in that year will be mature. Here L_y and w_y are random effects that represent annual variability in the shape of the maturity ogive

$$L_y \sim \mathrm{N}(\mu_L, \tau_L)$$
$$w_y \sim N(\mu_w, \tau_w)$$

where μ_L and μ_w are the mean L and w and τ_L and τ_w are the corresponding precisions. The parameters p_1 and p_2 represent respectively the probabilities that smallest and largest individuals will be mature. It is necessary that $p_1 > 0$ and $p_2 < 1$ to allow for the small number of individuals that mature unusually early or late, and any potential mis-identification of maturity stage, and Beta priors are adopted that constrain p_1 to be near 0 and p_2 to be near 1

$$p_1 \sim \text{Beta}(1{,}100)$$
$$p_2 \sim \text{Beta}(100{,}1)$$

Diffuse Normal and Gamma priors are chosen for means and precisions of the annual effects

$$\mu_L \sim \text{N}(45{,}0.01)$$
$$\mu_w \sim \text{N}(10{,}0.01)$$
$$\tau_L \sim \text{Gamma}(0.01{,}0.01)$$
$$\tau_w \sim \text{Gamma}(0.01{,}0.01)$$

where again the Normal distributions have been parameterized in terms of mean and precision.

The upper and lower limits $L_{\min}$ and $L_{\max}$ for L are determined as the 2.5 and 97.5 percentiles for L_y, and w is determined as the 97.5 percentile for w_y.

Results

The model estimated L50% maturity to be 41.0 mm with and 2.5% and 97.5% quantile of 37.6 mm and 44.3 mm respectively. These were used as the minimum and maximum values of 50% maturity within the scenarios presented in the main text of this paper. The slope of the ramp, or the range over which maturity occurs, was estimated as the 97.5% quantile of the ramp width at 8.8 mm (Figure A2.2).

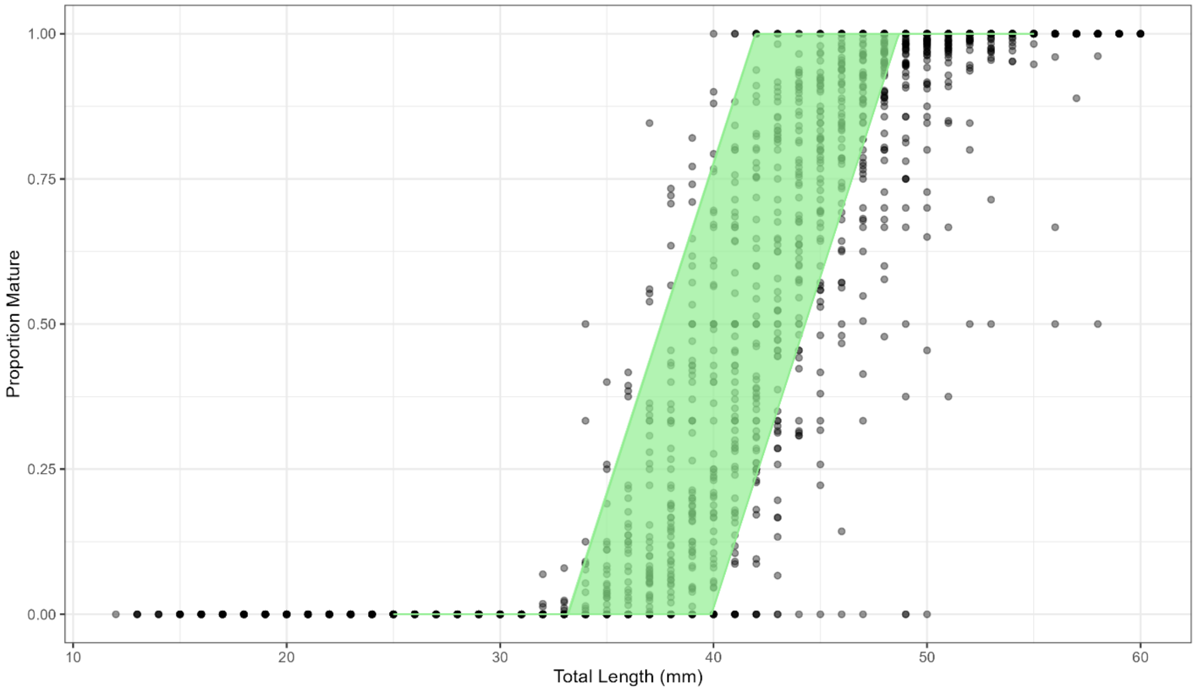

Figure A3.2: Ramp ogive for *Euphausia superba* maturity at length range (green) fitted to US-AMLR survey data 1992-2011 (excluding 2010) with Bayesian nonlinear Binomial random effects model.

Appendix 4: Spawning stock status projections.

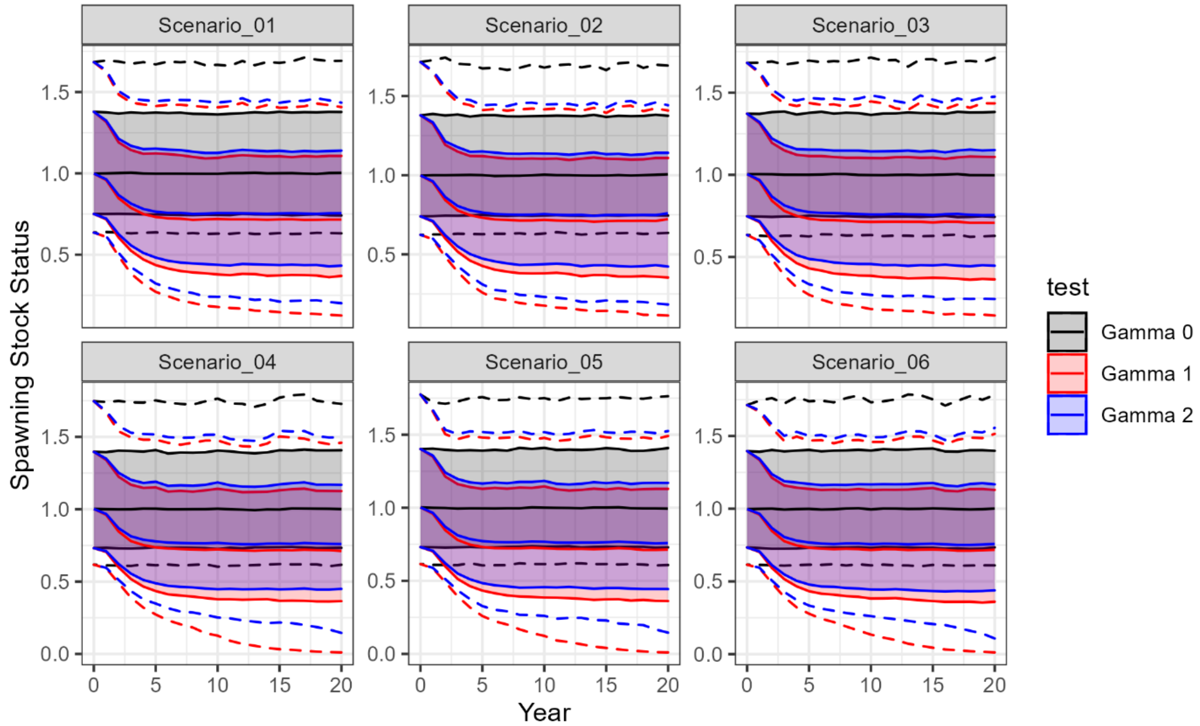

Figure A4.1: Spawning Stock Status for 20-year simulated krill population in Subarea 48.1 based on Recruitment Group 1 showing median with 90% (shaded) and 97.5% confidence intervals (dashed).

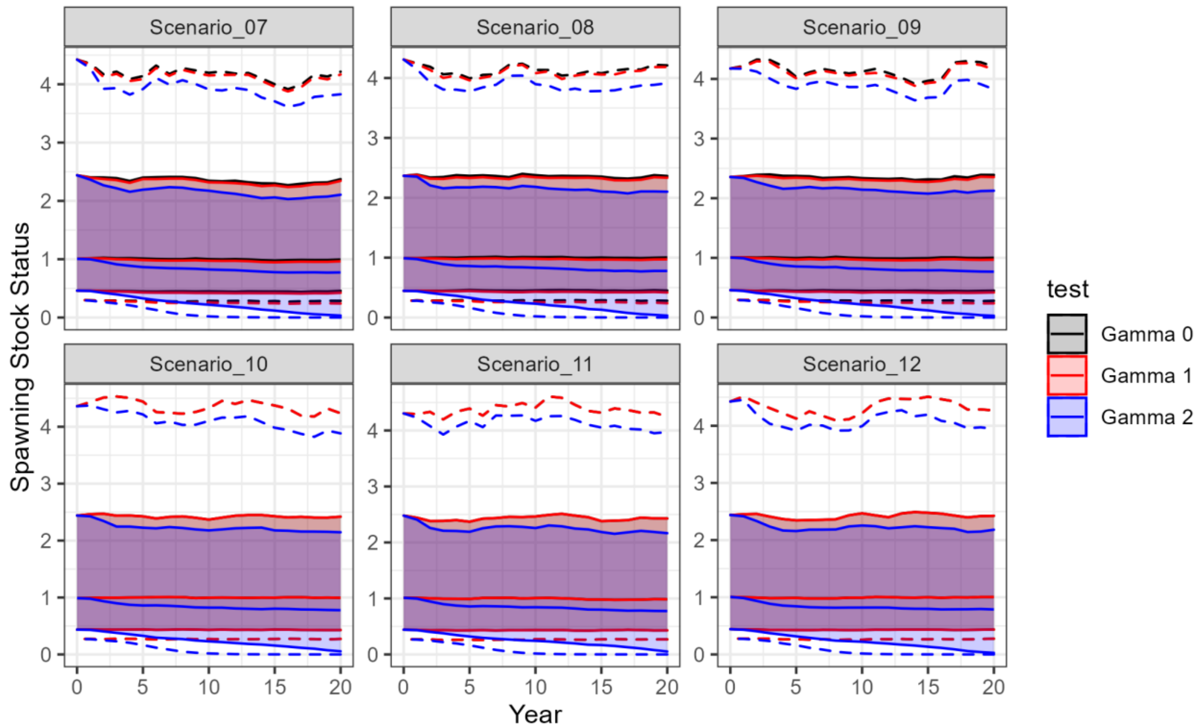

Figure A4.2: Spawning Stock Status for 20-year simulated krill population in Subarea 48.1 based on Recruitment Group 2 showing median with 90% (shaded) and 97.5% confidence intervals (dashed).

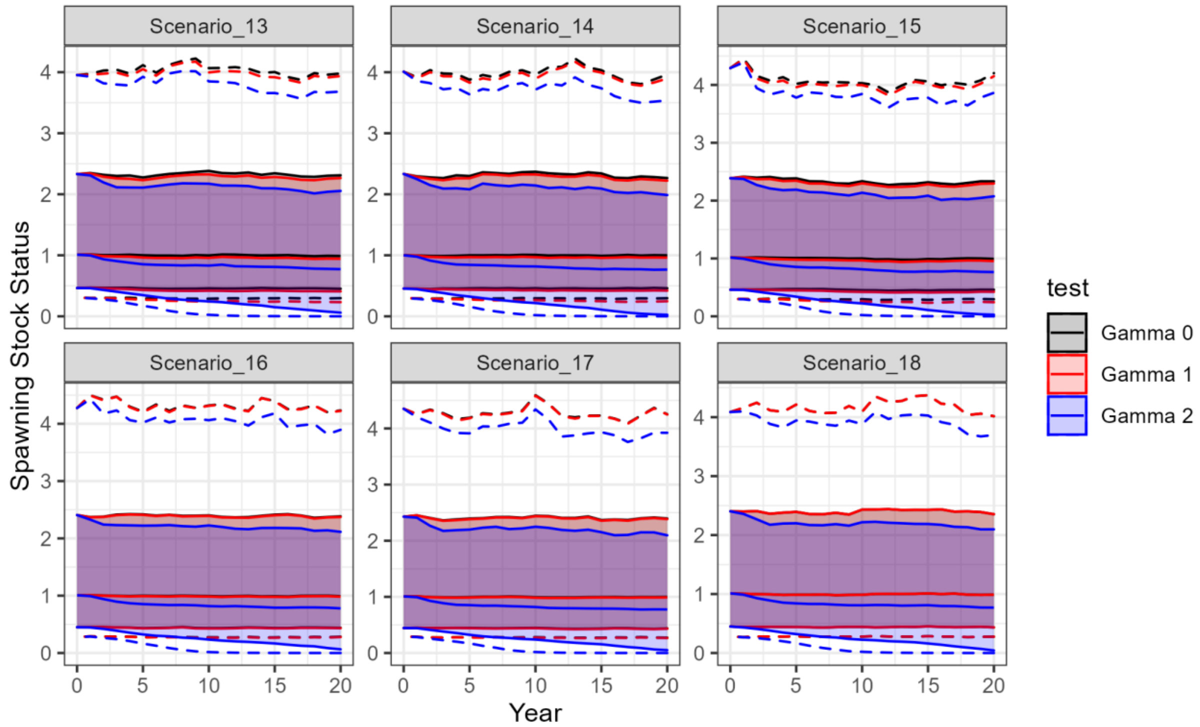

Figure A4.3: Spawning Stock Status for 20-year simulated krill population in Subarea 48.1 based on Recruitment Group 3 showing median with 90% (shaded) and 97.5% confidence intervals (dashed).

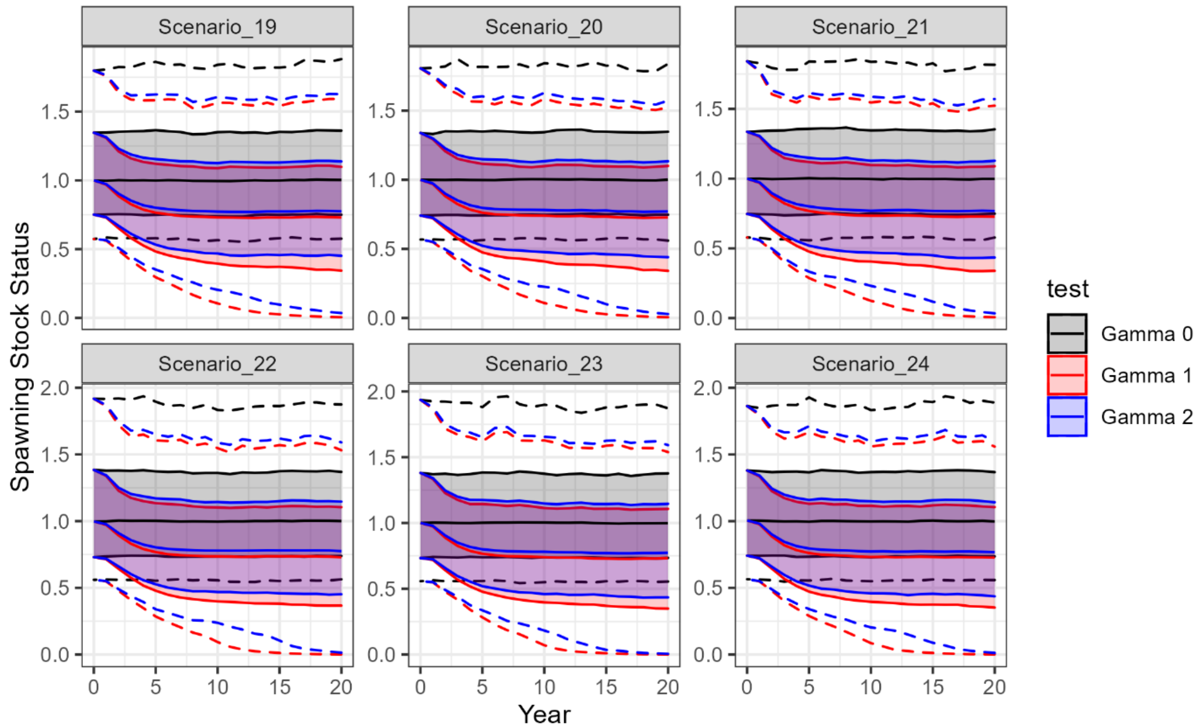

Figure A4.4: Spawning Stock Status for 20-year simulated krill population in Subarea 48.1 based on Recruitment Group 4 showing median with 90% (shaded) and 97.5% confidence intervals (dashed).

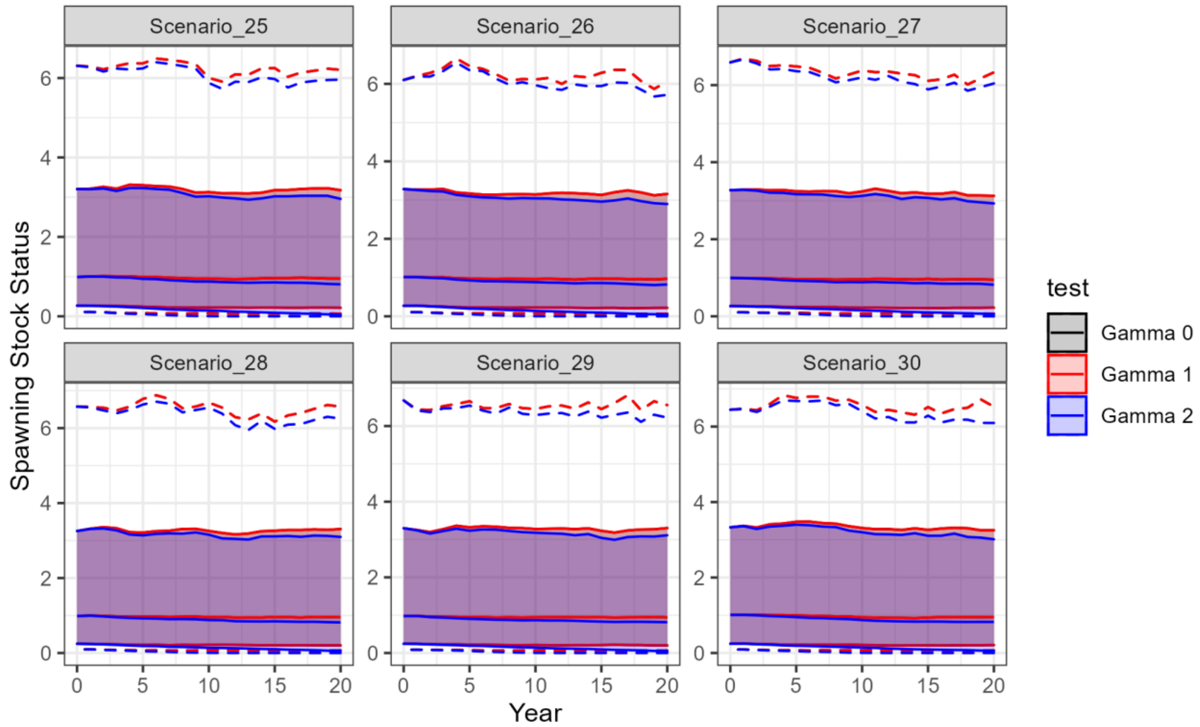

Figure A4.5: Spawning Stock Status for 20-year simulated krill population in Subarea 48.1 based on Recruitment Group 5 showing median with 90% (shaded) and 97.5% confidence intervals (dashed).

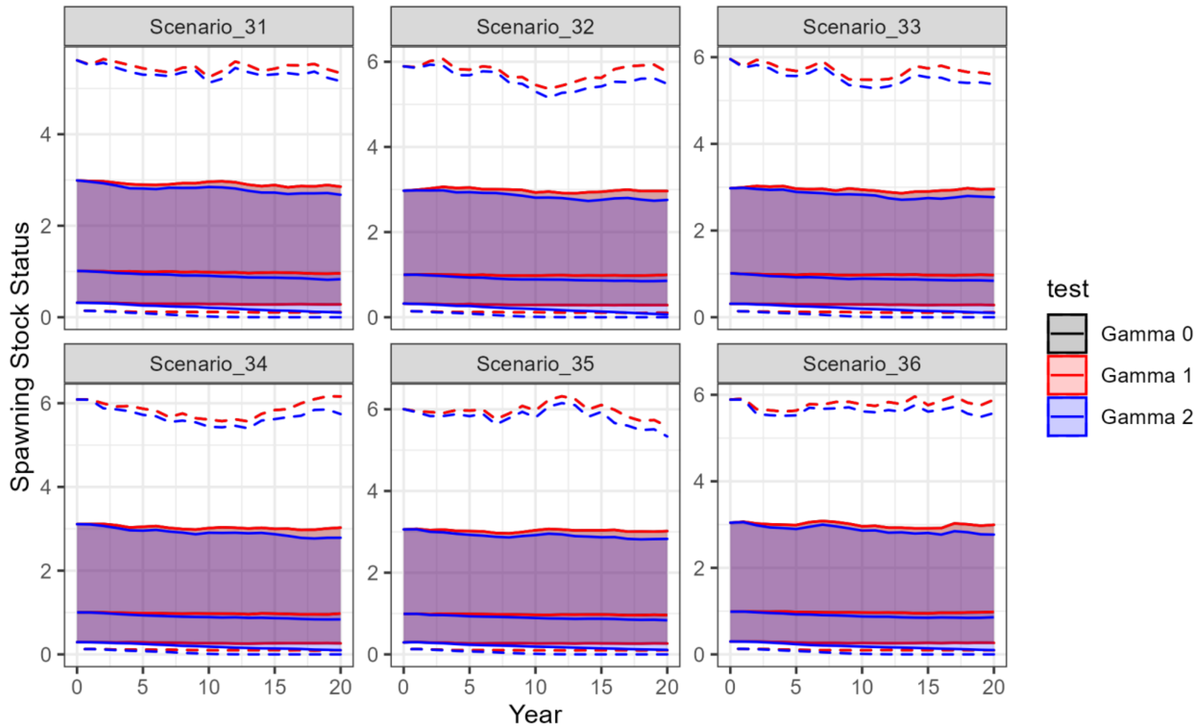

Figure A4.6: Spawning Stock Status for 20-year simulated krill population in Subarea 48.1 based on Recruitment Group 6 showing median with 90% (shaded) and 97.5% confidence intervals (dashed).