# Sardine projections based on constant catch scenarios

**C.L. de Moor***

Correspondence email: carryn.demoor@uct.ac.za

*Short- and medium-term projections of the sardine resource are considered under alternative constant catch scenarios. Recruitment to the west component is estimated to be the primary driver of the population as a whole, and thus management considerations focus on the west component.*

*Keywords: sardine, short-term projections, total allowable bycatch, total allowable catch*

## Introduction

Due to Exceptional Circumstances, the directed sardine Total Allowable Catch (TAC) and sardine Total Allowable Bycatches (TABs) for 2019 and 2020 were recommended by 'ad hoc' methods based on updated assessments and short-term projections (e.g. de Moor 2019a,b and de Moor 2020a,b). A similar process is to be followed in 2021. This document provides short- and medium-term projections of the sardine resource based on a recent updated assessment (de Moor 2021) to assess whether increases in the catches of adult sardine (either >14cm sardine TAB or directed sardine TAC) could be scientifically justified, and if so, to what extent the catch limits could be increased.

## Methods

The model used for projections was based on the most recent updated assessment of the sardine resource, without the inclusion of the parasite prevalence-at-length data (i.e. option i) of de Moor 2021). This was a conservative choice by the SWG-PEL TTG while further options of whether and how to include the parasite data in the assessment are undertaken. Most of the population dynamics were similar to those assumed historically (Appendix A) except that catch was modelled to be taken in a single pulse during the year. Other assumptions made during these projections are detailed in Appendix A.

The assessment provided a single set of model parameters at the joint posterior mode, including numbers-at-length (age) and biomass in November 2020 from which projections were initiated. Following a similar method[1] to de Moor (2020b), initial variability was incorporated by sampling from normal distributions using the Hessian-based CV of the model predicted November biomass in 2020:

$N^{S,i}_{j,2020,a} = N^{S}_{j,2020,a} e^{0.920\omega_{j,i} - 0.5*0.920^2}$ for $1 \le a \le 5^+$ and $B^{S,i}_{j,2020} = B^{S}_{j,2020} e^{0.920\omega_{j,i} - 0.5*0.920^2}$, for $j = 1$[2], and

$N^{S,i}_{j,2209,a} = N^{S}_{j,2020,a} e^{0.445\omega_{j,i} - 0.5*0.445^2}$ for $1 \le a \le 5^+$ and $B^{S,i}_{j,2019} = B^{S}_{j,2019} e^{0.445\omega_{j,i} - 0.5*0.445^2}$, for $j = 2$.

For these analyses, 500 simulations $i$ were run. Sensitivity to the variability in this starting point was also tested (see below).

Variability in the projections (over and above the variability in the starting point) was additionally included by running the 500 simulations with different future recruitment each year (see Appendix A). Future recruitment was assumed to be

---

* MARAM (Marine Resource Assessment and Management Group), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch, 7701, South Africa.

[1] de Moor (2020b) used the Hessian-based CV of the model predicted November survey biomass. The Hessian-based CVs between 'true' and survey biomass are very similar.

[2] The effective spawning biomass in 2020 was similarly adjusted for the purpose of reporting statistics only.

according to the recent 'regime' (Appendix A) in line with the relatively high autocorrelation in the historical time series of recruitment.

Sensitivity of results to the following alternative assumptions was examined:

i) $\mathrm{move}_{y,1} = 0.15$: The proportion of 1-year old sardine moving from the west to the south coast in November each year was 0.15 in all future years. Baseline has $\mathrm{move}_{y,1} = 0.35$.

ii) $\mathrm{move}_{y,1} = 0.55$: The proportion of 1-year old sardine moving from the west to the south coast in November each year was 0.55 in all future years. Baseline has $\mathrm{move}_{y,1} = 0.35$.

iii) No Init Var: No variability in the starting point.

Time constraints restricted sensitivity testing to alternative recruitment scenarios (e.g. according to a Beverton Holt or Hockey Stick stock recruitment relationship).

**Results and Discussion**

The resource was first projected forward assuming no future catch. The starting level of abundance for these projections is higher, although more uncertain, than that estimated a year ago for November 2019 (de Moor 2020b). Figures 1 and 2 show the one year projected additive change ("growth") in the west component effective spawner biomass and spawner biomass, respectively. This has a high probability of being positive (Table 1). Figure 3 shows the one year projected additive change ("growth") in the west component total biomass. Under the baseline hypothesis, there is a high probability of positive growth in biomass with the 20%ile being a 41 000t increase in total west component biomass from November 2020 to 2021 (Table 1). This measure could be taken to indicate the 'surplus' biomass in the population from which the catch in 2021 would be removed. Die *et al*. (2019) recommended that the proportion of the resource growth assigned to recovery of a depleted population, rather than to the fishery, should be higher the more depleted the population.

On the other hand, the projections indicate a high probability of a decrease in the south component abundance between November 2020 and 2021, under a no catch scenario (Figure 3, Table 2).

The impact of fishing on the sardine population was considered for the immediate (1-year) future as follows:

i) The multiplicative change in effective spawning biomass from November 2020 to November 2021;

ii) The additive change (increase or decrease) in effective spawning biomass from November 2020 to November 2021;

iii) The additive change (increase or decrease) in total biomass from November 2020 to November 2021; and

iv) The multiplicative change under alternative catch options relative to a no catch scenario.

The probability of the west component effective spawning biomass in November 2021 being below that in November 2007 (the sardine risk threshold) has not been evaluated due to time constraints.

Table 1 shows the 5%iles, 20%iles and medians of (i)-(iv) above for the west component under alternative catch options and models while Table 2 shows the same for the south component. The impact on the resource naturally increases with increasing catch alternatives. The catch options listed in Table 2 have a lower or equal "impact" on the west component (multiplicative 1-year change in effective spawning biomass under catch relative to no catch) than that considered in 2020 for the baseline hypothesis. As expected, the west component is projected to become larger under $\mathrm{move}_{y,1} = 0.15$ and lower under $\mathrm{move}_{y,1} = 0.55$ than that projected under the baseline model. The impact of the catch (compared to a no catch scenario) is greater for the lower movement scenario.

The alternative catch options all consider the same amount of sardine catch from the south coast. It is therefore unsurprising that there is little difference between the “impact” on the south component between the catch options, although differences are clear between the alternative model options.

Figures 4 and 5 show the medium-term impact of alternative catch options. Under these projection assumptions, the short-lived resource is expected to increase on the west coast to the level corresponding to average recent recruitment, while the level corresponding to average recent recruitment on the south coast is lower than that estimated in 2020 and a decline is thus projected.

**References**

de Moor CL. 2019a. Revision to the Initial Assessment of the South African sardine resource using data from 1984-2018. DAFF: Branch Fisheries Document FISHERIES/2019/MAR/SWG-PEL/06.

de Moor CL. 2019b. Sardine projections based on constant catch scenarios. DAFF: Branch Fisheries Document FISHERIES/2019/APR/SWG-PEL/07.

de Moor CL. 2020a. Baseline assessment of the South African sardine resource using data from 1984-2019. DEA: Branch Fisheries Document FISHERIES/2020/APR/SWG-PEL/30.

de Moor CL. 2020b. Sardine projections based on constant catch scenarios. DEFF: Branch Fisheries Document FISHERIES/2020/APR/SWG-PEL/33.

de Moor CL. 2020c. South African sardine assessment posterior distributions and sensitivity tests. DEFF: Branch Fisheries Document FISHERIES/2020/DEC/SWG-PEL/138.

de Moor CL. 2020d. Additional sardine projections based on constant catch scenarios assuming alternative November 2019 recruitment levels. DEFF: Branch Fisheries Document FISHERIES/2020/AUG/SWG-PEL/70rev.

de Moor CL. 2021. Updated assessment of the South African sardine resource using data from 1984-2020. DEFF: Branch Fisheries Document FISHERIES/2021/APR/SWG-PEL/23.

Die DJ, Punt AE, Tiedemann R, Waples R and Wilberg MJ. 2019. International Review Panel Report for the 2018 International Fisheries Stock Assessment Workshop. MARAM International Stock Assessment Workshop, 2-5 December 2019, Cape Town, Document MARAM/IWS/2019/General/5.

Szuwalski CS, Britten GL, Licandeo R, Amoroso RO, Hilborn R and Walters C. 2019. Global forage fish recruitment dynamics: A comparison of methods, time-variation, and reverse causality. Fisheries Research 214: 56-64.

**Table 1.** The 5%ile, 20%ile and 50%ile of the multiplicative and additive change in **west component effective spawning biomass** and additive change in **west component total biomass** from November 2020 to 2021 under alternative catch options and the alternative models considered. The 5%ile, 20%ile and 50%ile of the multiplicative change under the catch options relative to the no catch option are also given. Grey cells indicate cases for which the selectivity function needed modification to enable the catch to be taken; the percentage of times this occurred for ages 2 and below (S2) and ages 1 and below (S1) are given. The percentage of times the full bycatch could not be realised (By) or the full catch could still not be realised after selectivity was modified (C) are also given. These statistics (S2, S1, By and C) are given for 2021 only, although such problems in realising the catch are also projected to occur in subsequent years. The top two rows give the comparative statistics under the zero catch and 2019 TAC/B alternatives as estimated by de Moor (2019b). The next three rows give the comparative statistics under the zero catch and April 2020 TAC/B as estimated by de Moor (2020b) and August 2020 TAC/B under a more optimistic recruitment model (de Moor 2020d).

| | | | | | Multiplicative $\Delta$ in effSSB | | | Additive $\Delta$ in effSSB | | | Additive $\Delta$ in B | | | Relative Multiplicative $\Delta$ | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | West | South | ByC | 5%ile | 20%ile | 50%ile | 5%ile | 20%ile | 50%ile | 5%ile | 20%ile | 50%ile | 5%ile | 20%ile | 50%ile | S2 | S1 | C | By |
| 2019 | 0 | 0 | 0 | 0 | 2.20 | 2.67 | 3.40 | 25 | 35 | 50 | | | | | | | | | | |
| | 23 | 6.5 | 7 | 9.5 | 1.88 | 2.36 | 3.09 | 19 | 28 | 43 | | | | 0.86 | 0.88 | 0.90 | | | | |
| 2020 | 0 | 0 | 0 | 0 | 1.25 | 1.55 | 2.14 | 9 | 15 | 21 | -35 | -8 | 17 | | | | 0 | 0 | 0 | 0 |
| | 34.05 | 13.65 | 13 | 7.4 | 1.15 | 1.43 | 1.93 | 5 | 12 | 17 | -46 | -20 | 6 | 0.88 | 0.90 | 0.91 | 0.14 | 0.02 | 0 | 0 |
| | 45.05 | 16.65 | 18 | 10.4 | 1.27 | 1.59 | 2.14 | 10 | 16 | 21 | -44 | -19 | 5 | 0.88 | 0.89 | 0.9 | 0.20 | 0.01 | | |
| Baseline | 0 | 0 | 0 | 0 | 1.81 | 2.29 | 3.61 | 27 | 36 | 48 | 22 | 41 | 104 | | | | 0 | 0 | 0 | 0 |
| | 24.00 | 9.25 | 8.5 | 6.25 | 1.75 | 2.17 | 3.41 | 23 | 32 | 44 | 12 | 31 | 93 | 0.9 | 0.92 | 0.94 | 4.4 | 1.8 | 0 | 0 |
| | 25.00 | 10.25 | 8.5 | 6.25 | 1.74 | 2.17 | 3.38 | 23 | 32 | 44 | 11 | 30 | 93 | 0.89 | 0.91 | 0.94 | 6.0 | 2.8 | 0 | 0 |
| | 26.00 | 11.25 | 8.5 | 6.25 | 1.73 | 2.16 | 3.36 | 23 | 32 | 44 | 11 | 30 | 92 | 0.88 | 0.91 | 0.93 | 7.2 | 5.4 | 0.2 | 0 |
| | 27.00 | 12.25 | 8.5 | 6.25 | 1.72 | 2.15 | 3.34 | 22 | 31 | 43 | 10 | 29 | 92 | 0.88 | 0.90 | 0.93 | 7.6 | 6.2 | 0.6 | 0 |
| $move_{y,1}=0.55$ | 0 | 0 | 0 | 0 | 1.35 | 1.80 | 3.01 | 18 | 25 | 35 | -34 | 11 | 51 | | | | 0 | 0 | 0 | 0 |
| | 24.00 | 9.25 | 8.5 | 6.25 | 1.30 | 1.72 | 2.81 | 15 | 22 | 32 | -41 | 4 | 43 | 0.91 | 0.93 | 0.95 | 4.4 | 1.8 | 0 | 0 |
| | 25.00 | 10.25 | 8.5 | 6.25 | 1.30 | 1.71 | 2.80 | 15 | 22 | 32 | -41 | 3 | 43 | 0.90 | 0.93 | 0.95 | 6 | 2.8 | 0 | 0 |
| | 26.00 | 11.25 | 8.5 | 6.25 | 1.29 | 1.70 | 2.78 | 15 | 22 | 31 | -42 | 3 | 42 | 0.90 | 0.92 | 0.94 | 7.2 | 5.4 | 0.2 | 0 |
| | 27.00 | 12.25 | 8.5 | 6.25 | 1.29 | 1.69 | 2.77 | 15 | 22 | 31 | -42 | 2 | 42 | 0.89 | 0.91 | 0.94 | 7.6 | 6.2 | 0.6 | 0 |
| $move_{y,1}=0.15$ | 0 | 0 | 0 | 0 | 2.25 | 2.80 | 4.24 | 34 | 44 | 60 | 61 | 73 | 156 | | | | 0 | 0 | 0 | 0 |
| | 24.00 | 9.25 | 8.5 | 6.25 | 2.18 | 2.64 | 3.99 | 30 | 39 | 55 | 47 | 59 | 142 | 0.89 | 0.91 | 0.94 | 4.4 | 1.8 | 0 | 0 |
| | 25.00 | 10.25 | 8.5 | 6.25 | 2.17 | 2.62 | 3.96 | 30 | 38 | 55 | 47 | 58 | 142 | 0.88 | 0.91 | 0.94 | 6 | 2.8 | 0 | 0 |
| | 26.00 | 11.25 | 8.5 | 6.25 | 2.16 | 2.61 | 3.94 | 29 | 38 | 54 | 46 | 57 | 141 | 0.87 | 0.90 | 0.93 | 7.2 | 5.4 | 0.2 | 0 |
| | 27.00 | 12.25 | 8.5 | 6.25 | 2.16 | 2.60 | 3.91 | 29 | 38 | 54 | 45 | 57 | 140 | 0.86 | 0.89 | 0.93 | 7.6 | 6.2 | 0.6 | 0 |
| No Init Var | 0 | 0 | 0 | 0 | 2.52 | 2.57 | 2.80 | 36 | 37 | 44 | 20 | 20 | 92 | | | | 0 | 0 | 0 | 0 |
| | 24.00 | 9.25 | 8.5 | 6.25 | 2.37 | 2.41 | 2.65 | 36 | 37 | 43 | 19 | 19 | 92 | 0.94 | 0.94 | 0.95 | 0 | 0 | 0 | 0 |
| | 25.00 | 10.25 | 8.5 | 6.25 | 2.35 | 2.40 | 2.64 | 36 | 37 | 43 | 19 | 19 | 91 | 0.93 | 0.93 | 0.94 | 0 | 0 | 0 | 0 |
| | 26.00 | 11.25 | 8.5 | 6.25 | 2.34 | 2.38 | 2.62 | 35 | 36 | 43 | 18 | 18 | 91 | 0.93 | 0.93 | 0.94 | 0 | 0 | 0 | 0 |
| | 27.00 | 12.25 | 8.5 | 6.25 | 2.33 | 2.37 | 2.61 | 36 | 37 | 44 | 20 | 20 | 92 | 0.92 | 0.92 | 0.93 | 0 | 0 | 0 | 0 |

**Table 2.** The 5%ile, 20%ile and 50%ile of the multiplicative and additive change in **south component effective spawning biomass** and additive change in **south component total biomass** from November 2020 to 2021 under alternative catch options and the alternative models considered. The 5%ile, 20%ile and 50%ile of the multiplicative change under the catch options relative to the no catch option are also given. There were no problems in the scenarios tested being able to realise the catch from the south component. The top two rows give the comparative statistics under the zero catch and 2019 TAC/B alternatives as estimated by de Moor (2019b). The next three rows give the comparative statistics under the zero catch and April 2020 TAC/B as estimated by de Moor (2020b) and August 2020 TAC/B under a more optimistic recruitment model (de Moor 2020d).

| | | | | | Multiplicative Δ in effSSB | | | Additive Δ in effSSB | | | Additive Δ in B | | | Relative Multiplicative Δ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | West | South | ByC | 5%ile | 20%ile | 50%ile | 5%ile | 20%ile | 50%ile | 5%ile | 20%ile | 50%ile | 5%ile | 20%ile | 50%ile |
| 2019 | 0 | 0 | 0 | 0 | 0.45 | 1.05 | 1.55 | -70 | 6 | 70 | | | | | | |
| | 23 | 6.5 | 7 | 9.5 | 0.44 | 1.01 | 1.51 | -72 | 1 | 65 | | | | 0.96 | 0.97 | 0.97 |
| 2020 | 0 | 0 | 0 | 0 | 1.27 | 1.31 | 1.39 | 43 | 53 | 65 | 10 | 42 | 79 | | | |
| | 34.05 | 13.65 | 13 | 7.4 | 1.23 | 1.27 | 1.33 | 34 | 43 | 56 | -10 | 22 | 59 | 0.93 | 0.95 | 0.96 |
| | 45.05 | 16.65 | 18 | 10.4 | 1.23 | 1.27 | 1.33 | 34 | 44 | 56 | 17 | 42 | 75 | 0.91 | 0.93 | 0.94 |
| Baseline | 0 | 0 | 0 | 0 | 1.45 | 1.48 | 1.52 | 55 | 74 | 98 | -280 | -143 | -52 | | | |
| | 24.00 | 9.25 | 8.5 | 6.25 | 1.42 | 1.45 | 1.49 | 50 | 69 | 93 | -292 | -155 | -64 | 0.96 | 0.97 | 0.98 |
| | 25.00 | 10.25 | 8.5 | 6.25 | 1.42 | 1.45 | 1.49 | 50 | 69 | 92 | -292 | -155 | -65 | 0.96 | 0.97 | 0.98 |
| | 26.00 | 11.25 | 8.5 | 6.25 | 1.42 | 1.45 | 1.49 | 50 | 69 | 92 | -293 | -155 | -65 | 0.96 | 0.97 | 0.98 |
| | 27.00 | 12.25 | 8.5 | 6.25 | 1.42 | 1.45 | 1.49 | 49 | 69 | 92 | -293 | -156 | -65 | 0.96 | 0.97 | 0.98 |
| $move_{y,1}$ =0.55 | 0 | 0 | 0 | 0 | 1.46 | 1.51 | 1.58 | 61 | 84 | 108 | -237 | -95 | -3 | | | |
| | 24.00 | 9.25 | 8.5 | 6.25 | 1.44 | 1.48 | 1.54 | 55 | 78 | 103 | -252 | -110 | -18 | 0.96 | 0.97 | 0.98 |
| | 25.00 | 10.25 | 8.5 | 6.25 | 1.44 | 1.48 | 1.54 | 55 | 77 | 102 | -252 | -111 | -18 | 0.96 | 0.97 | 0.98 |
| | 26.00 | 11.25 | 8.5 | 6.25 | 1.44 | 1.48 | 1.54 | 54 | 77 | 102 | -253 | -111 | -19 | 0.96 | 0.97 | 0.98 |
| | 27.00 | 12.25 | 8.5 | 6.25 | 1.44 | 1.48 | 1.54 | 54 | 77 | 102 | -253 | -112 | -19 | 0.96 | 0.97 | 0.98 |
| $move_{y,1}$ =0.15 | 0 | 0 | 0 | 0 | 1.43 | 1.44 | 1.47 | 46 | 64 | 86 | -345 | -189 | -113 | | | |
| | 24.00 | 9.25 | 8.5 | 6.25 | 1.41 | 1.42 | 1.44 | 41 | 59 | 82 | -354 | -198 | -122 | 0.97 | 0.98 | 0.98 |
| | 25.00 | 10.25 | 8.5 | 6.25 | 1.41 | 1.42 | 1.44 | 41 | 59 | 82 | -354 | -199 | -122 | 0.97 | 0.98 | 0.98 |
| | 26.00 | 11.25 | 8.5 | 6.25 | 1.41 | 1.42 | 1.44 | 41 | 59 | 82 | -354 | -199 | -122 | 0.97 | 0.98 | 0.98 |
| | 27.00 | 12.25 | 8.5 | 6.25 | 1.41 | 1.42 | 1.44 | 41 | 59 | 82 | -355 | -199 | -122 | 0.97 | 0.98 | 0.98 |
| No Init Var | 0 | 0 | 0 | 0 | 1.50 | 1.51 | 1.53 | 98 | 99 | 104 | -129 | -108 | -69 | | | |
| | 24.00 | 9.25 | 8.5 | 6.25 | 1.47 | 1.48 | 1.50 | 92 | 94 | 99 | -141 | -120 | -81 | 0.98 | 0.98 | 0.98 |
| | 25.00 | 10.25 | 8.5 | 6.25 | 1.47 | 1.48 | 1.50 | 92 | 94 | 99 | -141 | -121 | -81 | 0.98 | 0.98 | 0.98 |
| | 26.00 | 11.25 | 8.5 | 6.25 | 1.47 | 1.48 | 1.50 | 92 | 94 | 98 | -142 | -121 | -81 | 0.98 | 0.98 | 0.98 |
| | 27.00 | 12.25 | 8.5 | 6.25 | 1.47 | 1.48 | 1.50 | 92 | 94 | 98 | -142 | -121 | -82 | 0.98 | 0.98 | 0.98 |

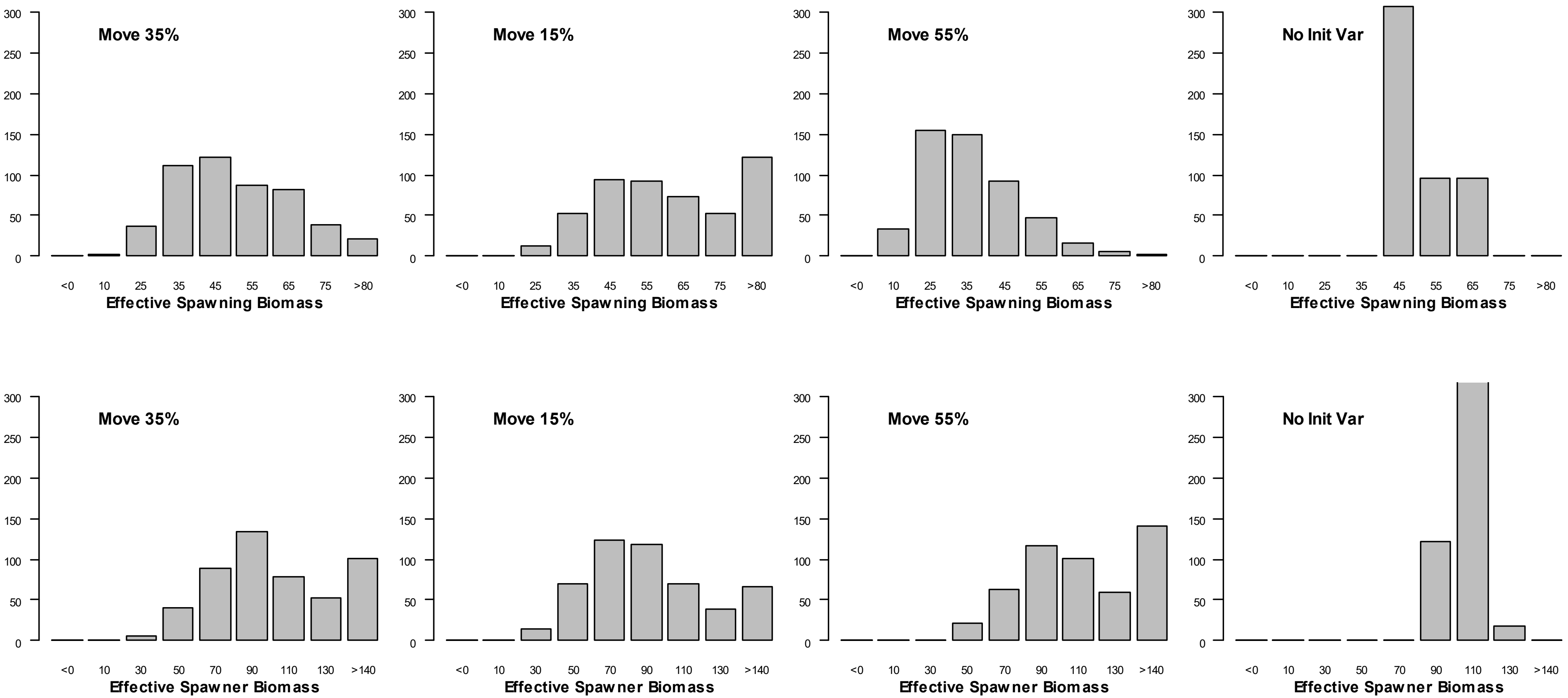


**Figure 1.** The histogram of the additive change (growth or shrinkage) in the **west component effective spawner biomass** (upper) and **south component effective spawner biomass** (lower) from November 2020 to November 2021 under a zero catch option and the alternative models considered. Note that the bin widths are not equal.

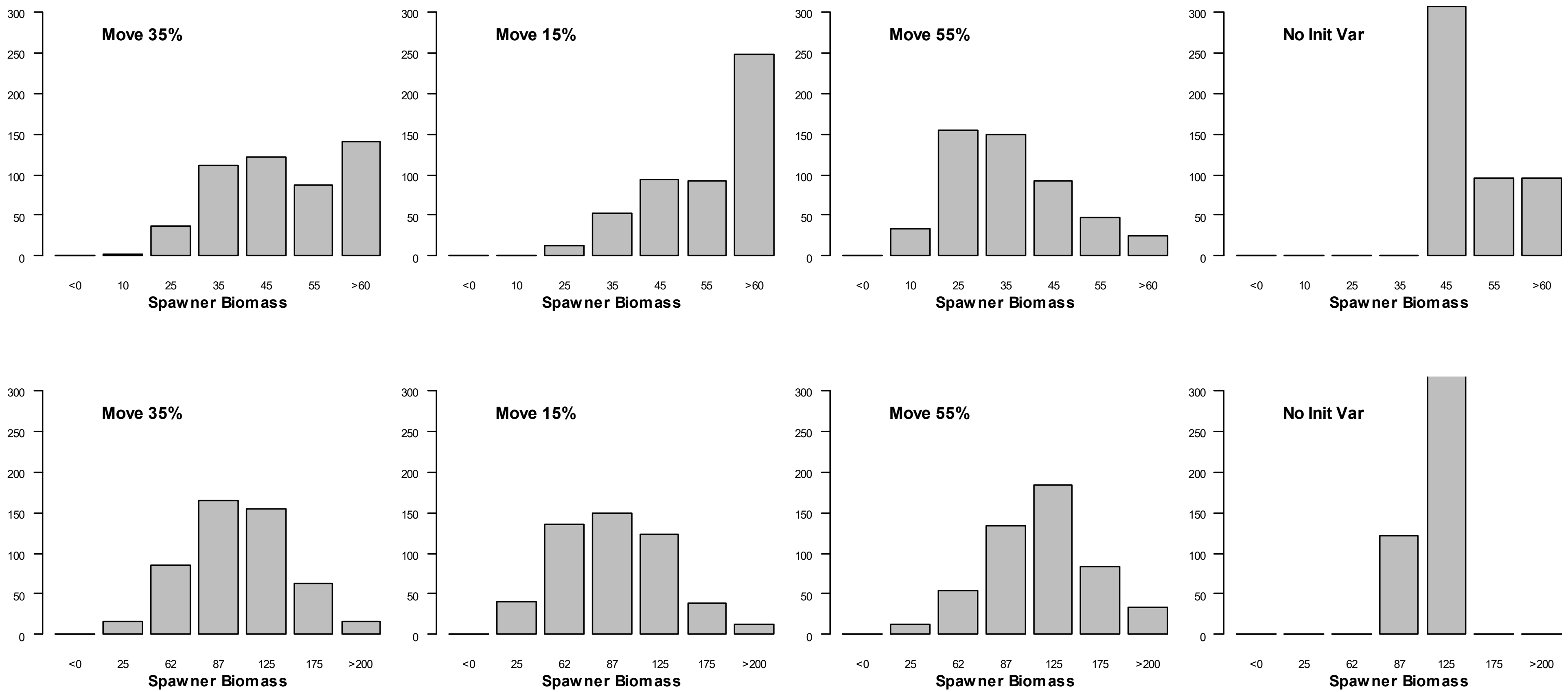


**Figure 2.** The histogram of the additive change (growth or shrinkage) in the **west component spawner biomass** (upper) and **south component spawner biomass** (lower) from November 2020 to November 2021 under a zero catch option and the alternative models considered. Note that the bin widths are not equal.

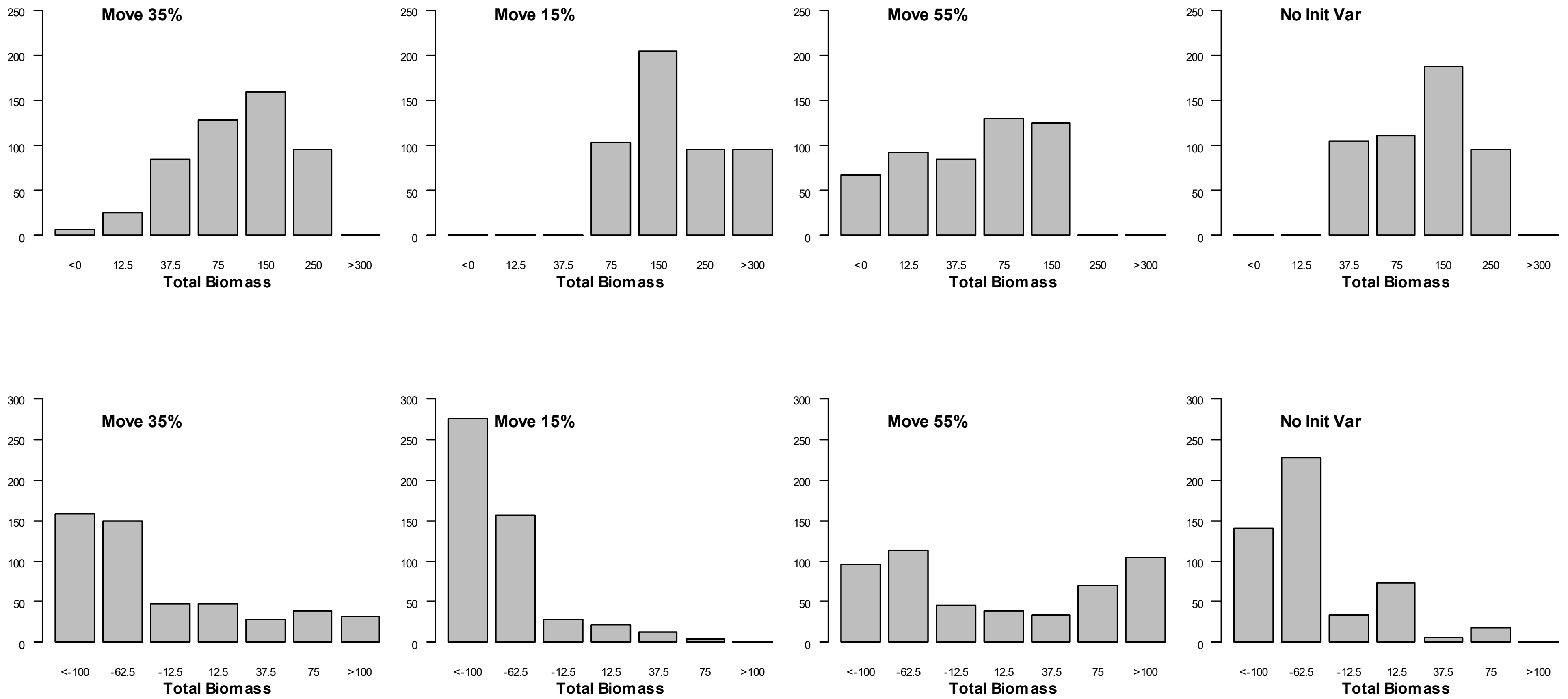


**Figure 3.** The histogram of the additive change (growth or shrinkage) in the **west component total biomass** (upper) and **south component total biomass** (lower) from November 2020 to November 2021 under a zero catch option and the alternative models considered. Note that the bin widths are not equal.

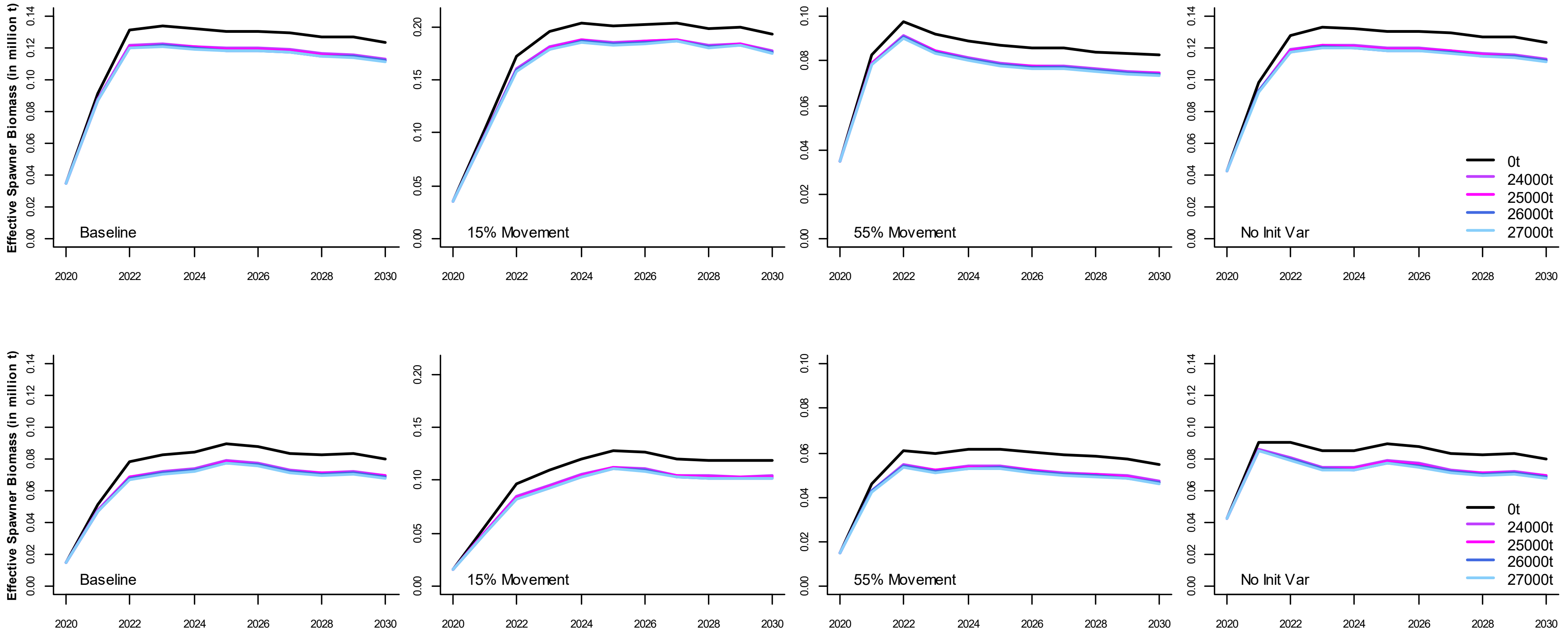


**Figure 4.** The projected medians (upper) and 5%iles (lower) of sardine **west component effective spawner biomass** from 2020 to 2030 under a no catch and four alternative catch scenarios corresponding to Table 1, for the alternative models considered. Note that the vertical axis differs between alternative models.

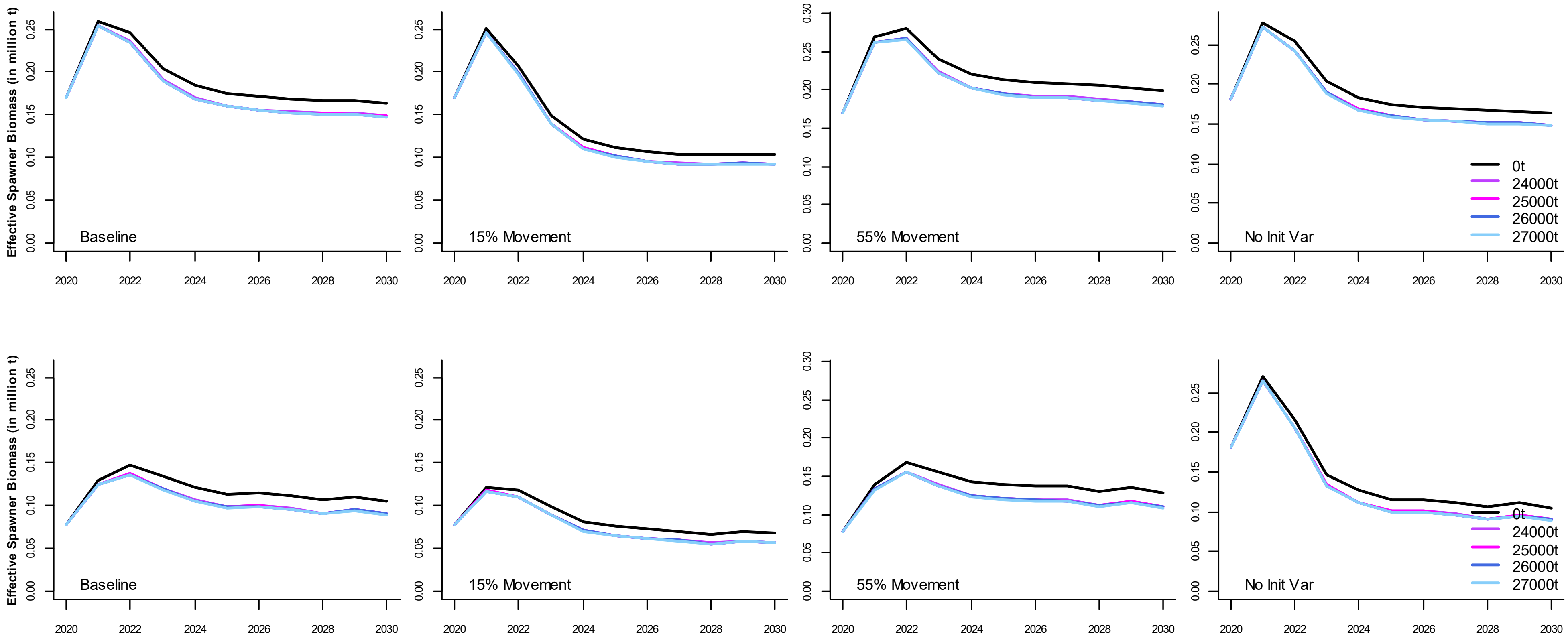


**Figure 5.** The projected medians (upper) and 5%iles (lower) of sardine **south component effective spawner biomass** from 2020 to 2030 under a no catch and six alternative catch scenarios corresponding to Table 2, for the alternative models considered. Note that the vertical axis differs between alternative models.

**Appendix A: Baseline projections using constant catch assumptions**

The projections will be run from November $y_1 = 2020$ to November $y_n = 2040$. The notation is the same as that of Appendix A and Tables A1 and A2 of de Moor (2020c). The following assumptions were made:

- The numbers-at-age are calculated as follows:

$$N^{S*}_{j,p,y,a} = \left(N^{S}_{j,p,y-1,a-1}e^{-M^{S}_{y,a-1}/2} - C^{S}_{j,p,y,a-1}\right)e^{-M^{S}_{y,a-1}/2} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le a \le 5^+ \qquad \text{(A1)}$$

$$N^{S*}_{j,p,y,5^+} = \left(N^{S}_{j,p,y-1,4}e^{-M^{S}_{y,4}/2} - C^{S}_{j,p,y,4}\right)e^{-M^{S}_{y,4}/2} + \left(N^{S}_{j,p,y-1,5^+}e^{-M^{S}_{y,5^+}/2} - C^{S}_{j,p,y,5^+}\right)e^{-M^{S}_{y,5^+}/2}$$
$$p = I, NI,\ y_1 \le y \le y_n \qquad \text{(A2)}$$

and

$$\mathrm{N}^{\mathrm{S}}_{\mathrm{W,p,y,a}} = \left(1 - \mathrm{move}_{\mathrm{y,a}}\right)\mathrm{N}^{\mathrm{S**}}_{\mathrm{W,p,y,a}} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le a \le 5^+$$
$$\mathrm{N}^{\mathrm{S}}_{\mathrm{S,p,y,a}} = \mathrm{N}^{\mathrm{S**}}_{\mathrm{S,p,y,a}} + \mathrm{move}_{\mathrm{y,a}}\mathrm{N}^{\mathrm{S**}}_{\mathrm{W,p,y,a}} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le a \le 5^+ \qquad \text{(A3)}$$

- Future infection is assumed to be zero (this is inconsequential to projections).
- Future movement of 1-year olds from the west to the south component is assumed to be time-invariant and $\mathrm{move}_{\mathrm{y,1}}$ =0.35[3].
- Future recruitment is generated from the past 5[4] years of recruitment under the assumption that future recruitment, particularly in the immediate short-term future, may be from a similar 'regime' to that of the more recent years. For example, recruitment may depend more on environmental conditions rather than on spawning stock biomass (Szuwalski *et al*. 2019). Autocorrelation in the historical recruitment time series is non-negligible, lending further weight to this being a preferred baseline choice for these analyses. As there was no May recruitment survey on the south coast in 2018 or 2019, the model estimates of recruitment in November 2017 and 2018 are imprecise, and future recruitment to the south component is therefore generated from the 5 years preceding these (Novembers 2012-2016, Die *et al.* 2019).
- Natural mortality is assumed to be time-invariant: $M^S_{y,a=0} = \overline{M}^S_{ju}$ and $M^S_{y,a=1+} = \overline{M}^S_{ad}$.
- No allowance is made for early/late recruitment in future years, i.e. $\varepsilon^t_y = 0$ in de Moor (2020c) equation (A8).
- Growth curves at the mid-point of each quarter (de Moor (2020c) equation A16) and therefore the quarterly commercial selectivity-at-age functions (de Moor (2020c) equation A15) are the same[5] for all future years.
- Growth curves in November (de Moor (2020c) equation A7) are thus also the same for all future years.
- Only the logistic part of the selectivity-at-length curve is used for future projections of alternative directed catches. Small sardine bycatch with directed >14cm sardine is assumed to consist of recruits-of-the-year.
- Future annual selectivity-at-age is assumed to be year-invariant (because selectivity-at-length becomes year-invariant) and averaged over all quarters:

$$S^S_{j,a} = 0.25\sum_{q=1}^{4}\sum_{l=2.5^-}^{24^+} A^{com}_{j,2021,q,a,l}S_{j,q,l} = 0.25 \quad 0 \le a \le 5^+ \qquad \text{(A4)}$$

- The numbers-at-length are calculated according to de Moor (2020c) equations (A5) and (A6).

[3] The average over the past 5 years is 0.34 for the base case model, and 0.41 over 2015-2019 and 0.38 over 2014-2018. The average over the past 10 years is 0.32.
[4] The most recent 5 or 10 years are frequent choices for the "recent past" in projection analyses internationally.
[5] Except in cases where the selectivity is modified to allow catch to be spread to lower ages (described below).

- The same maturity-at-length relationship, based on that corresponding to the period 1965-1975, is assumed from 2004 onwards, for all projected years.
- The November biomass, spawner biomass and effective spawner biomass are calculated according to de Moor (2020c) equations (A11) to (A13).
- Catch weight-at-age is taken to be the average of the weight-at-age in November immediately before and after the pulse fishery is assumed, i.e.,

$$w_{j,y,a}^{catch} = 0.5\left(w_{j,,a}^{S} + w_{j,a+1}^{S}\right) \quad 0 \le a \le 4$$

$$w_{j,y,5^+}^{catch} = w_{j,,5^+}^{S} \qquad \text{(A5)}$$

where

$$w_{j,y,a}^{S} = \sum_{l=2.5^-}^{l=24^+} A_{j,y,a,l}^{sur} w_{j,y,l}^{S} \qquad \text{(A6)}$$

- Catch is assumed to be taken in a single pulse, mid-way through the year. Small sardine bycatch (assumed to consist of 0-year-olds only[6]) is calculated as:

$$C_{j,p,y,a}^{bycatch} = \frac{Bycatch}{\sum_{p=I,NI} N_{j,p,y-1,a}^{S} e^{-M_{y,0}^{S}/2} w_{j,0}^{catch}} \times N_{j,p,y-1,0}^{S} e^{-M_{y,0}^{S}/2} \le N_{j,p,y-1,0}^{S} e^{-M_{y,0}^{S}/2}$$

and large sardine catch (taken to include directed catch and large sardine bycatch) is calculated as:

$$C_{j,p,y,a}^{dir} = \frac{Directed+Large\ Bycatch}{\sum_{a=0}^{5+}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times \left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} \text{, with}$$

$$\frac{Directed+Large\ Bycatch}{\sum_{a=0}^{5+}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times S_{j,5}^{S} \le 0.95$$

$$C_{j,p,y,a}^{S} = C_{j,p,y,a}^{bycatch} + C_{j,p,y,a}^{dir} \qquad p = I, NI, y > y_n, 1 \le q \le 4, 0 \le a \le 5^+ \text{(A7)}$$

- In cases where the above constraints would otherwise result in the realised catch being less than the scenario being tested, the selectivity is increased, with the catch being progressively taken from the older ages first:

i) Selectivity at age 5 is increased, such that a maximum of 95% of the available biomass of 5+ year olds is removed:

$$C_{j,p,y,5+}^{dir} = 0.95\left(N_{j,p,y-1,5+}^{S} e^{-M_{y,5+}^{S}/2} - C_{j,p,y,5+}^{bycatch}\right) < Directed + LargeBycatch$$

ii) If $\frac{Directed+Large\ Bycatch - C_{j,p,y,5+}^{dir} w_{j,5+}^{catch}}{\sum_{a=0}^{4}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times S_{j,4}^{S} \le 0.95$, then

$$C_{j,p,y,a}^{dir} = \frac{Directed+Large\ Bycatch - C_{j,p,y,5+}^{dir} w_{j,5+}^{catch}}{\sum_{a=0}^{4+}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times \left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} \text{ for } 0 \le a \le 4,$$

else selectivity at age 4 is increased, such that a maximum of 95% of the available biomass of 4 year olds is removed:

$$C_{j,p,y,4}^{dir} = 0.95\left(N_{j,p,y-1,4}^{S} e^{-M_{y,4}^{S}/2} - C_{j,p,y,4}^{bycatch}\right) < Directed + LargeBycatch - C_{j,p,y,5+}^{dir} w_{j,5+}^{catch}$$

and catches for ages 0 to 3 are calculated as follows:

iii) If $\frac{Directed+Large\ Bycatch - \sum_{a=4}^{5+} C_{j,p,y,a}^{dir} w_{j,a}^{catch}}{\sum_{a=0}^{3}\sum_{p=I,NI}\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/2} - C_{j,p,y,a}^{bycatch}\right) S_{j,a}^{S} w_{j,a}^{catch}} \times S_{j,3}^{S} \le 0.95$, then

[6] de Moor (2020b).

$C^{dir}_{j,p,y,a} = \frac{Directed + Large\ Bycatch - \sum_{a=4}^{5+} C^{dir}_{j,p,y,a} w^{catch}_{j,a}}{\sum_{a=0}^{3} \sum_{p=I,NI} \left( N^S_{j,p,y-1,a} e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a} \right) S^S_{j,a} w^{catch}_{j,a}} \times \left( N^S_{j,p,y-1,a} e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a} \right) S^S_{j,a}$ for $0 \leq a \leq 3$, else selectivity at age 3 is increased, such that a maximum of 95% of the available biomass of 3 year olds is removed:

$C^{dir}_{j,p,y,3} = 0.95 \left( N^S_{j,p,y-1,3} e^{-M^S_{y,3}/2} - C^{bycatch}_{j,p,y,3} \right) < Directed + LargeBycatch - \sum_{a=4}^{5+} C^{dir}_{j,p,y,a} w^{catch}_{j,a}$

and catches for ages 0 to 2 are calculated as follows:

iv) If $\frac{Directed + Large\ Bycatch - \sum_{a=3}^{5+} C^{dir}_{j,p,y,a} w^{catch}_{j,a}}{\sum_{a=0}^{2} \sum_{p=I,NI} \left( N^S_{j,p,y-1,a} e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a} \right) S^S_{j,a} w^{catch}_{j,a}} \times S^S_{j,2} \leq 0.95$, then

$C^{dir}_{j,p,y,a} = \frac{Directed + Large\ Bycatch - \sum_{a=3}^{5+} C^{dir}_{j,p,y,a} w^{catch}_{j,a}}{\sum_{a=0}^{2} \sum_{p=I,NI} \left( N^S_{j,p,y-1,a} e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a} \right) S^S_{j,a} w^{catch}_{j,a}} \times \left( N^S_{j,p,y-1,a} e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a} \right) S^S_{j,a}$ for $0 \leq a \leq 2$, else selectivity at age 2 is increased, such that a maximum of 95% of the available biomass of 2 year olds is removed:

$C^{dir}_{j,p,y,2} = 0.95 \left( N^S_{j,p,y-1,2} e^{-M^S_{y,2}/2} - C^{bycatch}_{j,p,y,2} \right) < Directed + LargeBycatch - \sum_{a=3}^{5+} C^{dir}_{j,p,y,a} w^{catch}_{j,a}$

and catches for ages 0 to 1 are calculated as follows:

v) If $\frac{Directed + Large\ Bycatch - \sum_{a=2}^{5+} C^{dir}_{j,p,y,a} w^{catch}_{j,a}}{\sum_{a=0}^{1} \sum_{p=I,NI} \left( N^S_{j,p,y-1,a} e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a} \right) S^S_{j,a} w^{catch}_{j,a}} \times S^S_{j,max} \leq 0.95$, where $S^S_{j,max} = max\left(S^S_{j,0}, S^S_{j,1}\right)$, then

$C^{dir}_{j,p,y,a} = \frac{Directed + Large\ Bycatch - \sum_{a=3}^{5+} C^{dir}_{j,p,y,a} w^{catch}_{j,a}}{\sum_{a=0}^{1} \sum_{p=I,NI} \left( N^S_{j,p,y-1,a} e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a} \right) S^S_{j,a} w^{catch}_{j,a}} \times \left( N^S_{j,p,y-1,a} e^{-M^S_{y,a}/2} - C^{bycatch}_{j,p,y,a} \right) S^S_{j,a}$ for $0 \leq a \leq 1$, else $C^{dir}_{j,p,y,a} = 0.95 \left( N^S_{j,p,y-1,a} e^{-M^S_{y,2}/2} - C^{bycatch}_{j,p,y,a} \right)$ for $0 \leq a \leq 1$[7]

[7] Cases where the full catch is not realised because this equation reaches the constraint, even after the modifications to the selectivity are made are indicated by dark grey shading in the results tables.