# Update of future projection program SSfuture C++. [1]

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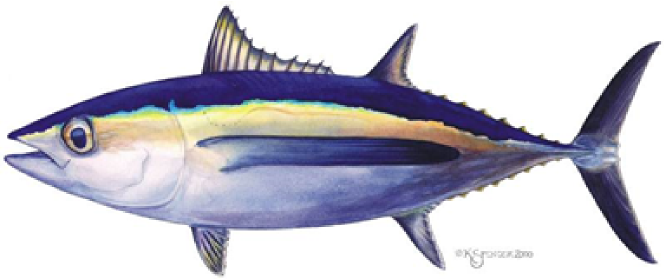

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# Abstract

R software SSfuture C++ is the future projection program that can use an output of Stock Synthesis 3 (SS3). This study constructed the new SSfuture C++ to reflect the updates of SS3. Two major revision points are 1) the population dynamics model change to quarterly, and 2) the fishing mortality rate calculates by age selectivity. Besides, the new version of the SSfuture C++ added the Harvest Control Rules (HCRs) and the options of process error due to the recruitment. As a result of these updates, consistency between SS3 and SSfuture C++ has increased. We also examined how to deal with uncertainty regarding the results of the stock assessment. SS3 ver3.30 can calculate the uncertainties of estimated values (e.g., the standard deviation from the Hessian matrix, bootstrap resampling, and MCMC). In the last stock assessment, the ISC albacore working group used the standard deviation given by the Hessian matrix, but this study will propose to use the result of bootstrap in the next stock assessment.


# Introduction

The result of future projection in the stock assessment is an essential indicator for decision making of management measures such as the Total Allowable Catch (TAC) and rebuilding for overfished stock. For example, in Pacific bluefin tuna, the International Scientific Committee for Tuna and Tuna-Like Species in the North Pacific Ocean (ISC) Pacific Bluefin tuna working group has operated R software SSfuture to support a rebuilding plan of Pacific bluefin tuna stock (Ichinokawa 2011), (Akita, Tsuruoka, Fukuda, Oshima, and Takeuchi 2015). SSfuture C++ corresponding to the population dynamics by sex was used in North Pacific albacore and Western central North Pacific swordfish stock assessment (Ijima, Sakai, Akita, and Kiyofuji 2016), (ISC 2018). These programs are implemented in R using the output results of Stock Synthesis 3 (SS3) (Methot Jr and Wetzel 2013). In recent years, the SS3 was updated (SS3 ver3.30). It is a major update, and the output format and population dynamics model were changed. Therefore, SSfuture C++ also needs to be updated.

Besides, future projections require the initial population numbers with uncertainties that are the result of stock assessment. SS3 can output uncertainties in multiple ways (e.g., the standard deviation from the Hessian matrix, bootstrap resampling, and MCMC). However the ISC albacore working group (ALBWG) has not discussed what kinds of uncertainties is the best for the stock assessment.

This study constructed the new SSfutureC++ reflecting the update of SS3. The new SSfutureC++ has two original options. First of all, the management options have been added to enable the Harvest Control Rule (HCR) and constant catch scenario. Secondly, we added process error options to evaluate the environmental effects on recruitment. To discuss uncertainties in SS3, we converted the previous SS3 files (ver. 3.24) of North Pacific albacore to the SS3 (ver. 3.30) and calculated three uncertainties, Hessian, bootstrap, and MCMC. These results were compared and examined the advantages of each methodology.

# Material and methods

## Population dynamics model

The population dynamics precess in the SSfuture C++ was set the same assumption as the SS3 ver3.30. The two sex quarterly population dynamics can explain as $N_{t,q+1,s,a} = N_{t,q,s,a}\exp(-Z_{t,q,s,a})$, where $N_{t,q,s,a}$ is number at age ($0 \leq a \leq A$) in year $t$ on quarter $q$ of sex $s$, $Z_{t,q,s,a}$ is total mortality at age $a$ in year $t$ on quarter ($q \in 1,2,3,4$) of sex $s$. Counting timing the number at age is the beginning of the calendar year. Thus the population number of the beginning year is

$$N_{t+1,1,a+1} = \begin{cases} N_{t,4,s,a}\exp(-Z_{t,4,s,a}) & (1 \le a \le A-1) \\ N_{t,4,s,A-1}\exp(-Z_{t,4,s,A-1}) + N_{t,4,s,A}\exp(-Z_{t,4,s,A}) & (a = A). \end{cases} \quad (1)$$

The seasonal total mortality is $Z_{t,q,s,a} = 0.25 \times M_{s,a} + F \times S_{t,q,s,a}$, where $F$ is a f multiplier, $S_{t,q,s,a}$ is selectivity at age $a$ in year $t$ on quarter $q$ of sex $s$, and $M_{s,a}$ is natural mortality at age $a$ of sex $s$. f multiplier $F$ can use the SS3 result of Spawning Potential Rate (SPR) analysis and can perform future projection at various fishing intensities. Furthermore, the option to set the constant catch and the HCR has been added, enabling more flexible future predictions.

The recruitment function is the Beverton Holt model that is the same as the SS3. The recruitment event occurs in quarter $q$.

$$N_{t,q,s,0} = cR_t, \quad (2)$$

$$R_t = \frac{4hR_0SB_t}{SB_0(1-h) + SB_{q,t}(5h-1)}\varepsilon_t, \quad (3)$$

where $c$ is constant sex ratio ($c$=0.5), $R_t$ is recruitment in year $t$, $h$ is steepness, $SB_0$ is the female spawning biomass in equilibrium condition, $R_0$ is the recruitment in equilibrium, $\varepsilon_t$ is a process error in year $t$. $SB_{q,t}$ is the amount of spawning female biomass in year $t$ at quarter $q$. The female spawning biomass calculates female population number $N_{t,q,fem,a}$ and fecundity at age: $f_a$ $SB_{q,t} = \sum_{a=0}^{A} N_{t,q,fem,a}f_a$. The process error $\varepsilon_t$ can be set a normal lognormal error ($\varepsilon_t \sim N(0, {\sigma_R}^2)$), autocorrelation, and an option considering an environmental index .

### Test run

The deterministic future projection of SS3 was compared with SSfutureC++ to evaluate the accuracy of SSfutureC++ update. As an example, the future projection of North Pacific albacore was carried out. The SS3 file used this test is the previous North Pacific albacore stock assessment result converted to SS3 ver3.30. Management option was assumed constant fishing mortality and set the fixes selectivity and F multiplier to the average of 2012-2014.

Various management options were also set to check the behavior of the program. Management options used for confirmation are $F_{msy}$, $F_{spr40\%}$, and constant catch scenario between 2012 and 2014. In these scenarios, the selectivity was fixed to the average value of 2012-2014, and the management option changed the F multiplier. As an alternative management option, SSfuture C++ can operate HCRs. In this study, we addressed a simple example of the HCR.

### Uncertainty of Stock Synthesis 3

SS3 can output the uncertainty of the estimated value by three methods that are a Hessian matrix, bootstrap and, Markov chain Monte Carlo methods (MCMC). For comparison of output results, the SS3 files of the North Pacific albacore stock assessment converted to SS3 ver3.30 were used. The Hessian matrix was given by the base case model, the Maximum Likelihood Estimate (MLE). The bootstrap created 100 boot files from the SS3 file of the base case model and obtained the results by running SS3 100 times. MCMC performed 1,000 re-samplings with MLE as the initial value. These results were summarized as a single figure. Also, paying attention to each output format, it was confirmed whether what is the best methodology for use in future prediction programs.

## Result and discussion

The future projection of the North Pacific albacore was carried out with the SS3 ver3.30 and SSfuture using the average selectivity of 2012-2014 and F multiplier to evaluate the accuracy of the projection results of the SSfuture C++. These projection results were almost identical (Figure.1, Figure.2,). This result indicates that consistency with SS3 has increased. Previous versions of the SSfuture needed time to calculate fishing mortality by solving the catch equation using the catch at age and the number at age. The new version is faster than the old version because the current version of the SSfuture C++ can directly use the selectivity of the SS3.

The projection accuracy of the management options set by the SSfuture C++ was evaluated. Three constant F and one constant catch management options were performed with the average selectivity of 2012-2014. SSfuture C++ outputted statistical results from 1,000 iterations considering the process error of ${\sigma_R}^2 = 0.5$. In the constant F option, the average value of the SSfuture C++ results almost coincided with the deterministic SS3 prediction results (Figure.3). The uncertainty of future predictions decreased with increasing fishing mortality (Figure.3). The SSfuture C++ can also perform a constant catch management option. When the future prediction was carried out with the average catch of 2012-2014, the amount of female spawning biomass was slightly larger than that of the constant F option of 2012-2014, indicating a considerable uncertainty (Figure.3).

The simple HCR options were applied in the SSfuture C++. The F multiplier reduces when the amount of spawning biomass will become less than $SB_{F40}$ (Figure.4 A). In this management scenario, the upper limit of F multiplier was set to an average value in recent years (2012-2014) (i.e., the fishing mortality would be not increased any more). Furthermore, fishing is prohibited when the stock amount below $20\%SB_{F=0}$. Considering that the stock assessment of North Pacific albacore is conducted once every three years, F multiplier changes once every three years (Figure.4 B). As a result of management by the HCR, the average amount of resources exceeded that of $SB_{F40}$ (Figure.4 C). In this projection, only the process error of the recruitment took into account the uncertainty. The range of recruitment was more extensive than the edge of past fluctuations (Figure.4 D). The estimated future catch will remain at the same as the 2012-2014 level (Figure.4 E).

It has been indicated that the SS3 result of the Maximum Likelihood Estimates (MLE) and MCMC were different (Stewart, Hicks, Taylor, Thorson, Wetzel, and Kupschus 2013). In future projection, the uncertainty of the initial value is required. Thus we compared the SS3 results of MLE, bootstrap, and MCMC and examined which calculation method is better (Figure.5 ). Each range of mean and uncertainty was very different. Comparing the average values, MLE was the lowest, and bootstrap was the highest. The range of uncertainty was highest for MLE and lowest for MCMC. The uncertainty of MLE was symmetrical, but the range of uncertainty of MCMC and bootstrap is asymmetrical. The Hessian matrix of MLE assumes that the data uncertainty follows a normal distribution, but the normal distribution can not explain the actual data variation. Therefore, bootstrap or MCMC is preferable for evaluating uncertainty. Regarding the stock status criteria, relative values such as a depletion late (e.g., $X\%SB_{F=0}$) have been used. The estimated reference points will change with the spawning biomass estimates. Thus it is considered that there is no significant change.

The output files of these uncertainty options are also different. The bootstrap provides all the necessary output, but the Hessian matrix of MLE does not have N at age output. It is necessary to calculate fishing mortality at age backward because the MCMC does not include selectivity in the output files. However, the accuracy of fishing mortality is low, and the calculation time is extended. Therefore, bootstrap is the best way to obtain an initial value for future projection. In addition, it is necessary to use the same uncertainty in the stock assessment and future projection (Stewart, Hicks, Taylor, Thorson, Wetzel, and Kupschus 2013). Thus, we suggest using the bootstrap results to evaluate the uncertainty of stock status.

## Summary and suggestions

- Two major revision points of the R software SSfuture C++ are 1) the population dynamics model changed to quarterly, and 2) the age selectivity and F multiplier in the output of SS3 can use directly for SSfuture C++.
- As a result of update, consistency between SS3 and SSfutureC++ were increased.
- The difference from SS3 ver3.30 is 1) The constant catch scenario can be executed, 2) flexible process error can use and, 3) there is a plurality of Harvest Control Rules.
- SS3 ver3.30 can calculate the uncertainty from the Hessian, the bootstrap sampling, and the MCMC, but each result is different.
- The methodology of uncertainty calculation used in future projection and stock assessment results should be unified.
- The Hessian matrix is not desirable. The Hessian matrix assumes that the data is normally distributed, but real data is not always normally distributed. Furthermore, SS3 ver3.30 does not calculate the standard deviation of the number of individuals.
- In the next stock assessment, we suggest using bootstrap for stock assessment model results, because the bootstrap can give all SS3 output files such as the number at age and selectivities.

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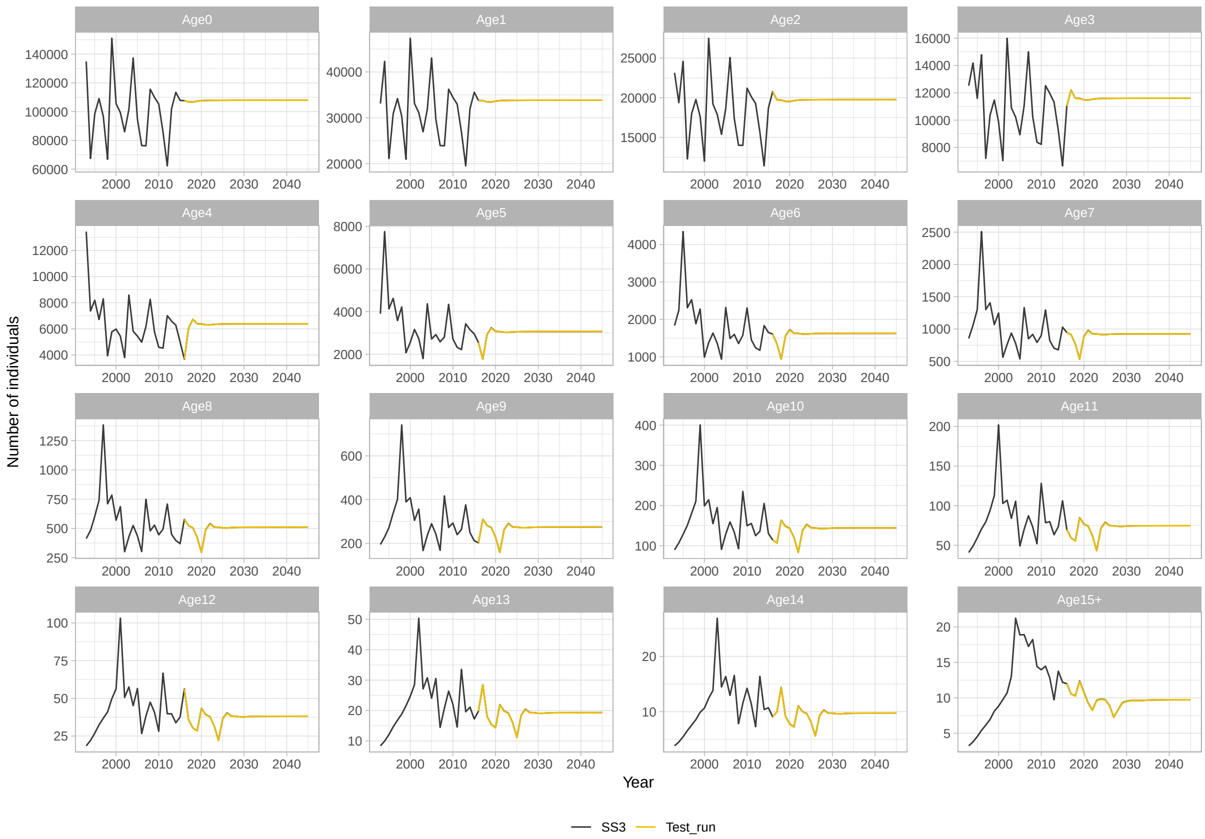


Figure 1: Comparison of the Stock Synthesis 3 ver 3.30 and the SSfuture C++. The female population number of North pacific albacore was projected thirty years with average fishing mortality (2012-2014).

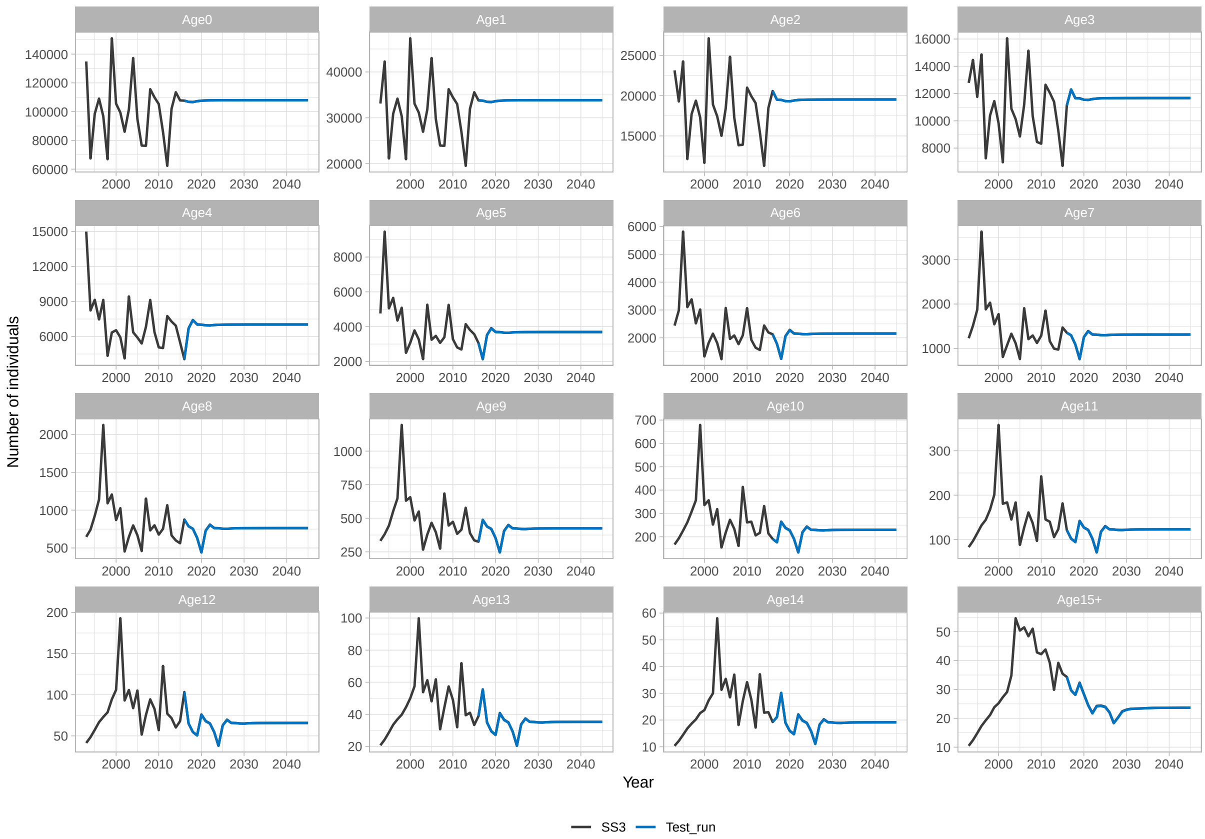


Figure 2: Comparison of the Stock Synthesis 3 ver 3.30 and the SSfuture C++. The male population number of North pacific albacore was projected thirty years with average fishing mortality (2012-2014).

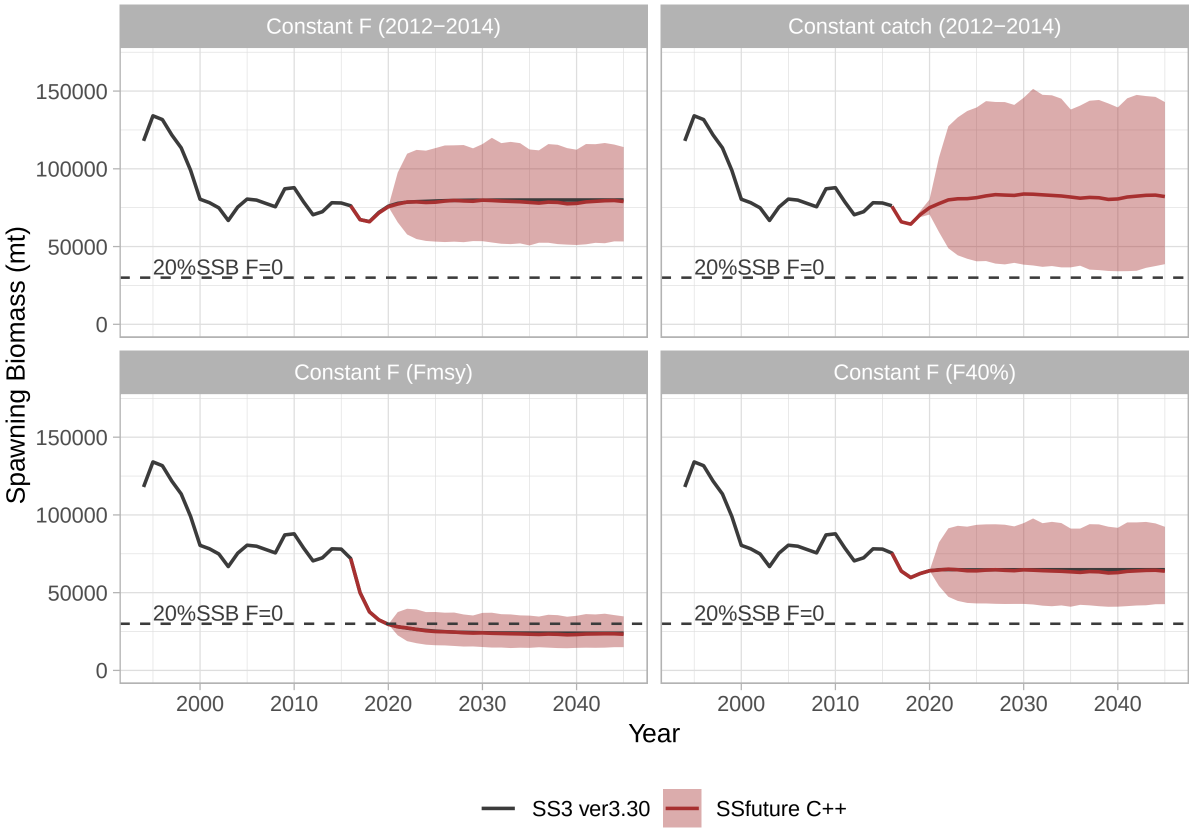


Figure 3: Future projection results with different management options. Option 1: Constant fishing mortality. Option 2: Constant catch. Option 3: Constant fishing mortality with F msy level. Option 4: Constant fishing mortality with F spr40% level. The selectivities assume average level of 2012-2014 in all options. SSfuture C++ calculated mean female spawning biomass and 95% tile using 1000 times iteration.

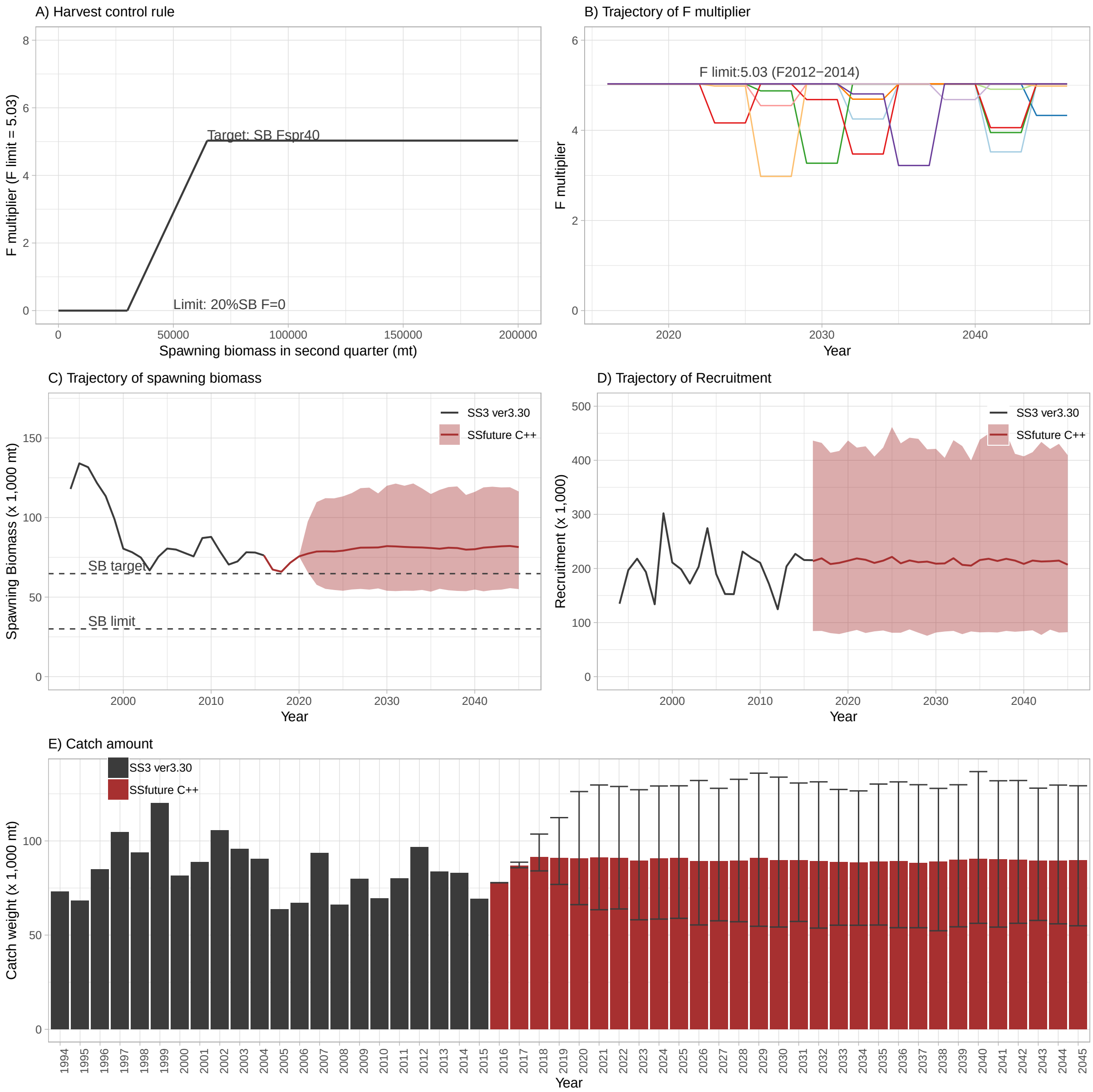


Figure 4: Results of future prediction using the Harvest Control Rule. A biological limit reference point is the 20% unfished spawning biomass ($20\%SB_{F=0}$). The biological target reference point set to the spawning biomass corresponds to the 40% spawning potential rate (SPR). The target reference point of fishing mortality set to the current level (2012-2014). When estimated spawning biomass below the target reference point, the F multiplier will decrease, and the limit reference point is a sleshhold of the ban of fishing. Management measures change every three years.

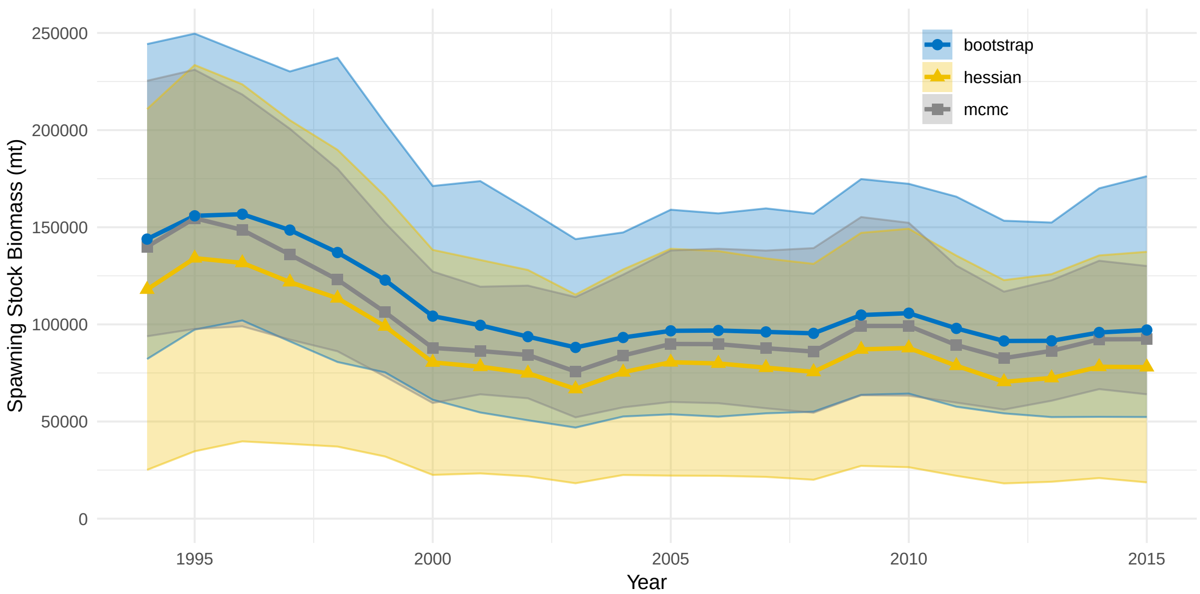


Figure 5: Stock Synthesis 3 ver 3.30 gives three outputs that are a Hessian matrix, bootstrap resampling, and MCMC. Solid lines are the likelihood estimate value (yellow), the mean value of bootstrap (blue), and the mean value of MCMC sampling (grey). The uncertainties denote 95% confidence interval (yellow), 95% tile of bootstrap samples (blue), and 95% credible interval (grey), respectively. The maximum likelihood estimate model gave the Hessian matrix. One hundred boot files were used for the bootstrap method. MCMC made one thousand samples.