Update of R packages ‘ssfuture’ for stochastic projections in future

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Summary
The detailed description of the updated software for stochastic future projection, especially the options used for the latest scenario for Pacific bluefin tuna in the PBFWG, was provided. Newly featured options include 1) flexible way of specifying periods in which estimated number of recruitment is resampled; 2) adjustment of fishing mortality not to exceed catch limits allocated for fleet groups and age classes. Under the condition where capping were set, both SSBs that are calculated by the old and new versions are almost the same. Furthermore, trajectory of catch by grouped fleets in future indicates that specified capping rules are accurately represented. Therefore, we conclude that updated version of the software works well and can be used for future projections in the next stock assessment.

1. Introduction

Pacific bluefin tuna (*Thunnus orientalis*) (PBF) is a highly migratory species found primarily in the North Pacific Ocean. PBF is an economically important fish stock with a long history of harvest by multiple Pacific Ocean nations, stock status determination and conservation advice for PBF are provided by both the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC).

Since 2008, future projections of PBF has been performed by using a software that is distributed as an R-package named 'ssfuture' and the detail is described in Ichinokawa (2012). This software can simulate quarterly age-structured population dynamics in a forward direction, which is identical in model structure used in the stock assessment model of PBF ('Stock Synthesis,' Method and Wetzel 2013).

Since 2012, in order to replicate management measures based on WCPFC CMMs and IATTC Resolutions, the software has been updated by adding several options for conducting complex scenarios (ISC-PBFWG 2012; Takeuchi et al. 2014; Fukuda et al. 2015). However, although the updated version of the software has played a major role in stock assessment of PBF, its detailed description has been remained unavailable.

In this document, the detailed description of the updated software is provided. First, we summarize a recent history of future projections for PBF from the 2012 stock assessment when the software was used before updating. Second, new options for both recruitment and harvesting scenarios are detailed, which were used for conducting requested scenarios for PBF. Third, we provide a comparison of results conducted by old version of the software in 2012 and that of new one in 2014 or later. Fourth, based on runs of the latest scenario that is introduced in ISC-PBFWG 2015 (Fukuda et al. 2015), we show the outputs indicative as to whether new options work well. Finally, we discuss the limitation and future update of the software. Note that the last author (Y.Takeuchi) updated the software, and the first and second author (T.Akita and I.Tsuruoka) carefully checked the source code and tested its behavior.

2. Recent history of future projections for PBF

Here, from the perspective of the implementation of new options associated with software updates, we provide a brief summary of the recent history of future projections for PBF (the details are well documented in Takeuchi et al. 2014 and Fukuda et al. 2015).

In recent several years, PBF has been managed by catch limit in the IATTC convention area, and combination of constant effort and catch limit strategy in the WCPFC convention area. This may be due to differences of general management approached between the IATTC (management of catch, or output controls) and WCPFC (combination of the fishing effort management and catch controls, or input/output controls). Thus, future projection reflecting the combination of various control methods (i.e., constant fishing mortality and catch limit) as a harvesting scenario has been required. In 2012 stock assessment (ISC-PBFWG 2012), several scenarios were conducted:

Stock assessment of PBF in 2012

Version: ssfuture 1.4 (old version)
Recruitment: randomly resampled from the whole stock assessment period (1952-2009)
Harvest: Constant fishing mortality with/without catch capping by fleet

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'ssfuture 1.4' is already documented version in Ichinokawa (2012) and can handle such recruitment and harvesting scenarios. In this document, we use the term 'catch capping' in the sense of annual catch limit, which limits maximum amount of catch with constant fishing mortality. This treatment mimics conditional constant effort policy and is imposed on each fleet (or group of fleets). In this version, same catch limit can be imposed onto all future projection years.

After 2012, updated version of 'ssfuture' has been used to handle further complicated scenarios for both recruitment and harvesting. In the 2014 stock assessment (ISC-PBFWG 2014, Takeuchi et al. 2014), additional projection scenarios were conducted to answer the request by the Northern Committee Ninth Regular Session (NC9):

Stock assessment of PBF in 2014

Version: ssfuture 1.8.6 (new version)
Recruitment: randomly resampled from a low period (1986-1988) for the first 2 years and

i. randomly resampled from a lower period (1980-1989) for the remaining projection years
ii. randomly resampled from the whole stock assessment period (1952-2009) for the remaining projection years

iii. randomly resampled from a lower period (1980-1989) for the next 10 years, but subsequently resampled from the whole stock assessment period (1952-2009)

Harvest: Constant fishing mortality with catch capping by fleet group, which can be separated into age0-2 and age3+

From this version of the software, several options are newly featured:

1. Resampling period can be specified in detail corresponding to a projected year.
2. Fleets can be lumped into groups of fleets. Number of group should be smaller than number of fleets.
3. Catch limit can be applied onto one or two contiguous age groups of a fleet group. In the latter case, e.g., considering age0-2 and age3+ separately, two more choices can be selected:
   (i) if catch limit is applied to an age group, no catch limit is imposed onto remaining age group;
   or
   (ii) setting two independent catch limits to two age groups.
4. "Block" catch limits was introduced. For example, catch limit with more than a year period, such as two-year period, can be applied.

With regard to the third new feature noted above, five out of seven scenarios including the scenario which gave the basis of conservation advise, considered in 2014 assessment, used 1st choice (3-i); while the remaining scenarios used the 2nd choice (3-ii).

In the ISC-PBFWG 2015 (Fukuda et al. 2015), latest scenario of future projection was conducted to consider the impact of possible very low level of recruitment in 2014:

PBF working group workshop in 2015

Version: updated 1.8.6 (same version used in the 2014 stock assessment)

Recruitment: randomly resampled from a low period in 1980s (1986-1988) for the first 2 years, resampled from a lowest year (1958) for the next year, and randomly resampled from a lower period (1980-1989) for the remaining projection years.

Harvest: Constant fishing mortality with catch capping by fleet group, which can be separated into age0-2 and age3+. Fukuda et al (2015) used the 2nd choice of the third new feature described in 2014 stock assessment.

Due to the newly featured options, it becomes possible to conduct a flexible scenario for future projections. For example, in the latest scenario, coastal fisheries in Japan (i.e., **F5-10**, **F14**) was classified into one group, and catch limit of the group for fish less than 30kg (younger than age 3) was set at 2,007 (mt/year) after 2014 while those of fish of 30kg or over was restricted to to 467 (mt/year).

Finally, we briefly note the background of recruitment scenarios used from the 2012 stock assessment. In 2012, stock assessment was conducted based on recruitment data obtained up to 2010, the level of recruitment seemed to be stable at that time, resampling of recruitment in future projections was from the whole stock assessment period (1952-2009). From 2013, however, the level of recruitment after 2009 was considered to possibly have started declining, resulting in a conservation advice based on the projections with lower recruitment scenarios. It should be noted that no spawner-recruitment relationships scenario was used in 2012 although the software is capable of implementing it, because the steepness of the representative run is very high ($h = 0.999$).

3. The options used for the latest scenario

Here, we describe the details of options newly incorporated into updated version of the software (ver. 1.8.6 or later), which is used for the latest scenario for PBF (Fukuda et al. 2015). While each projection is conducted from three hundred bootstrap replicates followed by twenty stochastic simulations (six thousand runs in total), following descriptions explain one run of the whole runs. **Table 1** summarizes all symbols used in this document.

3.1 Population dynamics

Currently, stock assessment for PBF is based on the time-interval with four seasons per year, thus future time series and ages are considered as sequential vectors with 0.25 intervals. In this document, years refer to *fishing years* unless otherwise specified, and **Table 2** summarizes the relationships between fishing year and other events relevant to future projections. Here, we introduce population dynamics of PBF in a forward direction, which provides the basis of a future projection. $N_{a,t}$ is the number of population at age a (= 0, 0.25, 0.5, 0.75, ..., 20.75) and year t (= 2012, 2012.25, ..., 2041.75). Recruitment is assumed to be occur at 1st quarter in a year (i.e., 2012, 2013, ...), written by

$$N_{0,t} = \begin{cases} R_t \ (t = 2012, 2013, \dots, 2041) \\ 0 \quad (\text{otherwise}) \end{cases}, \qquad (1)$$

where R_t means future recruitment that is resampled from estimated in a specified period of stock assessment, as explained later. Population dynamics follow a simple exponential decay, which is a function of fishing mortality ($F_{a,t}$) and natural mortality (M_a):

$$N_{a,t} = \begin{cases} N_{a-0.25,t-0.25}\exp[-F_{a-0.25,t-0.25} - M_{a-0.25}] \quad (0.25 \le a < 20.75) \\ N_{a-0.25,t-0.25}\exp[-F_{a-0.25,t-0.25} - M_{a-0.25}] \\ \quad +N_{a,t-0.25}\exp[-F_{a,t-0.25} - M_a] \qquad (a = 20.75) \end{cases}, \qquad (2)$$

where the last age (a = 20.75) is assumed to be an accumulating plus group. Estimated population numbers in 2012, denoted by $n_{a,2012}$, is used for the initial numbers ($N_{a,2012}$)

and $n_{a,2013}$ is not used due to effects of retrospective trend in the terminal year. M_a is given outside the stock assessment model. R_t and $F_{a,t}$ is determined by recruitment and harvesting processes, respectively, which are corresponding to a specified scenario.

3.2 Recruitment scenario: resampling from recruitments estimated in the stock assessment periods

Future recruitment, R_t, is randomly resampled from estimated number of age0 ($n_{0,t}$) in a specified period, mainly 1980s, which is considered as a low recruitment period:

$$R_t = \begin{cases} \{n_{0,1986}, n_{0,1987}, n_{0,1988}\} & (t = 2012, 2013) \\ \{n_{0,1958}\} & (t = 2014) \\ \{n_{0,1980}, n_{0,1981}, \ldots, n_{0,1989}\} & (t \geq 2015) \end{cases} . \tag{3}$$

As noted above, this complicated setting of recruitment reflects a knowledge based on the observation: 1) in 2012 and 2013, these recruitments were estimated to be very low, so three lower recruitment years in 1980s are used; 2) in 2014, as the estimated level of recruitment was less than that of 2012 or 2013, the estimated historical lowest level (in 1958) is used; 3) after 2015, it was expected that the low recruitment tendency continues (see also Takeuchi et al. 2014 and Fukuda et al. 2015). It should be noted that, under an estimated data set based on a certain bootstrap result (one of the three hundreds results), $n_{a,t}$ is a fixed value and future projections including a sampling uncertainty are repeated for twenty runs, but under another data set from a different bootstrap result, these values and thus R_t may change.

3.3 Harvesting scenario: constant fishing mortality with catch capping by fleet group, which can be separated into age0-2 and age3+

In the latest scenario, the combination of constant effort strategy and catch capping is taken into consideration in harvesting processes. Constant effort strategy can be interpreted as management of fishing mortality, F; therefore, averaged seasonal F in a specified period is used for determining catch levels for each quarter. Then, by each quarter, the amount of catch is subtracted from catch limit that is allocated every year; when the amount of catch with the F excesses the remaining catch limit, the F is modified to meet the catch limit.

Constant fishing mortality

Here, we show the essence of calculation of $F_{0204,a}$ that is geometrically averaged value of fishing mortality between 2002 and 2004, and is principally used for a future projection as constant fishing mortality. Fishing mortality at age in the stock assessment period, $f_{a,t}$ (a = 0, 1, .., 20; t = 1950, 1950.25, ..., 2012.75), can be obtained from numbers at age ($n_{a,t}$) and catch at age ($c_{a,t}$) by solving catch equation numerically:

$$c_{a,t} = \frac{f_{a,t}}{f_{a,t}+M_a}\left(1-\exp[-f_{a,t}-M_a]\right)n_{a,t}. \tag{4}$$

First, geometric mean of $F_{0204,a}$ is calculated by each quarter, because $f_{a,t}$ is different value between quarters reflecting the fishing term of each fleet, written by

$$\begin{aligned}
F_{0204,a,q=1} &= \left(f_{a,2002}\cdot f_{a,2003}\cdot f_{a,2004}\right)^{\frac{1}{3}},\\
F_{0204,a,q=2} &= \left(f_{a,2002.25}\cdot f_{a,2003.25}\cdot f_{a,2004.25}\right)^{\frac{1}{3}},\\
F_{0204,a,q=3} &= \left(f_{a,2002.5}\cdot f_{a,2003.5}\cdot f_{a,2004.5}\right)^{\frac{1}{3}},\\
F_{0204,a,q=4} &= \left(f_{a,2002.75}\cdot f_{a,2003.75}\cdot f_{a,2004.75}\right)^{\frac{1}{3}},
\end{aligned} \tag{5}$$

where q means quarter index (= 1, 2, 3, 4). Then, after some arrangements of $F_{0204,a,q}$, $F_{0204,a}$ (a = 0, 0.25, 0.5, 0.75, .., 20.75) can be obtained (e.g., $F_{0204,a=0.25}$ corresponds to $F_{0204,a=0,q=2}$).

$F_{0204,a}$ by fleet is also calculated using arithmetic mean of catch ratio of a certain fleet:

$$\begin{aligned}
F_{0204,a,f,q=1} &= \frac{1}{3}\left(\frac{c_{a,2002,f}}{c_{a,2002}}+\frac{c_{a,2003,f}}{c_{a,2003}}+\frac{c_{a,2004,f}}{c_{a,2004}}\right)F_{0204,a,q=1},\\
F_{0204,a,f,q=2} &= \frac{1}{3}\left(\frac{c_{a,2002.25,f}}{c_{a,2002.25}}+\frac{c_{a,2003.25,f}}{c_{a,2003.25}}+\frac{c_{a,2004.25,f}}{c_{a,2004.25}}\right)F_{0204,a,q=2},\\
F_{0204,a,f,q=3} &= \frac{1}{3}\left(\frac{c_{a,2002.5,f}}{c_{a,2002.5}}+\frac{c_{a,2003.5,f}}{c_{a,2003.5}}+\frac{c_{a,2004.5,f}}{c_{a,2004.5}}\right)F_{0204,a,q=3},\\
F_{0204,a,f,q=4} &= \frac{1}{3}\left(\frac{c_{a,2002.75,f}}{c_{a,2002.75}}+\frac{c_{a,2003.75,f}}{c_{a,2003.75}}+\frac{c_{a,2004.75,f}}{c_{a,2004.75}}\right)F_{0204,a,q=4},
\end{aligned} \tag{6}$$

and the arrangement noted above generates $F_{0204,a,f}$. Zero catch data are frequently existed in $c_{a,t,f}$, geometric mean of the catch ratio cannot be used.

Catch limit and its enforcement

Catch limit is potentially imposed on 12 categories which are classified as follows: 14 fleets are recognized into 6 groups, such as:

1st group: {**F1**-JLL}
2nd group: {**F2**-SPelPS, **F3**-TunaPSJS, **F4**-TunaPSPO}
3rd group: {**F5**-JpnTroll, **F6**-JpnPL, **F7**-JpnSetNetNOJWeight,
F8-JpnSetNetNOJLength, **F9**-JpnSetNetOAJLength_Q123,
F10-JpnSetNetOAJLength_Q4, **F14**-others}
4th group: {**F11**-TWLL}
5th group: {**F12**-EPOPS}
6th group: {**F13**-EPOSP}

and each group is divided into two classes: age0-2 and age3+. This age class reflects a boundary as to whether the catch of fish is less than 30 kg or not.

Let $\mathrm{CAP}_{g,i,t}$ be the amount of catch limit (mt/year) imposed on group g (= 1, 2, …, 6) and age class i (= 1, 2), and let $\mathrm{CAP}_{\mathrm{REST},g,i,t}$ be the amount of remaining catch limit. $\mathrm{CAP}_{g,i,t}$ is externally given (See Table1-3 in Fukuda et al. 2015 for detailed values of capping rules) and is allocated every year at beginning of 3rd quarter (corresponding to calendar year; i.e., t = 2012.5, 2013.5, …; see also **Table 2**), and is reduced by catch; thus, at beginning of each quarter, the amount of remaining catch limit can be written by

$$\mathrm{CAP}_{\mathrm{REST},g,i,t} = \begin{cases} \mathrm{CAP}_{g,i,t} & (t = 3^{\mathrm{rd}}\text{ quarter}) \\ \mathrm{CAP}_{\mathrm{REST},g,i,t-0.25} - \mathrm{TC}_{g,i,t-0.25} & (t \neq 3^{\mathrm{rd}}\text{ quarter and } \mathrm{CAP}_{\mathrm{REST},g,i,t-0.25} > \mathrm{TC}_{g,i,t-0.25}) \\ 0 & (t \neq 3^{\mathrm{rd}}\text{ quarter and } \mathrm{CAP}_{\mathrm{REST},g,i,t-0.25} \leq \mathrm{TC}_{g,i,t-0.25}) \end{cases}, \quad (7)$$

where $\mathrm{TC}_{g,i,t}$ means total catch in weight by group and age class. The case denoted in the third column indicates that fishing of the target age class is prohibited among the fleet group which excesses the catch limit; therefore, for all ages included in class i and all fleets included in group g, $F_{a,t,f}$ and $C_{a,t,f}$ equals zero.

At end of each quarter, $\mathrm{TC}_{g,i,t}$ is tentatively calculated under F_{0204} by catch equation and weight at age, $w_{a,f}$:

$$\mathrm{TC}_{a,f,t} = \frac{F_{0204,a,f}}{F_{0204,a}+M_a}\left(1 - \exp[-F_{0204,a} - M_a]\right)N_{a,t}w_{a,f}, \quad (8)$$

and by some arrangements (e.g., $\mathrm{TC}_{g=2,i=1,t} = \sum_{f=2}^{4}(\mathrm{TC}_{a=0,f,t} + \mathrm{TC}_{a=0.25,f,t} +, \ldots, +\mathrm{TC}_{a=2.75,f,t})$). Hereafter, the total catch under F_{0204} is denoted by $\mathrm{TC}_{g,i,t}|_{F0204}$. For all the groups and age classes, if the condition $\mathrm{CAP}_{\mathrm{REST},g,i,t} > \mathrm{TC}_{g,i,t}|_{F0204}$ (for all g and i) is not satisfied, the value of F should be modified; otherwise, F_{0204} is used for population dynamics at that quarter ($F_{a,t}$ is replaced by F_{0204} in Eq. 2).

As following, for all the groups and age classes such that $\mathrm{CAP}_{\mathrm{REST},g,i,t} > \mathrm{TC}_{g,i,t}|_{F0204}$, an algorithm to calculate modified F_{0204} that makes the corresponding fleet groups just run out the catch limit simultaneously (i.e., $\mathrm{CAP}_{\mathrm{REST},g,i,t} \approx \mathrm{TC}_{g,i,t}|_{F}$ for all corresponding groups and age class) is shown:

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1. $F_{0204,a,f}$ for corresponding age and fleet is multiplied by 0.5 and named $F_{0204\mathrm{NEW}}$
2. substituting $F_{0204\mathrm{NEW}}$ into Eq. (8), $\mathrm{TC}_{g,i,t}|_{F02004\mathrm{NEW}}$ is calculated
3. calculate $\Delta\mathrm{CAP}_{g,i,t} = \mathrm{CAP}_{\mathrm{REST},g,i,t} - \mathrm{TC}_{g,i,t}|_{F02004\mathrm{NEW}}$, that means the difference between the target and tentative value of total catch
4. if $|\Delta\mathrm{CAP}_{g,i,t}| < 0.1 \times \mathrm{CAP}_{\mathrm{REST},g,i,t}$, $F_{0204\mathrm{NEW}}$ is adopted and used for calculating population dynamics as $F_{a,t}$ (Eq. 2); otherwise, go next step

5. to make the difference ($\Delta \mathrm{CAP}_{g,i,t}$) close to zero, $F_{0204\mathrm{NEW}}$ is updated by multiplying $\frac{\mathrm{CAP}_{\mathrm{REST},g,i,t}}{\mathrm{TC}_{g,i,t}|_{\mathrm{F02004NEW}}}$ and go step 2
6. if this process is repeating 50 times, end the improving of $F_{0204\mathrm{NEW}}$ and use it

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Changes of F of certain group affect the catch of other groups (see Eq. 8); thus, for all the corresponding groups, improving of F needs to carry out simultaneously. In other words, for all relevant ages and fleets, F is approximately calculated such that Eq. 8 and $\mathrm{CAP}_{\mathrm{REST},g,i,t} = \mathrm{TC}_{g,i,t}|_F$ satisfied. In practice, there are some cases such that $\mathrm{CAP}_{\mathrm{REST},g,i,t} - \mathrm{TC}_{g,i,t}|_F < 0$; in this case, the amount of catch excesses the limit (perhaps slightly), the amount of catch in next quarter is zero (third column in Eq. 7) unless 3rd quarter comes. Note that this searching method is similar to an algorithm implemented in 'Stock Synthesis' as the current default option to solve catch equation.

In the latest scenario that reflects measures implemented in the respective year, there are two special cases for determining F. First, for **F12**, twice of F_{0204} is used as default setting in order to realize constant catch strategy (i.e., approaching to catch limit quickly) for both age classes. Second, for **F13**, default setting of F_{0204} is multiplied by some value to meet F_{0911}, that is mean value of fishing mortality between 2009 and 2011.

4. Results

4.1 Validation of the updated software with that of old version including capping options

A comparison of the results conducted by old version and new version is provided. Since capping option in the old version can be applied only for individual fleet without separation of age classes, i) **F12** that is corresponding to group 5 in new version is selected for a capping target and ii) age class of new version is divided into age0-21 and age22+ where the later class is dummy. **Figure 1** illustrates trajectories of median of SSB calculated under the old and new versions. The both seem almost identical, suggesting that there is no additional error associated with update processes. It should be noted that the old version has been validated as being capable of generating highly similar results on numbers-at-age and catch weight by fleets with deterministic future projections generated by 'Stock Synthesis' (Ichinokawa 2012).

4.2 Demonstration of how capping rule works

Based on a run of projection that is randomly chosen, effect of capping rules applied for each group is demonstrated. **Figure 2a** and **2b** illustrates the trajectory of SSB (defined by $\sum_{a=0}^{20.75} w_a Q_a N_{a,t}$) and recruitment of this run, respectively. While the run seems bad in terms of a stock rebuilding probably due to a long series of low recruitments, the projection tells us important points. **Figure 2c** and **2d** represents the trajectory of multiplier to $F_{0204,a,t}$ in this bad run for groups 2 and 3, respectively, illustrating effect of capping rule. First, between 2012 and 2014, there are less chances for enforcement of capping rule; after 2015 when 50% reduction of catch of < 30kg starts, the capping rule seems like working well to hold stable dynamics of PBF, although the level is lower. Second, unless rebuilding of SSB, there are less chances for enforcement of capping rules for age3+ than age0-2. Third, selectivity for targeting PBF and strength of fishing mortality among groups reflect the difference of frequency and strength of capping. For example, after 2015, while group 2 of < 30kg approaches to the catch limit every year (**Fig. 2c**), that of group 3 does not until PBF begins to rebuild and/or a relatively strong recruitment occurs (**Fig. 2d**).

Technically speaking, under an adoption of improved $F_{0204\mathrm{NEW}}$ with 10% intervals (i.e., the condition, $|\Delta \mathrm{CAP}_{g,i,t}| < 0.1 \times \mathrm{CAP}_{\mathrm{REST},g,i,t}$, is required), repeating of improving processes are always less than five times in the run (results are not shown), suggesting that the convergence seems to be quick and that the method of improving $F_{0204\mathrm{NEW}}$ to meet catch limit is well worked.

4.3 Stochastic projections in the latest scenario

Stochastic projections of recruitment and SSB is demonstrated, as shown in **Fig.3a** and **3b**, respectively, which are already shown in Fukuda et al. (2015) but modified very slightly by minor updates. Median of recruitment well reflects three phases of specified periods for resampling (**Fig. 3a**). As noted in Fukuda et al. (2015), probability that SSB is more than $\mathrm{SSB}_{\mathrm{med}}$ in 2024 is around 70% (**Fig. 3b**).

Figure 4 represents stochastic projections of catch by group 2 and group 3, which is separated into age0-2 and age3+. While median of SSB keeps increasing from around 2020 (**Fig. 3b**), in all groups and age classes, medians of catch converge into the corresponding upper limit of 90% confidence intervals, implying that capping rule works in many of runs. Furthermore, the convergent values associated with an increasing of SSB are identical to the catch limits (details are in Fukuda et al. 2015), suggesting that the software works well.

5. Discussion

In this document, we provide a description of updated version of the software, 'ssfuture,' which allows flexible options for both recruitment and harvesting scenarios, and thus can simulate a realistic nature of fisheries management and corresponding PBF dynamics in future. This software has an advantage of not only a treatment of stochastic nature, but also calculating *F* that is modified to meet catch limit among all fleets with holding a consistency between input and output controls. In other words, given capping rules, corresponding fishing mortality and effort which reflect many types of fisheries (e.g., selectivity, fishery timing) can be calculated. This point is important especially for PBF, which represents a complicated fishery form.

It is true that there is an opinion that maturity applied in the PBF stock assessment should be applied for definition of juvenile in the future projections (e.g., ‘adult’ includes 20% of age3 and 50% of age 4). However, the implementation of this complex definition to capping rule is not easy. It might be informative to conduct sensitivity analyses about stepwise changing of breakpoint of age separating ‘juvenile’ and ‘adult.’

Finally, we note the future plan of implementation or update for PBF. First, implementation of more realistic recruitment scenario may be desirable than simple resampling from estimated recruitments. For example, a recruitment scenario following the Beverton-Holt stock recruitment relationship (BH-SRR) with optional settings of parameters (steepness, h; unfished equilibrium spawning biomass, S_0; unfished equilibrium spawning recruitment, R_0; SD of log recruitment, σ_R) and random resampling of past deviances of recruitment (R_{dev}) is considered as one of candidates, written by

$$R_t = \widehat{R_t}\exp\left[-\frac{\sigma_R^2}{2} + \log R_{\mathrm{dev}}\right], \quad (9)$$

where

$$\widehat{R_t} = \frac{4hR_0\mathrm{SSB}_t}{S_0(1-h)R_0 + \mathrm{SSB}_t(5h-1)}. \quad (10)$$

The basis of this option is already implemented in the original version but later it was broken due to the update of SS software, and was reimplemented in the latest version but has not yet been fully tested. In addition, in the latest version, BH-SRR with parametric additional recruitment deviation with given σ_R is also implemented, written by

$$R_t = \widehat{R_t}\exp[\varepsilon], \quad (11)$$

where $\varepsilon \sim N\left(-\frac{\sigma_R^2}{2}, \sigma_R^2\right)$.

Second, usage of target fishing mortality as a constant effort would be more flexible than use of single fishing mortality. For example, if fishing mortality can be specified separately (by fleet, group, and age), effects of more flexible and realistic management can be evaluated, where these options are also implemented in the latest version.

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Table 1 List of mathematical symbols (See also Ichinokawa, 2012)

Variables and parameters	Definition	SS outputs
$n_{a,t}$	Estimated population numbers	#NUMBER AT AGE
$N_{a,t}$	Future population numbers (Eq. 1 and 2)	
R_t	Future recruitment (Eq. 3)	
$c_{a,t,f}$	Estimated catch number by fleer	#CATCH AT AGE
$c_{a,t}$	Estimated catch number ($\sum_{f=1}^{14} c_{a,t,f}$) (Eq. 4)	
$f_{a,t}$	Estimated fishing mortality (Eq. 4)	
$F_{0204,a,q}$	Geometric mean of F between 2002 and 2004 (Eq. 5)	
$F_{0204,a,f,q}$	Geometric mean of F between 2002 and 2004 by fleet (Eq. 6)	
M_a	Natural mortality at age	#Biology at age$M
$w_{a,f}$	Weight at age by fleet	#Biology at age$Selwt
w_a	Weight at age	#Biology at age$Wt_Beg
Q_a	Maturity at age	#Biology at age$ Age_Mat
SSB_t	Spawner stock biomass ($\sum_{a=0}^{20.75} w_a Q_a N_{a,t}$)	
$\mathrm{CAP}_{g,i,t}$	Catch limit by group at age class	
$\mathrm{CAP}_{\mathrm{REST},g,i,t}$	Amount of remaining catch limit by group at age class (Eq. 7)	
$\mathrm{TC}_{a,f,t}$	Total catch in weight at age by fleet (Eq. 8)	
$\mathrm{TC}_{g,i,t}$	Total catch in weight by group at age class	
$F_{0204NEW,a}$	Improved F to meet catch limit	
$\Delta\mathrm{CAP}_{g,i,t}$	Difference between the target and tentative value of total catch ($\mathrm{CAP}_{\mathrm{REST},g,i,t} - \mathrm{TC}_{g,i,t}\|_{F2004NEW}$)	
g	Group index (1-6, see main text)	
i	Age class index (*i*=1: age0-2; *i*=2: age3+)	
h	Steepness	
S_0	Unfished equilibrium spawning biomass	
R_0	Unfished equilibrium spawning recruitment	
σ_R	SD of log recruitment	
R_{dev}	Random resampling of past deviances of recruitment	

Note: $f_{a,t}$, $F_{0204,a,q}$, and $F_{0204,a,f,q}$ are in age 0, 1, 2, ... , but these three are easily converted into the value for quarter ages (see main text).

Table 2 Fishing year and corresponding events

Fishing year	2012				2013				2014				2015-			
Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Alloation of catch limit			✔				✔				✔				✔	
Recruitment	✔				✔				✔				✔			
Resampling years	{86',87',88'}				{86',87',88'}				{58'}				{80',81',…, 89'}			

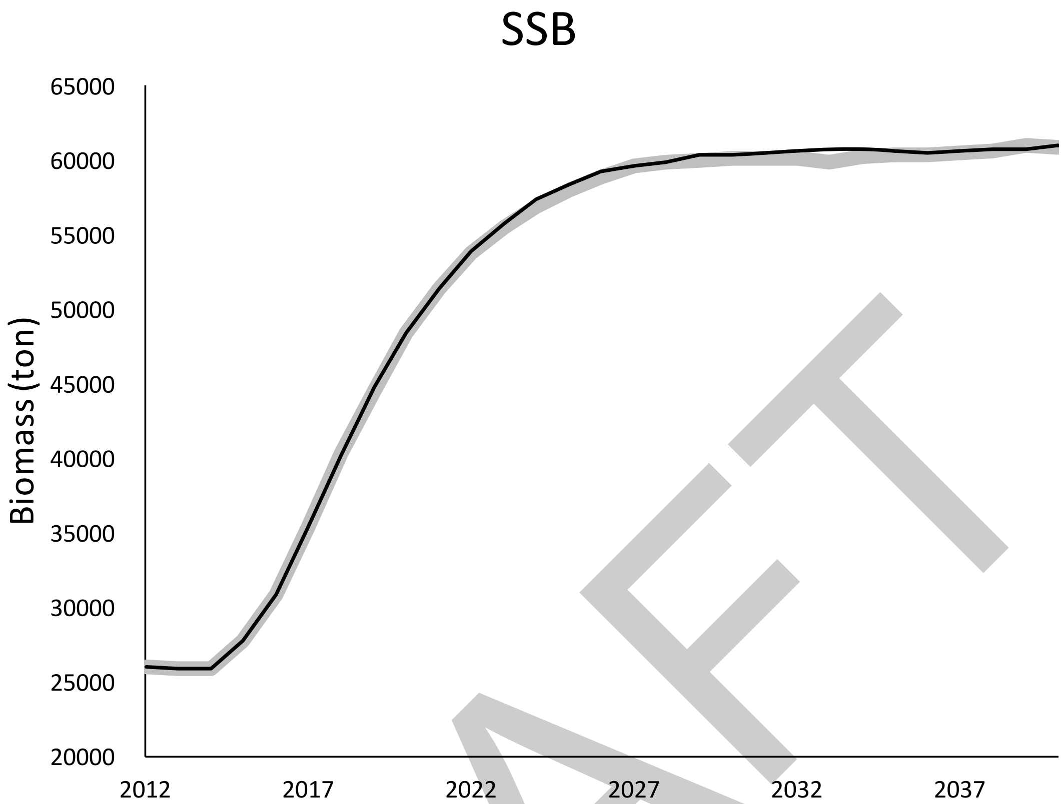

Figure 1: Comparison of median of SSBs calculated by old version (denoted by gray line) and new (denoted by black line) version of the software. For a simple comparison, capping is used only for **F12** with catch limit 3300 (mt/year).

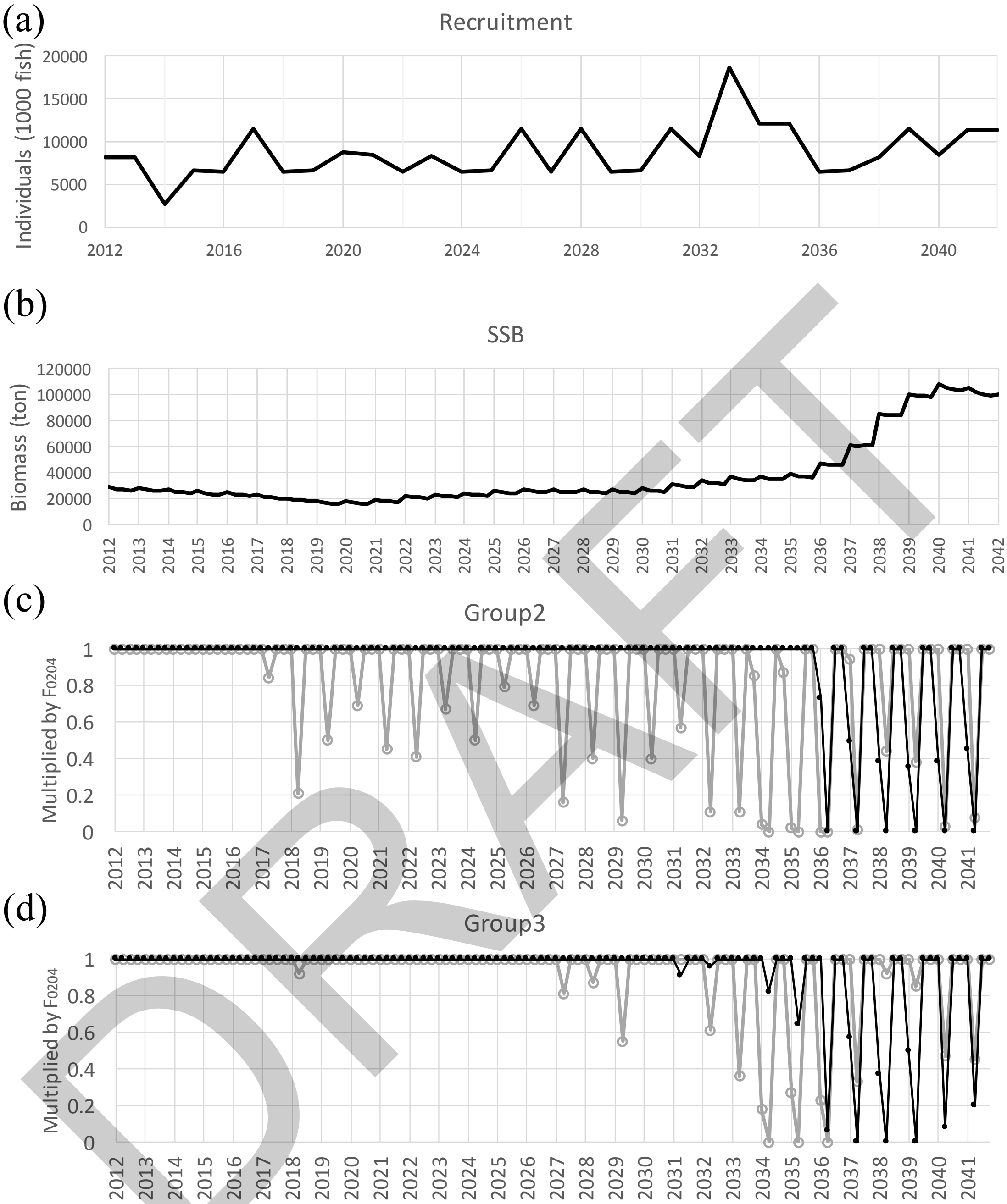

Figure 2: Trajectories of recruitment (a), SSB (b), and enforcement of capping rules (c and d) in a run that is randomly chosen. In (c) and (d), gray line and black line indicate the value multiplied by F_{0204} for age0-2 and age3+ class, respectively.

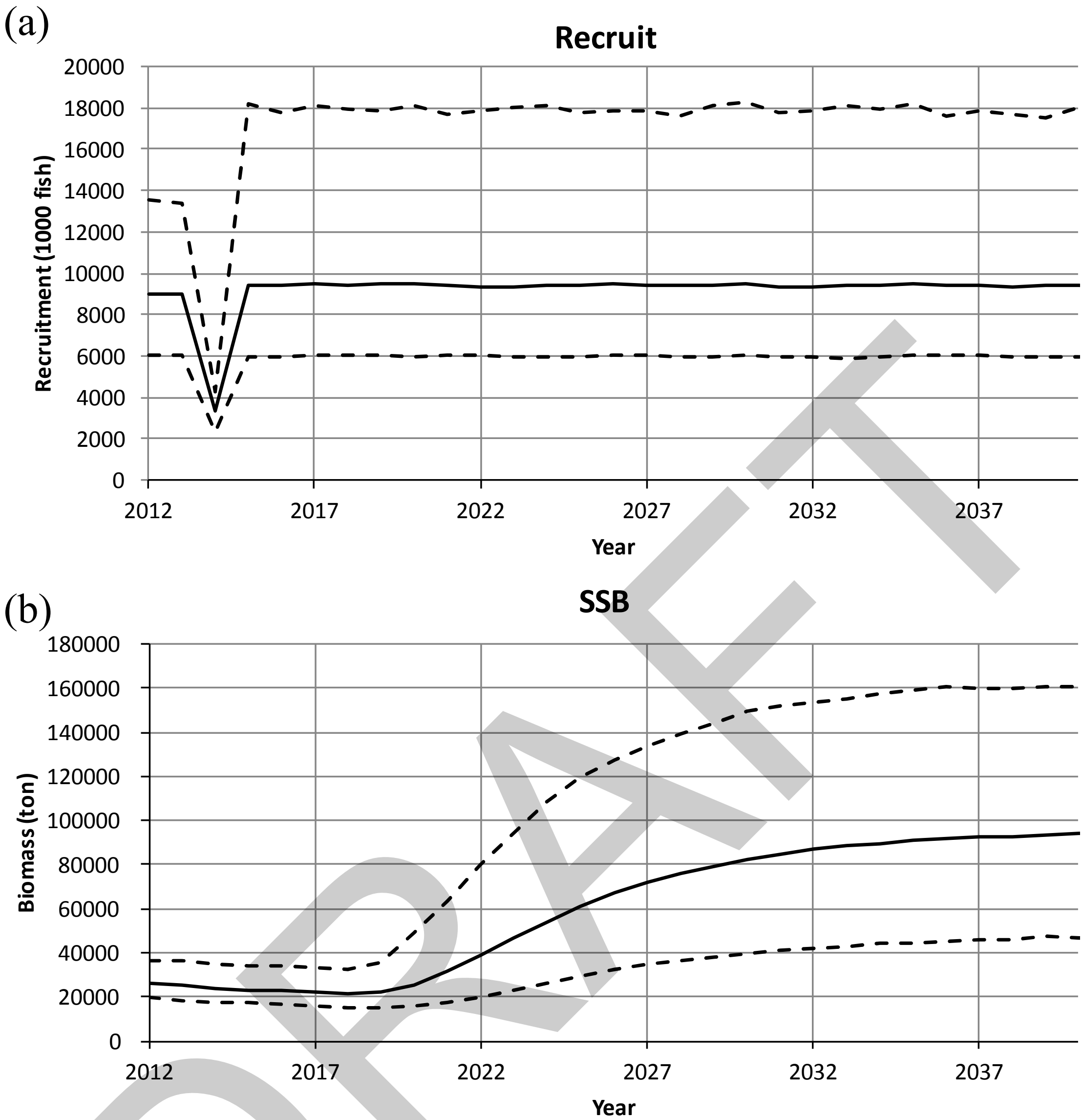

Figure 3: Trajectories of recruitment (a) and SSB (b). Solid line and dotted line represent median and 90% confidence intervals, respectively.

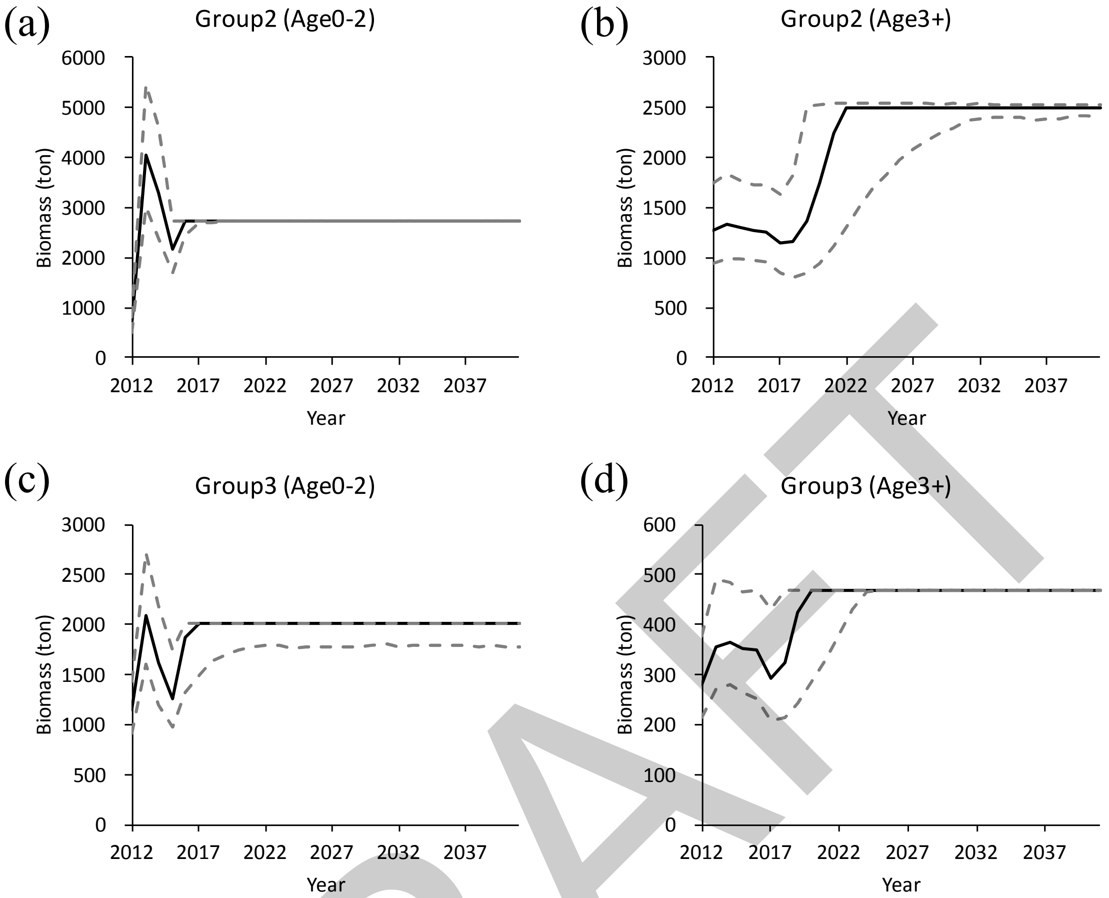

Figure 4: Trajectories of catch by group and age class. Solid line and dotted line represent median and 90% confidence intervals, respectively.